Proceedings of the

1st International Symposium on Academic Makerspaces

November 13– 16, 2016
Massachusetts Institute of Technology
Cambridge, MA 02139

ISAM was founded, and is run, by the

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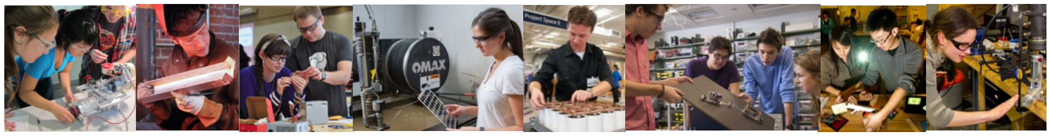


Dear Colleague:

Welcome to the 1st International Symposium on Academic Makerspaces (ISAM). *ISAM joins the people, knowledge, and inspiration that fuse to catalyze makerspaces that have maximum impact upon the student learning experiences in higher education and alumni success*. We foster community, networking, and interaction between people that are passionate about making. This community includes, but is not limited to, student and faculty advocates, upper administration/leadership, government policy makers, educational researchers, and designers/practitioners.

Why ISAM? Higher education makerspaces impact the efficacy of student learning in fields that include science, engineering, music, entrepreneurship, medical/biomedical, architecture, mathematics, literature, and more. These spaces have demonstrated an ability to foster highly beneficial interdisciplinary interactions and supportive peer communities that extend beyond the boundaries of a makerspace. This nascent field is fast growing, and now is the time to gather people and knowledge together so that resources are best used to rapidly and broadly infuse makerspaces in higher education. ISAM was created to make this happen.

ISAM gathers, and makes available, knowledge and best practices that this community may use to form student maker communities, get students excited about using these spaces, perpetuate a culture of safe, fun and responsible use, and to select appropriate practices, programming, safety policies, training, staffing, and equipment. ISAM believes in providing a balance of knowledge types, and approaches, that enable a broad understanding of diverse options for obtaining measureable impact makerspaces. We believe there is no right answer to how *all* makerspaces should be set up and run, just the right answer for *your* university.

The response to this event has been beyond our expectations, with over 50 papers and posters to be presented by participants from across the globe. These proceedings provide anecdotal, applied, and scientific knowledge related to community, culture, training, equipment, programming, funding/financial, metrics and data, and many other topics.

Our special thanks go to fellow members of the Higher Education Makerspace Initiative (HEMI), the MIT Innovation Initiative, the volunteers that reviewed papers, and our sponsors - Tormach, The Infosys Foundation, Autodesk, Formlabs, VentureWell, and Stratasys - for their support. We extend our thanks to the members of the organizing committee and the instructors of the short courses for devoting their time to making this event successful. We are immensely grateful to our industry sponsors, who made it possible to fund student maker travel/participation. Finally, we thank you for your participation, and hope that you will find your interactions with this community to be an enriching experience.

Professor Martin L. Culpepper
Co-chair, ISAM 2016
Massachusetts Institute of Technology

Dean Vincent Wilczynski
Co-chair, ISAM 2016
Yale University

Welcome to ISAM 2016

We, the principal representatives of each HEMI university, have sought to have the means to *form a community of maker advocates that help each other*. We believe this community will be the key ingredient to a future full of prosperous academic makerspaces. Feel free to come up and introduce yourself, we'd love to get to know you and hear about your school's efforts.

P. Zach Ali, Carnegie Mellon University
Favorite making activity: Robotic fabrication
Zach is Technical Director for Carnegie Mellon University's Integrative Design, Arts & Technology (IDeATe) Network. Zach has been researching and deploying makerspaces since 2005.

Prof. Malcom Cooke, Case Western Reserve University
Favorite making activity: 3D printing anatomical models for surgical research
Malcolm is an Associate Professor in the Department of Mechanical and Aerospace Engineering. He is the executive director for Sears Think[box].

Prof. Martin L. Culpepper, Massachusetts Institute of Technology
Favorite making activity: Wheelies on my Ducati, Waterjet, Glassblowing
Marty is a Professor of Mechanical Engineering. He is MIT's Maker Czar - advocate for MIT's makerspaces - and leads the Project Manus effort to upgrade and enhance MIT's maker system and capabilities.

Prof. Craig Forest, Georgia Institute of Technology
Favorite making activity: Halloween costumes
Craig is an Associate Professor of Mechanical Engineering at the Georgia Institute of Technology. He is the Faculty Founder of the Georgia Tech Invention Studio, a student run makerspace that serves all of Georgia Tech.

Prof. Björn Hartmann, University of California, Berkeley
Favorite making activity: PCB milling
Björn is an Associate Professor of Electrical Engineering and Computer Science. He is the Faculty Director of the Jacobs Institute for Design Innovation, a new undergraduate teaching institute focused on hands-on, human-centered design.

Prof. Aaron Hoover, Olin College of Engineering
Favorite making activity: Woodworking/furniture
Aaron is an Assistant Professor of Mechanical Engineering. He is currently leading an effort to reimagine Olin's creative spaces and fabrication resources to support its unique, hands-on, project-based curriculum.

Marlo Kohn, Stanford University
Favorite making activity: Silicone molding
Marlo is the Associate Director of the Product Realization Lab and a Lecturer in the Department of Mechanical Engineering. Marlo is the creator and founding manager of the PRL's satellite prototyping lab known as Room 36.

Dean Vincent Wilczynski, Yale University
Favorite making activity: CNC routing
Vince is the Deputy Dean of School of Engineering & Applied Science and James S. Tyler Director of the Center for Engineering Innovation & Design. He leads Yale's effort to promote collaboration, creativity, design and manufacturing in makerspaces.

Announcements

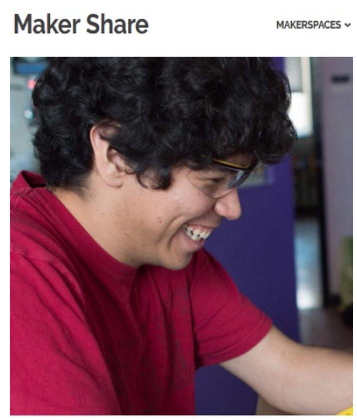
The Higher Education Makerspace Initiative (HEMI – hemi.mit.edu) is pleased to announce the following events and resources.

1. **ISAM 2017**

ISAM 2017 will take place during the Fall of 2017. We will provide more information via e-mail at a later date.

2. **MakerShare**

Live now! Visit - https://makershare.mit.edu



MakerShare is an online sharing and networking resource that enables members to share information and connect/communicate about topics related to academic makerspaces. Membership is free. On MakerShare, members can (i) share best practices, (ii) post or read reviews of maker equipment, tools, and materials for makerspaces, (iii) share activities/kits/ideas for making projects, (iv) participate in forums, (v) communicate with others about specific and general topics, (vi) announce events, and much more! To join the MakerShare community, visit https://makershare.mit.edu, create an account, and start sharing!

3. **International Journal of Academic Makerspaces and Making**

1st call for paper proposals: December 5, 2016 - more updates during ISAM 2016

IJAMM will provide a vehicle that student/faculty advocates, government policy makers, educational researchers, and practitioners can use to share best practices in academic making and learn proven methods that will enable them to maximize the impact of their university makerspaces. IJAMM will publish original high quality papers and case studies. Topics covered by IJAMM include but are not limited to:

- Culture and community and programming
- Types and characteristics of makerspaces
- Assessing impact/justification via metrics and data
- Staffing, training, conventional equipment, and new equipment
- Safety, legal, and regulatory issues
- Space definition and design layout
- Makerspace and makersystem management

4. **Global Academic Maker Society**

Join starting December 5, 2016 - updates during ISAM 2016

The Global Academic Maker Society fosters the use of academic makerspaces within higher education. GAMS promotes the sharing of best practices, the formation of collaborations, and the availability of resources and knowledge that enable safe and effective makerspaces that maximize their impact on the student educational experience.

Organizing Committee

Martin L. Culpepper, Co-chair *Massachusetts Institute of Technology*	**Vincent Wilczynski, Co-chair** *Yale University*
Craig Forest *Georgia Institute of Technology*	**P. Zach Ali** *Carnegie Mellon University*
Malcom Cooke *Case Western University*	**Marlo Kohn** *Stanford University*
Aaron Hoover *Franklin W. Olin College of Engineering*	**Bjoern Hartmann** *University of California, Berkeley*

Types of Academic Makerspaces, Their Import to the Education Mission, and The Characteristics of Their Culture and Community

ISAM 2016 Paper No.: 01

Martin L. Culpepper
Martin L. Culpepper; Project Manus & Mechanical Engineering, MIT; e-mail: culpepper@mit.edu

INTRODUCTION

The *intent* of this talk is to discuss the types of fabrication spaces that one finds in academic settings and note their different characteristics. These differences are *important* as they determine what each type of space is best suited for and the boundaries that students experience when trying to use them. Understanding these differences is the key to creating a space that will satisfy the needs of your students and thereby maximize the *impact* on their educational experience. In this paper I provide a high level overview of the topic. The intent is to provide some background which compliments the presentation.

We will talk about three 'flavors' of spaces that are commonly found on academic campuses - Machine Shops, Project Spaces and Community Spaces. These spaces typically have similar spaces and maker tools, but their community elements differ, and they are purposed and managed in a different way. What differentiates them is how they are programmed, staffed and the mindset of the culture within the space. Each type of space *could* be a makerspace, but each type might also fail as a makerspace. To understand this, let us consider the existence of a "space" with 'X' square footage that is populated by tools and equipment. If that space sits empty, no matter what kinds of space it is, it's not a makerspace. Too many boundaries, or boundaries that are too high can lead students to avoid the space, to feel unwelcome. We will discuss factors beyond the equipment, space and tools that determine if there is a vibrant maker community within the space… and this is what turns a room with machines into a makerspace.

In the following sections, we use several MIT spaces as examples of the types of "flavors." These flavors are not unique to MIT, one can find them walking around nearly any campus or described/assessed in the review of the literature [1, 2]. Here we are explicit about the types and the characteristics of these spaces and what this means for decision making.

MACHINE SHOP

Spaces that specialize in training/mentoring/making on creation of complex systems and/or fine-detailed components. Interaction with staff (skilled machinist educators) is their key value, so they specialize in quality of maker education/work vs. quantity of students served. This skilled, one-on-one instruction model may make it hard to have many students in the space as this model relies upon a technician to safely oversee many people at once. This limits the number of students that may be in the space, especially when there are new, unskilled students that require a lot of oversight and help. Scaling access to these spaces requires addition of technical staff which is often cost prohibitive.

Figure 1 shows the ME Manufacturing Shop at MIT [3]. This is a machine shop that serves the manufacturing research community at MIT and the manufacturing classes that are taught in the Department of Mechanical Engineering.

Fig.1 Machine Shop - ME Manufacturing Shop at MIT

PROJECT SPACE

Spaces that primarily support class projects. These spaces usually contain more resources to facilitate collaboration, i.e. meeting space and open working space. The key value of these spaces is in their ability to integrate specific resources that enable programmed, curriculum-based learning. Figures 2 and 3 show an example of two sections in a project space that work together to enable making, meetings and classroom teaching within the same facility. In some cases, scaling access to these spaces is problematic. Typically, classes 'own' these spaces. Non-class access must take place outside of class times so as to not interfere with class activities… and this obviously limits access. In addition, if a piece of equipment is critical to a class, access to this may be severely restricted for fear that it could be broken during non-class times. Scaling access in spaces with the preceding time and equipment constraints requires scaling up the number of people in the classes that are using the space. Scaling up non-class users is often very difficult.

Fig.2 ME Pappalardo Facility - This is the Fabrication Section

Fig.3 ME Pappalardo Facility - This Section Contains Areas for Prototyping, Assembly and Meeting Rooms (far rear).

COMMUNITY SPACE

Spaces that prioritize fostering unrestricted making via a community effort. The community serves as stewards of the space/resources and educate users in safe making practices. The key value of these spaces is the communities' ability to facilitate access to more users, particularly early/novice users. The figure below shows the MakerWorkshop community space [4] at MIT. This space is run by a community of 38 students, primarily graduate students, which care about, and care for, the space and the users that rely on it. These types of spaces often do not have a technician that oversees making in the space and therefore the decades of available expertise are sometimes not available for advanced projects. Scaling access in a community space is often easier than the other types of spaces, *if* a vibrant maker community exists. Such a community will have many makers that are available to help teach and train others. Those that get trained and become a part of the community tend to be absorbed into a culture of "helping others" and so more people are available to help train and mentor peers. This can have a snow balling effect until a steady state of community users is reached. The MakerWorkshop started with 5 students, grew to 8, then 16, then 25, and so on until they reached a steady state that hovers around 40 students.

Fig. 4 ME MakerWorkshop Meeting of Student Mentors On National 'Tool Worship' Day

Fig. 5 ME MakerWorkshop During Time When They Are Open To Student Users

WHICH SPACE IS THE BEST?

There is no 'right' answer when it comes to this question. These spaces all serve different purposes, so the 'right' answer depends on what one is trying to accomplish. If you need a space to support involved class projects that need making, meeting and assembly/fabrication space, then the project space is a good option. Often research at universities requires expert fabrication expertise, and the probability of finding this is higher in a machine shop. If open and easy access is the main goal, then a community space may be the 'right' answer.

I often hear the question, "If you want a makerspace, which one is the best pick?" Again, there is no 'right answer.' The key is to create the right type of space first and enable a community to grow within it. With that said, at MIT we have had an exceedingly difficult time growing maker communities inside of machines shops. We have had better luck growing maker communities inside of community spaces. Project spaces are interesting in that the community is formed in the classroom. For example, the Pappalardo space in Figs. 2 & 3 has a vibrant community during the senior capstone course, 2.009. The course focuses on community (project teams may be 16 or more students) and this translates into the space. During terms when the sophomore design class, 2.007, is taught… the level of community is lower as students are working on individual projects and the class focuses on the design process and fabrication rather than community.

A pure space would be at one of the vertices of the triangle shown in Fig. 6. Many spaces lie somewhere between the three vertices, meaning that they incorporate elements of the three types. The important thing is that a space does what it is meant to do.

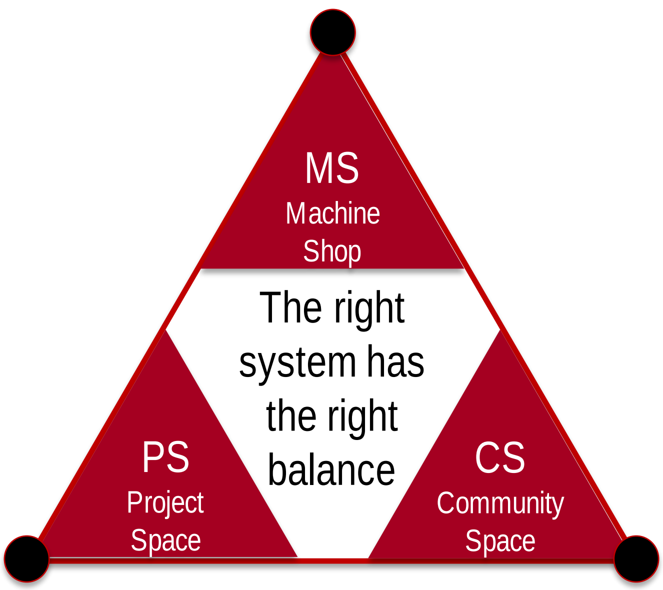


Fig.6 Method for Visualizing the Flavors of Spaces

When a university has several makerspaces, these spaces often form a makersystem. If this system is properly balanced, the spaces can work together to provide the requisite access to tools, expertise and communities. This balance is important. For example, I was once asked, "Why don't you get rid MIT's machine shops and replace them with community spaces?" My answer contains the need for MIT students and faculty to have access to technicians that have a high level of expertise. Machines shops are needed.

Recently, we became aware that our system at MIT was un-balanced. We did not have enough community spaces and this led to student access issues. Sometimes students could go for months before they gained access to a space. This imbalance is shown in Fig. 7. After a great deal of data collection and working to understand the issues affecting our students, we were able to identify access as the main issue. Figure 7 was shown to the administration and this led to the decision that MIT's new 20,000 ft^2 MET Makerspace [5] would be a community space. The addition of the 20,000 ft^2 to the community 'bin' of space is helpful, but more could be done.

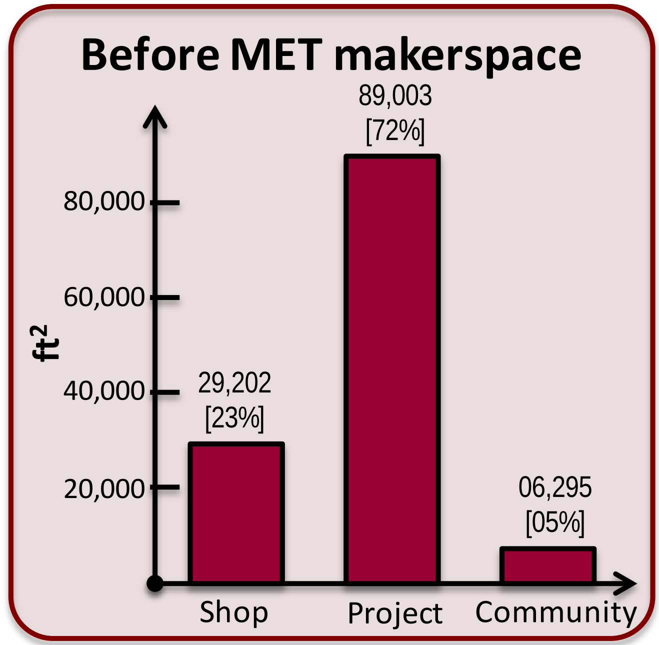


Fig.7 Initial Distribution of the Types of Spaces on the MIT Campus

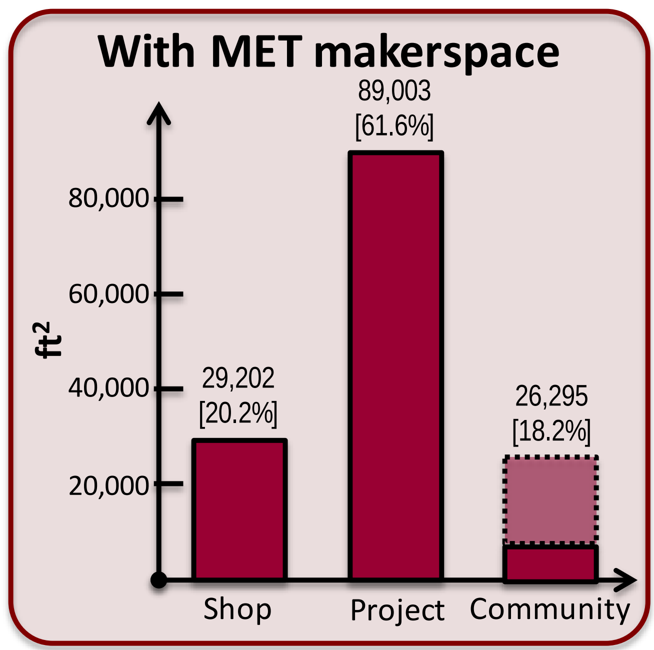


Fig.8 Planned Distribution of the Types of Spaces on the MIT Campus After Adding the MET Makerspace

BRINGING COMMUNITY TO SHOP AND PROJECT SPACES

In the spring of 2016, Project Manus staff were able to partner with several facilities on campus to start the formation of maker communities within them. This project is ongoing and results are not available, however the concept is described so that the intended benefit may be understood and discussed. Figure 9 shows a map with roughly half of the fabrication facilities on campus. They are color coded according to how easy it is for students to gain entry as of 2015. Green is near immediate access, Yellow spaces may require that you join a waitlist for training or pay a user fee and Red spaces are often limited to use by a small group, for example a Department or Research group.

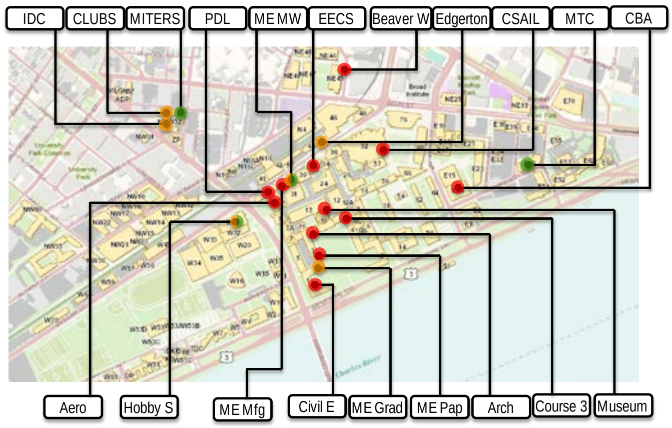


Fig.9 Initial Distribution of the Types of Spaces on the MIT Campus

Figure 10 shows the expected impact of the MakerLodge Program [6] on the freshman class. This program builds freshman maker communities at facilities. These facilities, for the freshmen, are then immediately available after a 4 hour training + 45 minute skills test.

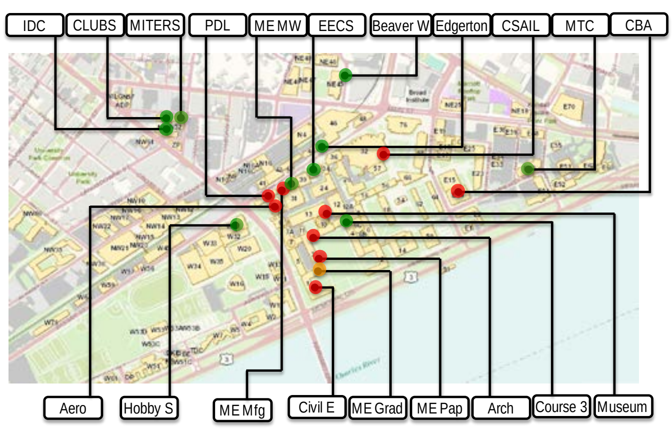


Fig.10 Initial Distribution of the Types of Spaces on the MIT Campus

SUMMARY

With hybrids, there are many types of spaces that may be found on an academic campus. It is easier to understand the type of space to suit student needs by considering the pros and cons of the three 'pure flavors' of spaces, and creating a hybrid space if necessary. Having a space and machines doesn't guarantee that you'll have a makerspace, you need a vibrant community of makers to help make that happen. In the end, what is most important is the maker community and seeing to it that their needs are met by starting off with good decision about the type of space one selects.

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[4] http://makerworks.mit.edu

[5] http://news.mit.edu/2016/new-makerspace-supported-by-victor-and-william-fung-foundation-0531

[6] http://makerlodge.mit.edu

Sustaining a diverse and inclusive culture in a student run makerspace

ISAM 2016
Paper No.: 02

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INTRODUCTION

The Invention Studio at Georgia Tech a student run makerspace equipped with over $1 Million worth of fabrication equipment within a 4,500 square foot facility. The space is free for all students, faculty and staff of Georgia Tech to use, regardless of major, age or experience. The most unique aspect of the Invention Studio is its student-led culture; more than 75 students, known as "Prototyping Instructors" (PIs), volunteer three hours a week to staff the space. During this time, the PIs oversee the safety of users, provide one-on-one machine training and offer design advice for projects. On a typical day, nearly 400 students use this space for various projects, ranging from class assignments to research to personal projects.

The Invention Studio is located in the heart of the mechanical engineering building on campus. Although the Invention Studio is open to all students, we find through observation that the majority of daily users are mechanical engineering students. There is a drive for diversification within our users and volunteer PIs to help foster innovative collaboration in class, research and start-ups. Recently, studies have observed a positive correlation between knowledge diversity and innovation within companies [1]. Since its founding in 2009, the Invention Studio has run various outreach programs and workshops to reduce the barriers to entry and to stimulate interest in the makerspace. Through various outreach activities, the studio was able to reach diverse groups of people through a variety of teaching methods aimed at promoting STEAM topics. These activities help the Studio accomplish one of its core missions, which is to instill creative confidence outside of the course curriculum. This paper presents some of the best practices and programs developed to foster diversity and inclusion in higher education makerspaces.

REDUCING BARRIERS TO ENTRY IN MAKERSPACES

Before developing sustainable programs for diversification, existing barriers to entry for the Invention Studio must be identified. Qualitatively, the Invention Studio has observed four main barriers to entry over the past eight years: anxiety due to lack of experience, a lack of information regarding equipment and usage, a fear of alienation, and a pre-existing notion that makerspaces are only for engineering. Here we list various techniques used to reduce each barrier and promote inclusion.

Figure 1: Photos from the Ladies night at the Invention Studio

A. PROVIDING EQUIPMENT TRAINING SESSIONS AND TOURS

A significant barrier to entry observed among most users of the Invention Studio is the preexisting notion that machining experience is needed when using the space. While this may be true for traditional machine shops, our student run makerspace culture promotes "learning through doing" under student supervision for all our machines. Basic machine training is offered by PIs on a walk-in basis during open hours and advanced machine training group sessions are organized throughout the semester. These group sessions are targeted primarily at users who wish to become Prototyping Instructors, but are open for anyone [2].

In order to increase awareness about the Invention Studio among the students, the Studio hosted numerous advertised workshops focused on providing fabrication experience to newcomers. In 2016, the Invention Studio hosted an event titled "Collectible Creations" to provide group based hands-on training on various machines through a simple project. Advertising was done through the Student Center Programs Council (SCPC) at Georgia Tech to reach a larger spread of students. The event consisted of hour-long workshops over a three-day period, in which four different projects were available each day. Projects included a laser cut 3D puzzle, a waterjet steel figurine, a 3D printed candy dispenser and an electronic LED Altoid tin bike light. Recorded attendance was over 150 students.

Weekly tours of the Invention Studio are provided to inform students of the resources available within the Studio. Numerous tours are offered to primarily target freshman level courses, specifically GT1000, a first-year seminar that works to ease students from all majors into college life. On an average, over 100 new students per week attend these tours.

B. PROMOTING INCLUSION THROUGH GROUP EVENTS

During Fall of 2014, the Invention Studio hosted its first and largest outreach event titled "Ladies night at the Invention Studio". The event developed as a way to generate more female interest in the studio; out of the 65 Prototyping Instructor's, only 9 were female at the time. The Invention Studio had run workshops in the past, but none had been specifically targeted towards introducing women to the Maker culture. Even within the Georgia Tech community, females are only 31% of the total student body. Within engineering, the percentage is only 28%. The national average of female engineering students is at 18% [3]. With such a small female population, it can be difficult to find like-minded female students, or even to inspire women to become designers and innovators.

The event consisted of participant's laser cutting their own 3D acrylic or wood puzzle (**Figure 1**). The laser cutter is a great tool for introduction into fabrication; it requires no previous knowledge in engineering and can be easily taught to a large group. After cutting their own puzzle, the students would build their puzzles among other

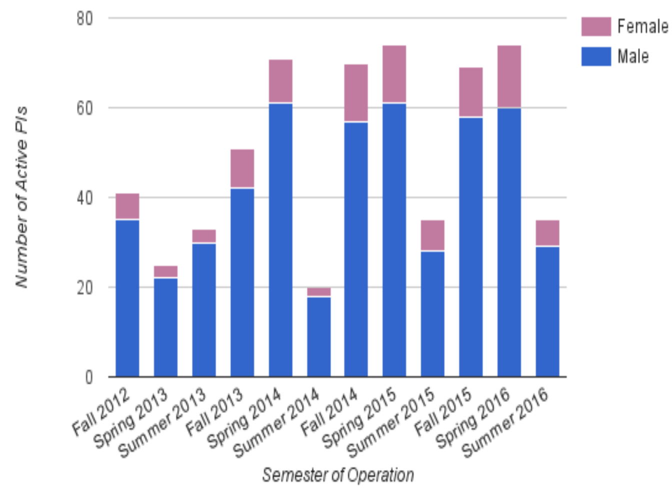

Figure 2: Gender demographics for the Invention Studio

participants, giving them an opportunity to meet similar-minded students and start to build a tighter-knit female community. By the day of the event, over 300 RSVP's were received, as well as a request from the director of the Women in Engineering group to video record the entire event.

Attendees had a very positive experience, and they said: "If you guys hosted something every other week I would come to it [workshops] every time because it's such a neat opportunity!", "I would like more events where I can learn tools and make something creative", and "Please have more events to build things! This was such an awesome idea!!!". Faculty members who attended the event stated "This event was amazing. Students had a great time. It was a wonderful outreach activity for the Invention Studio and a great way to increase membership and PIs [student makers] long term!" The demographics from the event are seen Appendix A.

Since the first event in Fall of 2014, the student leadership has made "Ladies night at the Invention Studio" a biannual occurrence, with each event showing similar demographics. The number of female Prototyping Instructors has risen since the introduction of "Ladies night", as seen in **Figure 2**.

C. PROMOTING DIVERSE INTERESTS

How does a makerspace reach out to students whose interests lie outside engineering? Science, technology, art and math (the four additional components of STEAM education) can be incorporated into makerspace culture through targeted workshops, much like the biannual Ladies Night event. One recent event, titled "Steel Roses," proved to be an effective introduction to metalworking for students. This workshop walked participants through creating a rose out of a steel sheet and rod (**Figure 3**). The students used the waterjet cutter to create the flat pattern for petals and leaves, then the belt sander, spot welder, and pliers were used to shape their rose. Students were creative with how they shaped their rose. Some were quite ornate, while others were more simplistic. This project connected engineering and art, as students had to consider how the steel would behave as they bent it into shape. “Steel Roses” had room for 36 attendees. Upon being announced on social media, the workshop slots filled within an hour. Within a day, nearly 100 students indicated interest in the event. Gender and department of study were recorded for all 36 participants and are presented in Appendix B. Over the following week, many students returned with their roses to heat treat and color them. One participant decided to become a Prototyping Instructor from her experience at the workshop.

Another popular workshop incorporating art and engineering is “Introduction to Stained Glass”. Using the copper foil technique, participants wrap cut glass pieces in copper foil and solder them together along the seams to create colorful patterns. Over 100 students have participated in this workshop in the three years it has been hosted.

During Summer of 2016, the Invention Studio hosted a workshop titled “Give a Helping Hand!” In this workshop, participants assembled 3D printed plastic prosthetic hands as gifts for children whose families cannot afford conventional prosthetics. Each participant was given 31 3D printed parts, wires, Velcro, and fasteners and asked to assemble the parts into a fully-functional prosthesis. The finished hands were donated to the Hand Challenge, an initiative to give prosthetic hands to children in need. This event was marketed heavily toward biomedical engineering students to attract them to the Invention Studio, though all majors and years were welcome. Attendance was evenly distributed among seven different majors as shown in Appendix C. Participants were primarily fourth year students, along with one alumnus, some graduate, third year, and second year students. Interestingly, one attendee was a student at nearby Clayton State University majoring in Information Technology. He had no formal connection to Georgia Tech and attended purely out of interest in makerspaces and 3D printing.

D. THE IMPORTANCE OF STUDENT LEADERSHIP

A critical component to outreach success is having efficient and effective student leadership in place. For a workshop or event to run smoothly, student leaders must be organized and communicate clearly with each other and workshop participants. In the Invention Studio, workshops are typically a collaboration between the Director of

Figure 1: Photos from the Steel Roses workshop

Programming, Director of Communications, Director of Finance, and other Prototyping Instructors who are interested in helping. Programming coordinates event times, dates, venues, and activities. Communications handles promotion and advertising. Finance purchases materials and records spending for the event. This system has worked well to prevent overburdening a single student in organizing large events. When the management is efficient, few problems occur and workshops run smoothly, making participants happier and less frustrated.

CONCLUSION

By providing equipment training sessions and tours, promoting inclusion through group events, and encouraging diverse interests, the Invention Studio is able to lower the boundaries to making for students across campus. While some students are brave enough to walk in and immediately use the space on their own, the vast majority need guidance to build confidence in the space. The Invention Studio’s successes in diversification and inclusion are primarily due to the student-run culture. Newcomers feel they can relate more easily to other students, lowering anxiety and creating a space of psychological safety. A student leadership that delegates work proficiently is also important for outreach success.

However, there are still barriers to entry that may deter students from utilizing the space. Namely, students must still purchase their own building materials, except for 3D printing filament. Access to materials, whether out of expense or out of close proximity to the space, can be problematic for students. Currently, the School provides materials for those who wish to complete the PI checklist. Those who are PI's can apply for a "Maker Grant"; the student submits a full proposal for a project, detailing new skills and techniques they will learn. Proposals go through an approval process with the student executive board and the Director of Design & Innovation. If approved, the PI can receive funds for materials and supplies to build their personal project. The student organization is also currently working on establishing a materials' cabinet. Students will be able to purchase building supplies and hardware inside the Invention Studio; this will help those who may not have access to transportation.

Providing a variety of workshops and events is key to attracting a diverse group of students. Traditionally, women and non-engineering majors have stayed away from using the space for personal projects, likely out of a feeling of alienation. However, by hosting events that cater to diverse interests, it is possible to attract diverse groups and make them feel welcome in the space.

Acknowledgements

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1148903.

The authors of this paper would also like to thank the following supporters of the Invention Studio and its mission:

The George W. Woodruff School of Mechanical Engineering - particularly School Chair, Dr. Bill Wepfer - for the continuous commitment to hands-on education, and for the belief in and support of the student-run makerspace model.

Dr. Craig Forest, for inspiring the founding members of the Invention Studio, reminding the space of its history and roots, and for the constructive advice and encouragement on this paper. The Invention Studio would not be what it is today without his invaluable input and creative vision.

Dr. Julie Linsey, for the advisement, resources, and time devoted to the Invention Studio and its student volunteers.

Mr. Clint Rinehart, for his expert guidance and mentorship on tool operation, repair and assistance with organizing the workshops and tours.

References

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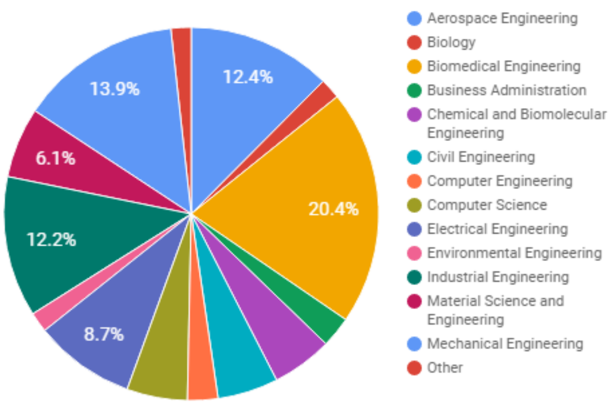
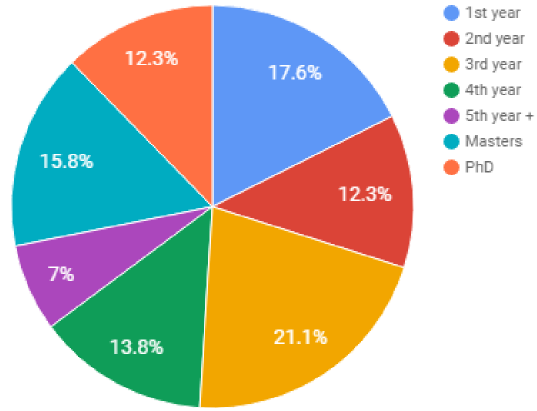
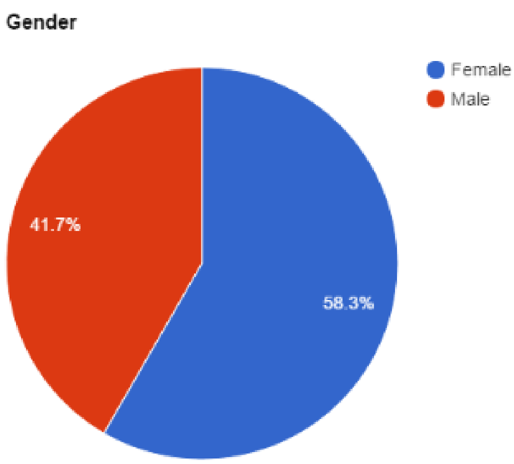
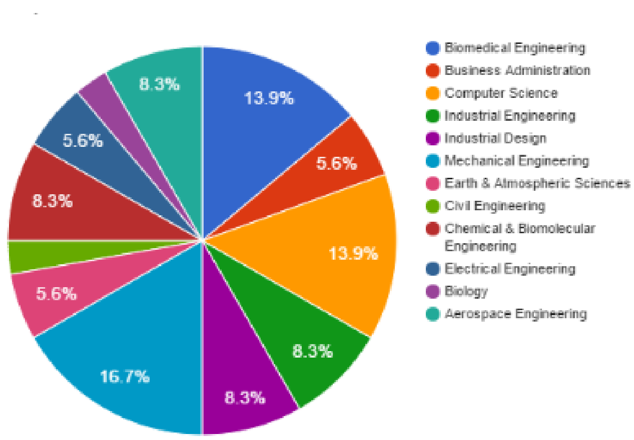
APPENDIX A: LADIES NIGHT DEMOGRAPHICS



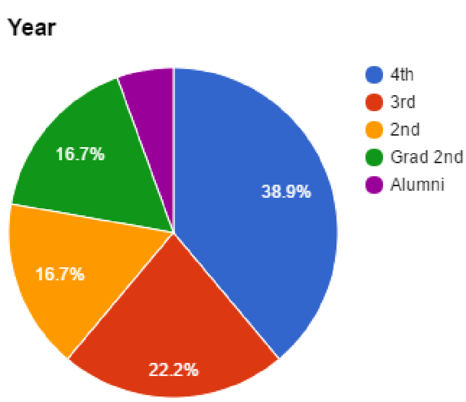


APPENDIX B: STEEL ROSE WORKSHOP DEMOGRAPHICS





APPENDIX C: GIVE A HELPING HAND WORKSHOP DEMOGRAPHICS



Creating a Maker Community at the MIT-SUTD International Design Center

ISAM 2016
Paper No.: 03

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INTRODUCTION

The MIT-SUTD International Design Center (IDC) is a ~1100 m^2 facility of shops, conference rooms, offices, labs and multi-use spaces that has been located on the MIT campus since 2011 [1]. The IDC has fused together multiple facets of design, education and research by creating a community that can be uniquely described as:

International: It is part of a larger collaboration with a sister institution at the Singapore University of Technology and Design (SUTD) [2].

Multi-disciplinary: It is composed of faculty, researchers and students from all five schools and departments at MIT: Architecture and Planning, Engineering, HASS (Humanities, Arts-and Social Science), Management and Science.

Research-infused: Both research labs and education programs co-exist within a shared facility.

Experimental: The shops and spaces are used as an experimental platform to test best practices of design spaces.

Inclusive and collaborative: Continually developing and revaluating policies and procedures to provide access to a large and diverse user group.

This paper will discuss the last three points after providing a general description of the IDC. The aim is to review the challenges that were faced while creating the IDC, some of the design intent and methods that were used and examples of research that has been done within the IDC related to making.

ABOUT THE IDC

The IDC community is composed of the following user groups:

Research Labs: Seven resident research labs have both private space and access to the shared resources including the shops.

Educational Programs: Four main educational groups use the IDC shops. One example is the Integrated Design and Management Program, which is a 2-year masters program [3]. Another is the Global Leadership Program, which is a 10-week program where 45 undergraduate students build small electric vehicles [4]. Also, multiple semester-long design courses are held at the IDC.

Clubs and Teams: Approximately 15 MIT clubs and teams are run through the Edgerton Center [5]. The students have office and shop space in the same building as the IDC and have access to most of the IDC's community resources.

Makers: A group of students that are given shop access and training opportunities in return for volunteering time to upkeep and run the shop. See a later section for more details.

Partners: The IDC also works closely and shares resources with other design focused organizations including D-Lab [6].

Approximately 500 MIT students, researchers and staff flow through the IDC as users each year. At least double this amount attends IDC-sponsored events.

The IDC layout was designed to mix research and education in a making environment (Fig. 1). The space continually evolves as needs change and the knowledge of maker spaces advances. The next two subsections describe part of the design process used to continually evolve the space.

A. GENERAL

It has been useful to think of the IDC space in the functional domain, similar to methods used for designing products and services [7]. In this case the physical layout and intended use for each space is being designed. The rows of Table 1 list the functional requirements for the IDC space. For example, it must have space for classes, meetings, etc. The columns are the needs for each function: the amount of space, privacy, security, equipment and quietness needed, the amount of noise generated in the space and finally the amount of time the space will be in active use. Arrows qualitatively measure the need as high (🡅), medium (🡆) or low (🡇).

A key takeaway from Table 1 is that the needs for classes, meetings, events and workspaces are very similar and thus can all be done in the multi-use spaces shown in Fig. 1. These spaces must be highly reconfigurable to meet the varying needs, which has been accomplished using:

- Folding tables with wheels and stackable stools.
- No other fixed equipment in the space besides whiteboards and projector screens.
- Two glass garage doors to close off the space.

Having reconfigurable, multi-use space has increased the utilization, which has been essential in forming a maker community.

Fig. 1 The floorplan of the IDC (~1100 m²). The dark gray areas are shared spaces and the light gray areas are assigned to resident labs or programs. The shops and work areas are shown in green.

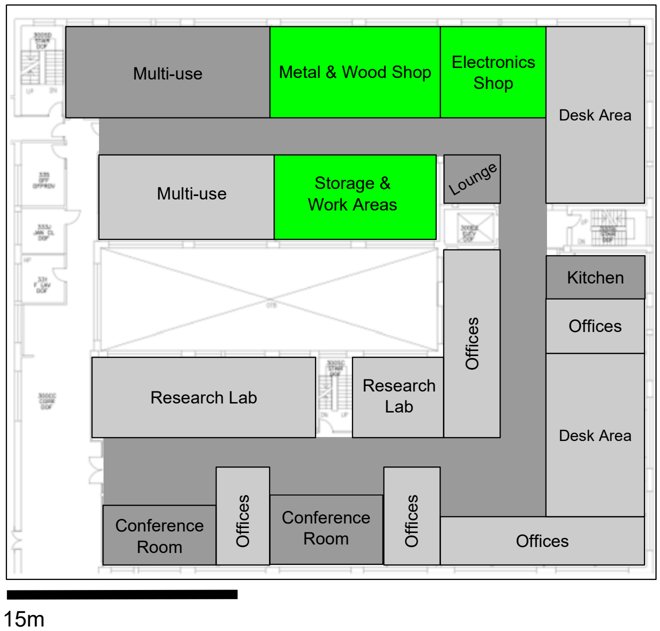

Table 1 The rows of the table below list the functional needs of the IDC space. The columns are the needs of each function. Arrows qualitatively measure the need as high (↑), medium (→) or low (↓).

		Needs of Functions						
		Space	Privacy	Security	Equipment	Quietness	Noise	Use
Functions of Space	Classes	↑	↑	↓	↓	↑	→	→
	Meetings	↑	↑	↓	↓	↑	→	→
	Events	↑	↑	↓	↓	↑	→	→
	Work	↑	↓	↓	↓	↓	↑	→
	Storage	→	↓	↓	↓	↑	↓	↑
	Machines	↑	↓	↑	↑	↓	↑	→
	Research	→	↑	↑	↑	→	↑	↑
	Desk-work	↓	↑	↑	→	↑	→	↑

B. DESIGNING THE SHOP

A key element to the IDC has been the creation of metal, wood and electronics shops that are open to any members of the IDC community. The Metal and Wood shop has a 3-axis gantry-based router, laser cutter, band saws, drill presses, miter saw, table saw, mini-mill, mini-lathe, grinder and spray booth. One side of the shop is for wood machines with a dust collection system. The other side is mainly for metal machines. The Electronics Shop has all the soldering equipment plus multiple 3D printers, vinyl cutter and table-top printed circuit board (PCB) mill. The Storage and Work Areas have hand-tool storage on one end and material storage on the other end.

When laying out the shop, it was useful to think in the functional domain as discussed in the previous subsection. Functionally the shop has:

(1) Machines: high-powered tools that require an increased level of vigilance during use (e.g. bandsaw, drill press, mill/lathe, etc.).

(2) Work Area(s): A space where components are assembled and or hand-tools are used (low to non-powered tools). Typically, workbenches are needed.

(3) Storage Area(s): A place to store materials, hand-tools, projects, etc. Items are often stored on racks, shelves, drawers and cabinets.

The layout of the IDC shops evolved over the first 5 years into a configuration where the functions listed above were mixed. For example, the hand tools were stored underneath the bandsaw table. Thus the placement of tools posed a safety risk for anyone simply wanting to obtain a hand tool from storage. This arrangement would be categorized as a Fixed Position Layout using facility management terms [8]. More recently we reconfigured the space so that the work area, storage and machines are completely separate. So the room with machines does not contain storage or benches for general assembly work. This arrangement would be categorized as a Process of Functional Layout [8]. Though a seemingly simple change, *the general design principle of separating machines, work areas and storage in the shops has acted as a great guide and yielded a considerably safer and more organized shop.*

RESEARCH INFUSED

One of the most unique aspects of the IDC is that it is a place where research, teaching and making co-exist. In other words, the IDC is more than just a maker space. Having multi-disciplinary research labs within the IDC yields the following benefits:

Expanded tool / equipment inventory: Each resident research lab has their own domain expertise, which requires a specialized set of tools and equipment (e.g. medical-specific equipment). This equipment is privately owned and maintained by the lab, though sharing is encouraged. Since all resident labs have a focus on making, their tools are often useful to the broader community. This essentially expands the inventory of specialized tools and equipment to the community.

Diffusion of domain expertise: Researchers reside in the IDC full-time and are often available to help students and fellow researchers when their domain expertise is needed.

Conduit between students and research: Proximity and culture creates a permeable membrane between teaching and research and can lead to undergraduate research opportunities.

EXPERIMENTAL

The IDC strives to be a place where best practices for maker spaces are advanced. This is accomplished by using the IDC shops as an experimental platform. One example is the Little Devices Lab (LDL) [9], which is housed in the IDC. Their researchers have developed a number of makerspace experiments within the IDC and below are two examples:

Example 1: Digital shop assistant. Mastering the skills of machining, tools and assembly of a makerspace requires a certain level of familiarity with the physical space (where machines and parts are located and/or how to obtain components). Advanced users can be hampered by the overall workflow of a space simply because they do not know the location of a tool or component. Likewise, beginners may struggle because they do not know how or where to begin their project.

Ideally a personal assistant would help guide each user through the shop based on their specific project and needs. But unfortunately this is not always possible because of limited human resources. So instead LDL has experimented with creating a “digital shop assistant.” Algorithms plus a network of LEDs navigates the user through the shop based on their project. First a user selects the project they would like to make from a digital library of projects, which are accessed from a wall-mounted tablet. Next, an algorithm determines which tools and parts are needed for the selected project and uses blinking LEDs to guide the user through the build process (e.g. the tool and component bins each have an LED).

Example 2: Making in healthcare. The MakerNurse project is a nationwide program to find frontline nurses that are natural makers and enable them with specially designed prototyping tools to realize their medical hardware ideas [10]. This project has shown the importance of co-location of disciplines and prototyping tools. Multiple hospitals systems have invested in “innovation labs” that serve as engineering bureaus for medical staff, analogous to a Central Machine Shop facility at a university. Since they lack the ethos of a makerspace’s self-service model, they tend to prioritize funded projects over frontline projects by nurses, leaving many underground innovators out of options for advancing their ideas. The MakerNurse project created the first makerspace in a hospital using some techniques pioneered and tested at the IDC: Kits, specialized instrumentation access, flexible architecture, and horizontal culture of expert access. The latter has been important in growing a community of health makers, especially in a hospital system that is often dominated by traditional hierarchies of authority.

INCLUSSIVENESS AND COLLABORATION

The IDC aims to offer community members:

- Opportunities to *collaborate* (e.g. with other researchers, industry partners)
- Access to *shared resources* (e.g. shops, equipment)
- Use of private and shared *spaces* (e.g. labs, classrooms, conference rooms)
- Clear and consistent *policies*
- Spaces that are *safe*, *clean* and have an *efficient* layout and operation

The subsections below describe example policies and programs that have been initiated to foster inclusiveness and collaboration.

A. SHARED EQUIPMENT

A frequent question is whether to store individually or lab purchased equipment in the shop. For example, a research lab may have funds to buy a piece of equipment and would like to put it in the shop. Effort has been made to keep the shop a shared resource. Thus the policies require that all equipment in the shops must be useful to many shop users and made available to all members of the community. This has prevented the shop from being full of machines that are private and/or have limited use.

B. MAKER PROGRAM

It is common to receive requests by a student outside the IDC community to use the shop. As mentioned in the introduction, one of the values of the IDC is to be inclusive but opening the shop to the entire MIT community is not sustainable. To address this in a fair and consistent way, the IDC Maker Program was established. The second impetus in creating the program was the desire to bring talented and dedicated MIT students into the IDC community.

Thus the IDC Maker Program provides a channel for any MIT student to join the IDC community and become trained on the tools and machines. In return, the participants are required to volunteer their time to help sustain and improve the IDC. There are three different levels in the program:

Bronze-Makers: Typically for students that are (though not exclusively) freshmen and/or new to the IDC shop. They may use the shop only when an IDC shop monitor is present. The bulk of the Bronze-Makers are students participating in the IDC MakerLodge program (see Section C below).

Silver-Makers: Students that have spent one semester as a Bronze-Maker and demonstrated active involvement before graduating to Silver status. Shop use is granted only when an IDC Shop Monitor is present.

Gold-Makers: Students that have spent one semester as a Silver-Maker and demonstrated active involvement in the IDC community before graduating to gold level. Thus they must have an exceptional safety record and have demonstrated a high skill level with the IDC tools and machines. The Gold-Makers have full access to the shop and may serve as shop monitors and trainers.

All IDC Makers have access to:

- Tool and machine training
- “Maker Events” hosted by the shop managers or silver/gold makers where an artifact is designed and fabricated to help train students on the machines and processes.
- A small locker for storage

The aim is to coach students through the entire multi-year program, produce super-users of the IDC equipment and engage them in the community.

C. MAKERLODGE

This spring the IDC will participate in the MIT "MakerLodge" program, which is a new campus-wide initiative to train ~1,500 students per year on introductory maker technology including 3D printers, laser cutters, bandsaws, drill presses, handtools and more [11]. The program was designed to solve the campus-wide problem of limited training and shop access. After completing the MakerLodge training, students will be eligible to join over 10 existing makerspace communities called "MakerLodges." Students will also receive a small amount of money to be spent at the shops for tool use or consumables.

The IDC will participate in the MakerLodge program in two ways: The first is to create an IDC MakerLodge comprising of 10 to 20 freshmen, which will join the community as Bronze-Makers (see Section B). The second will be by opening the IDC shop weekly during a limited period of time for any student that has gone through the general MakerLodge training.

ONGOING AND FUTURE WORK

Now that the IDC is built and operating, it is an ideal platform for makerspace research and innovation. *A key goal will be to collect data to measure the impact of changes made to the layout and operations.* Below are ongoing and possible future projects.

A. DATA COLLECTION

A tablet was recently installed to collect user information; when users enter the shop, they are asked to sign in with their name, affiliation and planned activities. Additional use data is being collected for high-cost machines such as 3D printers (e.g. material, runtime, cost). This yields a better understanding of how particular machines are being used by each user group. It also provides a sense of accountability to the user, which may reduce machine abuse and/or overuse. Additionally, the shop manager gives feedback to the user for 3D printer requests before running a job on high-end machines. This feedback includes a cost estimate and whether or not a different machine or fabrication technique would be more appropriate. Qualitatively, a reduction in wasteful 3D printing has already been observed.

B. ELECTRONIC ACCESS TO MACHINES

Automatically controlling access to individual machines based on affiliation and past training could greatly increase safety. Currently the IDC has ID card readers on the shop doors that control access. A more ideal scenario may be for a student to unlock the shop door via an app on their phone. In that same app they could select the machine they would like to use and reserve a time. Once the student enters the shop, the specific machine would be enabled if the user has proper credentials.

The architecture shop at MIT has created a customized access control system for their machines using an addressable circuit breaker panel designed for lighting control systems by Schneider [12][13]. They integrated their system into the campus-wide door access system and are quite satisfied with the results.

There are other DIY and commercial options that perform some of these functions. For example, the MakerBarn has created a Makerspace Access Control System (MACS) that controls access to individual machines through Wi-Fi with a card reader [14]. And a more traditional route may be through existing commercial products such as those offered by CBORD Group, Inc. [15].

C. ELECTRONIC SAFETY MONITORING

An additional feature to increase shop safety would be sensors that check for proper personal protective equipment (PPE) on the machine operator. For example, video cameras and machine-learning algorithms could prevent a machine from being turned on if the operator does not have the proper safety glasses, shoes, hair ties, etc.

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Fostering Student Autonomy in an Undergraduate-only, Mixed-Use Machine Shop

ISAM 2016 Paper No.: 04

Invited

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ABSTRACT

The Olin College Machine Shop is in the early days of transitioning from a traditional, production-focused facility to a true learning environment focused on student growth and development. This paper examines the design of shop operations with an emphasis on enabling and supporting student autonomy in a mixed-used facility that supports approximately 350 students as well as faculty and staff in endeavors as diverse as personal projects, engineering research, coursework, and club teams. We outline specific aspects of the operation of the shop that we've designed to foster student autonomy such as universal early access to training, training information management, a student support team, and student-generated media. Because re-imagining our shop primarily as a learning environment is a relatively young initiative, we also reflect on opportunities for future improvements.

Fig. 1 – One student training another in the safe operation of a metal cold saw. Peer-to-peer learning is one key component of supporting autonomy in Olin's shop.

INTRODUCTION

A. BACKGROUND

Olin College of Engineering is an undergraduate-only institution with approximately 350 students and 45 full time faculty. It was founded in 1997 with the mission to educate exceptional engineering innovators and the aspiration to change engineering education broadly. To promote innovation, experimentation, and risk-taking there are no departments at Olin and faculty are not granted tenure. The college offers three accredited degrees – electrical and computer engineering, mechanical engineering, and engineering (in which students must declare a concentration that meets requirements for breadth, depth, coherence, and rigor).

Approximately 40% of Olin's curriculum is common across all majors, with engineering design, and hands-on project-based learning featuring prominently. For example, in the first semester of their first year, all Olin students take an introductory design course in which every student individually designs and builds a mechanical system and also participates in a team-based final project to create a play experience for fourth-graders. It is common for Olin students to be enrolled in at least one course every semester in which they are expected or required to make something – from mechanical toys and autonomous robots to circuits and software.

In addition to coursework, students engage in making activities as participants in research labs, members of competition teams like SAE Mini-Baja and Formula, ASME Human-Powered Vehicle, co-curricular experiences, personal projects, and independent endeavors to learn about new or unusual topics called "Passionate Pursuits." As a result, Olin has developed an active and vibrant culture of making on campus that permeates just about every facet of a student's educational development.

B. THE MACHINE SHOP

Because of its size, Olin does not have the resources (space and financial) to create separate fabrication or making spaces to support niche applications that are common at larger research universities. At a larger school, parts produced for research might be machined in a dedicated shop that employs full-time master machinists; coursework might be confined to a single shop with dedicated instructional support; and competition teams might be given their own fabrication facilities entirely. Makerspaces are very common at a variety of institutions and support informal fabrication, often without dedicated staff available. At Olin, a single facility supports all those use cases and more.

Olin's machine shop is staffed by a Director of Design and Fabrication Operations (who also holds a faculty appointment as a senior lecturer of mechanical engineering), a full-time master instructor of machining, a full-time instructor of design and fabrication, and a half-time instructor of welding and fabrication. The full-time staff members work together to supervise a team of 12-17 students who work approximately 6 hours per week each.

AUTONOMY SUPPORT

Olin students practice engineering design early through a variety of project-based experiences. Critical to their success in these endeavors is their ability to be or become autonomous learners. Real engineering projects are often not initially well-posed and, in many cases, require students to develop new skills or knowledge to solve problems that are new to them. Navigating the uncertainty and ambiguity of real problems requires a significant amount of autonomy and demands a high degree of motivation on the part of the student.

Self Determination Theory (SDT) [1] is a theory of motivation that posits that optimal motivation and ability to grow personally is achieved when people's needs for autonomy, competence, and relatedness are met. Autonomy is the ability to freely make decisions that directly impact our experience. Competence (sometimes also called mastery) results from the acquisition of deep knowledge or skills in a particular domain and usually entails a progression from novice to expert. And, relatedness is feeling connected to others and their experiences. SDT suggests that supporting student autonomy to explore, define, and creatively solve real problems is likely to increase engagement and begin to enable them to develop intrinsic motivation, finding inherent value in their work as opposed to working for some extrinsic reward like a good grade or praise from an instructor.

IMPORTANCE OF AUTONOMY TO LEARNING

The high level philosophy of Olin's machine shop is shaped by the goals of providing students autonomy, opportunities to pursue mastery (or competence), and a sense of relatedness or connectedness. For example, any Olin student (and any cross-registered student from a partner institution like Wellesley or Babson College) can request to be trained to use any machine in the shop – enabling autonomous learning to occur through the realization of a project. Frequently, those trainings are performed by one of their peers – developing a sense of community and connectedness. At a certain level of proficiency in machine operation, teaching, and interpersonal interaction, a student may apply to become a paid assistant in the space – a mastery experience that leads to becoming an expert with skills that are recognized and valued by the community.

This philosophy of supporting autonomy to increase engagement and facilitate the development of intrinsic motivation also plays out in the policy, programming, and operational decision-making on a day-to-day basis. Some of the unique autonomy supportive elements of the Olin machine shop are detailed in the following section.

AUTONOMY SUPPORTIVE ELEMENTS

The high level goal of autonomy support for students must still be operationalized through a variety of different mechanisms. Every policy, procedure, document, personal interaction, support system design, and space layout is an opportunity to promote student autonomy and engagement with the resources available in the shop.

A. EARLY ACCESS TO TRAINING

In the first semester of their first year, all Olin students take an introductory design course, ENGR 1200 – Design Nature. The course is an introduction to engineering design, prototyping, and design thinking. As part of the experience, each student individually designs and builds a bio-inspired hopping toy from a kit of raw materials using simple fabrication methods like laser-cutting, drilling, sanding, and sawing.

A critical component of the success of the hopper project is developing students' abilities to use machines safely and effectively. At the start of the project, the entire class (approximately 100 students) is all introduced to the shop and its code of conduct and safety rules and trained in the safe operation of the bandsaw, the drill press, and the belt/disc sander. Students are trained in groups of five by a staff or faculty member who is paired with a student. Their training consists of laying out and cutting 1"x¼" steel stock to size, drilling and deburring a hole, and deburring and rounding edges on the belt sander. Each training session lasts a maximum of two hours and afterward, students are welcome to come use those machines during normal shop hours.

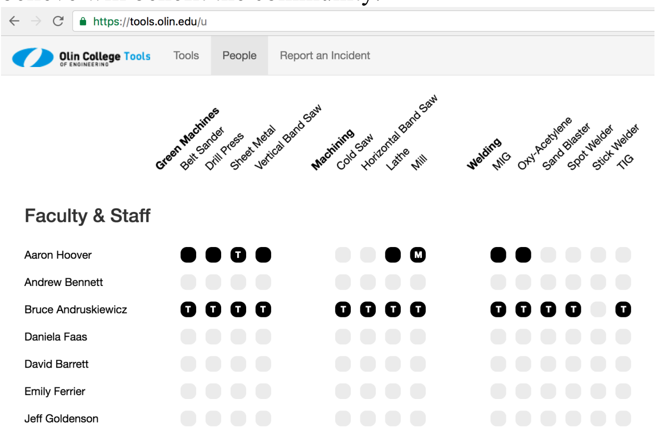
This early, uniform access to training ensures a baseline of competence for every student but is also an opportunity to make every student feel welcome in the space regardless of major (since at this point, students have not yet declared majors). For those students who are interested in learning and doing more in the shop, it's their first chance to learn about the training process for more advanced machines and processes.

B. TRAINING INFORMATION SYSTEMS

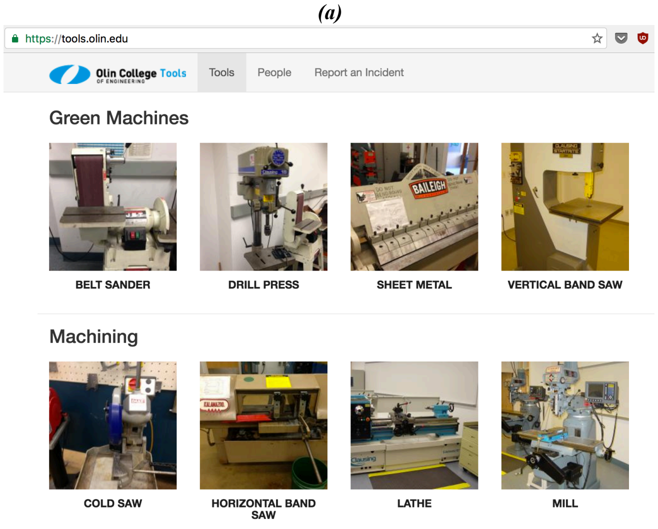
Because students have access to use any machine in the shop (with appropriate training), maintaining accurate and accessible training records is critical to safe day-to-day operation.

Machines are classified into three classes (green, yellow, and red) according to potential injury severity and probability of that injury occurring. The time and effort commitment to be trained on a particular machine is approximately commensurate with the level of risk entailed in operating that machine. (In some cases, that risk assessment may also account for damage a machine could sustain if operated improperly.) Students, faculty and staff are able to sign up for trainings via a simple online system; reducing entry barriers for getting trained. Furthermore, individual courses may request training, but in most cases, training is done through the online system enabling a standardized entry point for all.

Training records for all users (students, faculty, and staff) of machines and facilities are maintained in a custom-built database and are accessed through a simple web application all of which were designed and built by student as part of a summer project. All training records for all users, all machines, and all access-controlled facilities are available to any member of the community at a single URL – tools.olin.edu. A scrolling display of training records for every community member similar to the screenshot depicted in figure 2 is located immediately outside of the main entrance to the machine shop. Making skill acquisition conspicuously visible creates transparency, supports accountability, makes individuals' mastery experiences visible, and helps establish a community of practice [2] in which less experienced or knowledgeable members have an easy way of identifying those with expertise. Instead of being relied upon as the defacto (and only) experts, faculty and staff (and students, themselves) can use the display to make connections between users with skill differentials to facilitate peer-to-peer learning. The fact that the system was designed and built by a student also reinforces the message that student users of the shop are empowered to make changes they believe will benefit the community.



(a)



(b)

Fig. 2 – Screenshots from a student-designed and developed web application for tracking user training levels. The application allows anyone to view any other user's training level on all equipment (a). Training records are also available on a per-machine basis (b). Machine-specific training materials can also be accessed through the application.

C. STUDENT STAFFING MODEL – "NINJAS"

Despite not having graduate students, the culture of student course assistants has been strong at Olin since its founding. Student assistants at Olin are referred to as NINJAs – an acronym that stands for "Need Information Now, Just Ask." While most NINJAs are typically associated with a course, Machine Shop NINJAs are only associated with shop resources – space and tools. The NINJA team comprises up to 17 students and is divided into sub-teams dedicated to supporting specific processes like milling, turning, laser-cutting, welding, and 3D printing.

NINJAs are primarily responsible for training students on machines and processes and updating training records accordingly. Their primary directive is ensuring students operate machines safely to prevent 1) personal injury and 2) damage to equipment. At any given time, a staff member of the shop is supervising and ensuring that safety and training standards are met.

However, the NINJAs are also full-fledged team members who are empowered to make improvements to spaces and processes as they see fit. Early in the semester, NINJAs identify projects they'd like to work on to improve the operation of the shop. Past projects have ranged from fabricating long stock storage racks to designing icons for visually communicating shop rules with vinyl-cut graphics.

The entire shop support team, including NINJAs, meets weekly to discuss upcoming events, trainings, times of anticipated high utilization resulting from course projects or club team competition deadlines, and progress of shop improvement projects.

C. STUDENT-CREATED MEDIA AND VISUAL IDENTITY

An often-overlooked element of a makerspace facility, but one with significant potential to build community engagement, is the creation of a visual identity and related media. Encouraging students and other community members to design signage, videos, logos, and other media for the facility engenders a sense of ownership and creates the opportunity for individuals to feel like their work will have a lasting impact.

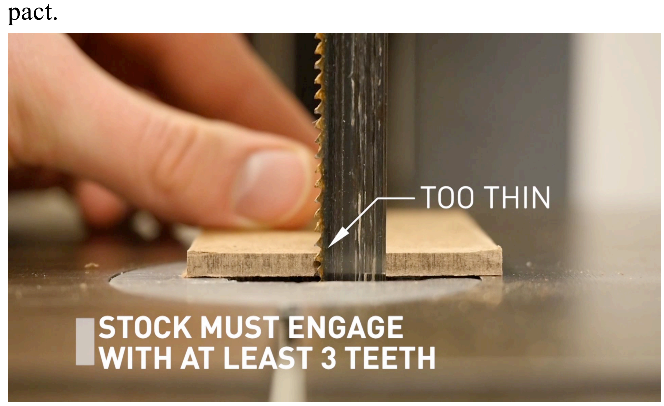


Fig.3 – Screenshot from a student-made refresher video for the band saw.

An important part of our NINJA team in the Olin shop has been dedicated documentation NINJAs. Example projects that have emerged from student design and documentation efforts include training refresher videos (figure 3) and a transition from a poster listing basic shop rules in text to a visual icon system (figure 4). The position of documentation NINJA has the added benefit of creating an explicit access point to the shop NINJA team that intentionally requires zero prior experience with tools or physical making in general.

FUTURE IMPROVEMENTS

Though we believe that the elements discussed above have begun to shift the culture of Olin's shop from an emphasis on production to an emphasis on autonomous learning, we recognize that there are still improvements to be made. Our goal is to provide an environment where all students, faculty and staff are welcome and where good shop habits including safety and cleaning up are embedded in the community.

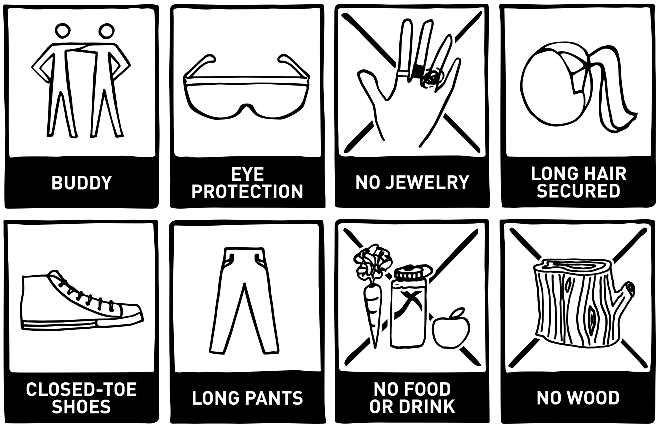


Fig.4 – Student-designed vinyl icons illustrating the 8 basic safety rules for Olin's metal machine shop.

Streamlining training and standardizing the process across all equipment and access-controlled spaces would greatly reduce barriers to entry and encourage more student ownership of the training process. Currently, some machines have a multi-step training process consisting of a reading/video, a quiz, an in-person training session, and a test piece while other machines may have only one or two of those elements. We are currently in the process of building a consistent training process into the tools.olin.edu application.

How might we create new entry points into the shop that encourage students who haven't yet discovered making to become involved? The Olin shop currently supports courses and certain extracurricular activities like competition club teams well. However both of those contexts tend to present well-defined needs, encouraging community members to view the shop in an instrumental or transactional way. Yale's Center for Engineering Innovation and Design [3,4] has done a good job of creating programming that engages the community in experiences across a spectrum of formality that ranges from social events to lectures and classes. Shop-specific programming that invites in curious, but inexperienced users will be critical to creating new "on-ramps."

NINJA team cohesion and sense of stewardship is critical to establishing a healthy and safe culture of student autonomy in the shop. Though the NINJA team has been successful in building a sense of collective ownership for the shop's resources and processes, it could be improved further still. For example, Olin's version of resident assistants, resident resources (R2's), arrive a week early for school in the fall to undergo intensive training and prepare for the arrival of a new class of students. Having the NINJA team arrive on campus one or two weeks early to clean and maintain the shop and learn pedagogical techniques to prepare to train an entire class of first year students (similar to what is done in the Stanford Product Realization Lab [5]) would be a significant step for NINJA team- and culture-building.

Finally, the relative effectiveness of the changes intended to promote student autonomy needs to be quantified with data. We have limited survey data from past years, but future efforts to perform data collection and analysis through surveys, longitudinal training tracking, and student narratives will help us evaluate our experiments.

CONCLUSION

The Olin College machine shop is in the early stages of shifting its culture from a production focus to be more of a learning environment that puts experimentation, learning, and growth at the center of community members' experiences in the facility.

To do that effectively, we have tried to draw on ideas from Self Determination Theory to design aspects of the day-to-day operation to enable and support a high degree of student autonomy. Viewing decisions about training, documentation, staffing, access, and programming through the lens of autonomy support enables us to operate in a manor that's consistent with Olin College's aspiration to change engineering education more broadly.

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Best Practices for A Newly Established Academic Makerspace in a Nascent Maker Ecosystem

ISAM 2016 Paper No.: 05

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INTRODUCTION

This paper discusses the different practices that can be infused in an academic makerspace's culture to enhance learning and to remove barriers to making. Best practices with examples and their corresponding results observed at an academic makerspace in Pakistan have been discussed. The makerspace in question is the first and currently the only academic makerspace in Pakistan, appropriately named Make-i-stan. It is based in Information Technology University of the Punjab (ITU) which offers STEM degrees at undergraduate, graduate and doctorate level.

Makerspaces are playing their role in many different learning landscapes as making has evolved itself as an adaptive concept that can be adapted to different cultures, regions and settings. In addition to being adaptive, a makerspace's culture is transformative. Makerspaces thrive in collaborative and open culture and in academia this culture makes the process of learning and making much more fun and rewarding for the students and educators alike.

1. Description of Setting

Since the practices and their results included in this paper are by and large based on the experiences, it is important to describe the educational setting Make-i-stan is based in. Make-i-stan is the first and only recognized makerspace in Pakistan. It is embedded in a public sector university named Information Technology University of the Punjab (ITU). ITU is based in Lahore, a populous city of 11 million people which is considered the cultural hub of Pakistan. Lahore is also the home to numerous high ranked universities of the country. Despite being the project of ITU, a major portion of the users of the makerspace come from other universities. We get visitors from outside of Lahore as well.

1.1. Description of Programs

Make-i-stan has multiple programs making it a hybrid of a workshop and a community makerspace. It does trainings and offers its space and tools for development of projects. Other than the trainings offered on specific technologies, customized trainings with external organizations have also been done. For people who want to work on their hardware projects, we offer our space and tools through open days every week and through the 2 months long designers in residence programs. All of its programs are currently being offered for free to ITU and non ITU students. Although a majority of our visitors are engineering and computer science students, the space is not exclusive. As can be seen in "Fig. 1," we get people having varying professional and educational back

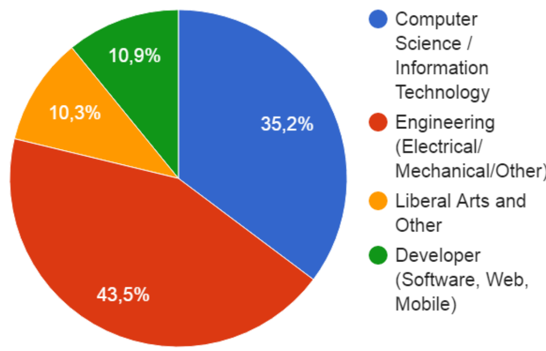

Figure 1. Make-i-stan's Visitors Educational Backgrounds

grounds.

1.1.1. Regular Events and Open Days

Make-i-stan has been holding free events and workshops since its inception. The idea of a community makerspace is still very new in this part of the world, so we have kept all of our events free so far. It has helped us remove a major barrier to engage a large number of students at our makerspace. Finding expert trainers for teaching specific technologies and tools becomes difficult at times without any monetary incentive but in an environment in which all the community members get the opportunity to learn for free, willingness to contribute back to the community remains very high.

a. Weekly Arduino Workshops

Arduino Nights are semi structured weekly workshops on Arduino. The reason for choosing the platform of Arduino for conducting regular free workshops is because it allows for reaching a wide audience. Kids, high school students, undergraduate and graduate students from varying disciplines and fields can all learn the easy to use open source platform. The loosely structured workshops allow for discussion and implementation of new ideas. Participants can come up with their own ideas or they can join a group lead by a facilitator. Anyone can become a facilitator provided that they have enough exposure of working with arduino and can help a group to follow a series of instructions from well documented project manuals. Participants are allowed to bring their equipment but a majority of them borrow the equipment for the duration of the workshop and return it back at the end of workshop. Arduinos and basic electronic components such as sensors etc are accessible to everyone. Although there is always a team of volunteers who facilitate this workshop, but the participants can borrow the equipment without asking anyone.

b. Weekly Open Days

Two days every week are designated to be open days. Anyone either with an idea for a project or with an ongoing hardware project is invited to come in and work. Visitors can use the space and the available tools for prototyping and testing, but they have to return the borrowed equipment before they leave the space. Currently the equipment that we have on offer is mostly inexpensive components and prototyping boards. In order to use fabrication tools such as a 3D printer they have to pay in cash for the materials they use. Visitors also get unrestrained access to inexpensive consumable components.

1.1.2. Designers in Residence Program

Designers in Residence program is a two months program where the selected DiRs are given access to the space for six days a week. Designers are selected on the basis of strength of their skill set and are required to commit for two months to work in teams on hardware projects. The induction to program is completely free and each team is given $100 credit for buying consumable components for their projects. As opposed to working on a predefined task assigned by someone else [1], DiR program allows students to work on projects of their choosing.

2. Best Practices and Processes

There are certain practices which have elicited exciting results at the makerspace in question. Following are the practices which can be adapted in a similar setting for creating a stronger community, creating an environment for enhancing educational impact of the makerspace and for lowering boundaries to making.

2.1. Forming a Strong and Diverse Community Through Culture of Openness, Equality & Responsibility

Creating a culture of openness which allows for free flow of information from management of the makerspace to each member of the community is essential for creating an environment in which each community member takes ownership of the space and its resources. There are multiple ways of communicating this information, and including the community in decision making process.

2.1.1. Steering committee

A committee consisting of the most avid contributors to community are part of the decision making process. Committee can consist of members of the institute administration, makerspace management, volunteers and interns or regular visitors of the space. Organization of the space; events and workshops to be organized; and assessment of the needs in terms of tools and equipment at the space should all be discussed in committee meetings. Makerspace management remains an important part of the decision making process, as they provide and arrange logistics for the implementation of the ideas.

Having a committee to oversee all the organizational decisions ensures that the community also takes ownership of the successes and failures. Since the committee members keep changing overtime, the organizational decisions keep evolving accordingly.

2.1.2. Organizational Hierarchy

The organizational hierarchy of a makerspace should be simple and the community as a whole should be able to delegate tasks to its members. Each community member is accountable to the community. From keeping the space organized and clean, to helping organize workshops and events, a community that feels empowered can keep a space up and running with or without any help from the university.

2.2. Transforming Learning & Making at Universities

Learning outside of classroom or informal learning helps students retain the content better than traditional education[2,3]. Working environment at makerspaces should take pressure away from students. Removing the administrative hassles that come with the typical lab equipment usage policies of universities can create an open and free environment that for a better learning experience.

2.2.1. Unrestrained Access to Space, Tools and Consumables

Though giving unsupervised access to expensive equipment to non registered members is infeasible but by providing unrestrained access to less expensive tools creates an environment of self accountability and is likely to increase the affinity towards the community space. Since students are not strongly prepared to take advantage of the hands-on time in the laboratory period [4,5] this policy of unrestrained access to less expensive equipment is one of the most important reasons that students prefer the community makerspaces over the highly equipped laboratory facilities of students' institutions.

2.2.2. Flexibility in Making

The weekly arduino workshops at Make-i-stan are loosely structured to cater to a wider audience having varying levels of expertise on the open source prototyping platform. Curriculum is not an overall order imposed on a course of material [6]. Even the most highly structured trainings which are conducted at a makerspace are adaptive to suit the needs of the audience. They are designed to be replicable and are short in duration. The adaptive and flexible curriculum elicits a higher level of engagement in students and is helping transform the traditional teaching methods at the universities.

2.3. Removing Barriers to Making

Students should be encouraged to engage with the academic makerspaces. There can be multiple barriers to entry depending upon the location and the social constructs of the region where the makerspace is located.

The biggest barrier to making in a nascent maker ecosystem such as Pakistan is the monetary cost associated with making. A major component of an academic makerspace's program should always remain free.

Language can also be a barrier to entry for some in a country such as Pakistan. Its reason is rooted in post colonialism. Language does not only create a communication gap but can also be a cause of discomfort for the audience. A community space should make its visitors feel comfortable while communicating in whichever language they communicate their

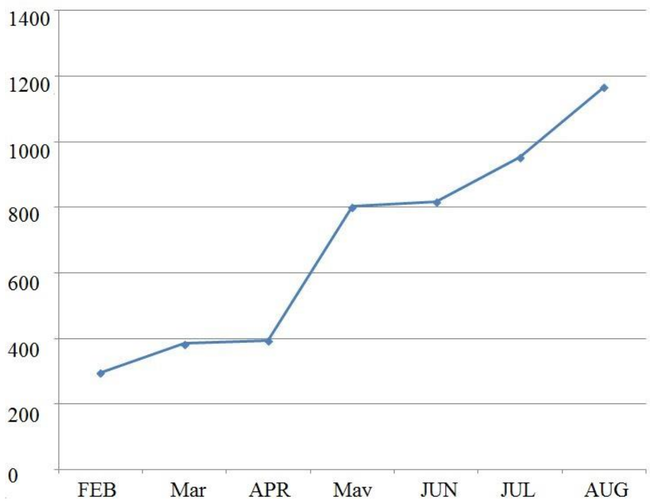

Figure 2. Number of Unique Email Subscriptions by Month

ideas in the best way possible. In case of Make-i-stan, we prefer using the national language Urdu and sometimes English, depending upon the type of audience present.

3. Results and Discussion

The practices described in this paper have performed well in our setting and can be replicated and adapted in a newly established academic makerspace. These practices are not new in their entirety but are highly effective in producing desirable results and can be used as a framework that makerspaces in similar settings can use. The application of these practices has produced positive results which can be quantifiably measured. Due to the limited capacity at our space, we send out confirmations to the selected participants for each event, but to keep things simple we avoid doing a roll call. We sent out a survey to the selected participants of our previous 8 events. Based on this survey and on the basis of headcount for each event, a summary of member data for these 8 events is given in table 1. People who attend our workshops are mostly students and through the survey we found out that reason for attending the event for an overwhelming majority was to add a new skill to their resume. Almost half of these participants are the returning visitors. We have found out that many of the returning visitors either do not wait for confirmations from our side or do not even formally register for the event. This shows that making the space more accessible encourage people to engage with us after their first visit. "Fig. 2," shows organic increase in the number of email subscriptions by month. "Fig. 3," shows number of organic facebook likes. We have analyzed the social media activity and found out that whenever we have we have seen an unusual increase in social media engagement; it has happened due to the following three

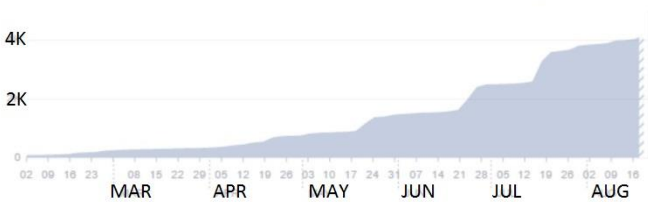

Figure 3. Organic Facebook Likes

Table 1. Summary of Visitor data for last 8 events

Number of participants (last 8 events)	Registered returning visitors	Unregistered returning visitors (estimate)	ITU students
260	28%	>25%	37%

reasons. 1. Showcasing the long-term hardware projects made by our users, 2. Having an expert over to do training or talk on a topic outside of our area of expertise. 3. Doing partnerships with external organizations having good social media reach.

Other than the increased student engagement, we have been able to engage students from outside of ITU including students from outside of the city of Lahore. Students from Wah, Gujrat, Layyah, Faisalabad, Okara and Hafizabad have visited us in order to seek help in last 6 months. They visit us because of the unavailability of makerspaces in their respective areas. These students are still in contact with our community members and can potentially play a pivotal role in introducing maker culture in their respective towns and cities.

4. Conclusion

The practices presented in this paper have elicited positive results. Similar practices can be adapted in similar settings to create an open and free environment which enhances learning; increases student engagement; and get students excited about these spaces.

The first and the biggest challenge for any new community makerspace is to form a community which takes ownership of space, resources, decisions and results of those decisions. Openness, equality and responsibility are the cornerstones of any strong community and the makerspace management needs to build the community on these values.

An academic makerspace should adapt to its setting but it should also work towards transforming the learning methodologies of the institute it's based in. Removing barriers to joining the community and giving unrestrained access to less expensive tools separates a makerspace from a university laboratory.

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All the Cool, Perfectly Safe Things You can Do in a Bio-Makerspace

ISAM 2016 Paper No.: 06

Invited

David Kong

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We are in an era of increasingly distributed biotechnolo-gy. The knowledge, tools, and infrastructure for the crea-tive exploration and construction of living systems are becoming more accessible, leading to an array of crea-tive, impactful, whimsical projects emerging from a growing network of bio-makerspaces around the world. A new generation of bio-makers—young people, artists, designers, and everyday citizens—are engineering mi-cro-organisms to make animal products (real vegan cheese) and sequencing the microbiome of our cities. This talk will explore this new network of bio-maker spaces, the projects being created, and im-portantly, the safety and security concerns therein.

The Making of a Makerspace; An Architect's Perspective

ISAM 2016 Paper No.: 07

Invited

Michael P. Maloof

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INTRODUCTION

Working with your architect represents an important step in the planning and implementation of your new makerspace. While the design process is linear in concept, it is also collaborative, iterative, and exploratory. Are you building new or are you renovating? Who are your anticipated user groups? Do your project goals align with your project budget? Space is an investment and the design process is mission-critical to your success.

I. PROJECT DEFINITION

Your project begins with an idea and a champion. The strongest designs spring from the strongest ideas and are heralded by the strongest-willed project champions. Champions range from forward-thinking administrators, to faculty advocates, to motivated groups of committed students.

Most often, an architect gets involved once your idea evolves into a space request. Architects are typically selected by Procurement and Purchasing offices within upper administration. Sometimes you may have a say in the selection process, other times you may not. In either case, being prepared with a clear set of project goals and realistic expectations will help set the tone for the design process.

II. THE DESIGN PROCESS

Design is an iterative process. The first step is to define the project parameters. These parameters help sharpen the project goals. Typical project parameters include the limitations of available space, population and utilization projections, equipment needs, project budgets, schedules, and life cycle analyses.

Once the project goals have been established, your architect will work with you to translate your ideas into physical space. Progress is documented through a series of checkpoints and approvals, usually with drawing submissions of the evolving plans accompanied by a cost estimate. Once the final design has been reconciled with the project budget, your architect will issue construction documents for bid. Typically, the bid process vets construction costs and lead times among several qualified contractors. Construction begins upon contractor selection and contract award.

III. ELEMENTS OF A MAKERSPACE

The task of the architect is to design space for people and space for equipment.

The basic design model for a makerspace involves some variation on the following program elements:

• work space/bench space for the intended user groups
• a widespread range of support functions, including: welding, woodworking, rapid prototyping, large format plotting, electronics, machining, textiles, etc.
• building necessities: restrooms, mechanical rooms, electrical closets, exhaust fans, plumbing risers, loading docks, storage space, etc.
• amenities: lounge, coffee bars, kitchenette, assembly and presentation areas, huddle rooms, outdoor space

IV. HELP ME HELP YOU

Despite these fairly common design elements, every project comes with surprises. Some common pitfalls that occur during the design process include:

• short-sighted approaches to mechanical, electrical, and plumbing infrastructure
• misalignment of expectations and budget
• underestimating campus-wide interest in making
• taking flexibility too far
• assuming your architect knows what you mean

Good architects will know the right questions to ask in order to keep the design process on track. Ideally, your architect has designed a makerspace before, appreciates your unique culture, and understands the way you will use the space when it is finished. Some of the most helpful tools you can provide for your architect include:

• equipment lists with model numbers, dimensions, utility requirements, and adjacencies
• precedent photos of aspirational spaces or design examples to avoid
• tours of benchmark makerspaces at other institutions
• live demonstrations of the work you do and the equipment you use to achieve your end result
• formal feedback one year after occupancy

In the end, the architecture is the easy part. Starting with a bold idea and a clear vision is paramount. Working with your architect in developing the right design within the project parameters will lead to a successful end result. The real challenge is cultivating a culture of making, sustaining that maker community, and upholding your makerspace as a cornerstone of your campus at large.

A Research Agenda for Academic Makerspaces

ISAM
2016
Paper No.:
08

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INTRODUCTION

A key characteristic of academic makerspaces that distinguishes them from fab labs in secondary schools, non-profit community spaces, or for-profit membership facilities is of course that they are embedded in institutions with significant research activity. Yet academic makerspaces also differ from traditional research labs in that they are open to a broader set of constituents and expertise levels, and often support a larger variety of possible uses. While many emerging academic makerspaces are primarily associated with instruction and student service goals, we argue that research and making can and should intersect in productive ways. This paper lays out the landscape of possible engagements based on our own experience and observations.

A tight connection to academic research promises benefits for both sides:

1) Educational research and qualitative observational research can improve our fundamental understanding of the values of making for students; as well as elucidate the conceptual and pragmatic hurdles makers face today through careful study of making in practice.

2) Makers can serve as a new target audience for technology research and development in engineering disciplines.

3) Research projects in a large number of domains can leverage makerspace resources to accelerate their progress and engage students to turn fundamental discoveries into usable devices and services.

In addition to these intellectual threads, research integration can also contribute to important pragmatic and operational goals, for example ensuring that makerspaces receive appropriate institutional attention, credit, and funding.

We next present our own institutional context, review the three major themes listed above and present illustrative example projects.

CONTEXT

Our review of research integration opportunities is based on our experience launching and running two makerspaces for the past four years at UC Berkeley within the College of Engineering (see Figure 1). The CITRIS Invention Lab, launched in 2012, started as a bottom-up effort to bring digital fabrication equipment out of restricted lab settings of individual faculty and make it available to the larger campus for teaching, independent project work, and research. The Invention Lab is located in a large, multi-disciplinary research building and has a focus on supporting researchers and university startups. Our experience in launching the Invention Lab strongly informed the design of the Jacobs Institute for Design Innovation, a 24,000sq ft building with three teaching studios, a 7,000sq ft maker space, and advanced fabrication and electronics labs spread throughout four floors. One of the main missions of the Jacobs Institute is to impact undergraduate education at UC Berkeley. An important feature of our programming in both locations is that community space, classroom space, and fabrication labs are all co-located, and that intersections between different cohorts of undergraduate students, graduate researchers, faculty and staff are explicitly encouraged.

Figure 1 - Top: The Jacobs Institute for Design Innovation at UC Berkeley. Bottom: Students working in Berkeley's CITRIS Invention Lab.

THEME 1: UNDERSTANDING THE VALUE OF MAKING AND HOW MAKING HAPPENS IN PRACTICE

Academic makerspaces offer easy access for education researchers who wish to study the impact of making-based curricula on STEM preparation and other learning outcomes. Claims in the maker movement about increases in self-efficacy or motivation towards STEM careers abound. But how can we rigorously test whether this is indeed the case? A growing body of research is investigating the impact of making, including crucial questions round what the right metrics for impact are [1,2]. Some existing research focuses on K-12 education [3], or specialized education settings [4]. There is significant need and opportunity to contribute sound assessments at the college level. The learning sciences provide relevant theories, such as constructionism

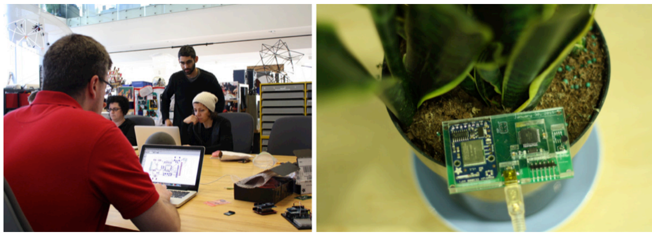

Figure 2: Makerspaces can serve as locations for qualitative research, such as Mellis et al,'s investigation into how novices approach circuit board design [8].

and project-based learning, and appropriate assessment methodologies, such as comparisons of pre- and post-tests and surveys of students engaged in makerspace activities and classes. It would be especially enlightening to find settings where such results can be compared against matching activities that take place without access to a makerspace. In the Jacobs Institute, we plan on hosting a graduate research course on pedagogy and assessment in engineering design education, led by Prof. Alice Agogino, where graduate students will be embedded as observers of the making activities in the building.

In addition to *formal* education, researchers are also seeking to gain insight into *informal* learning by makers – e.g., understanding how online tutorials, project sharing sites or communities help or confuse individuals [5,6,7]. Our collaborators have used community workshops located in academic makerspaces to investigate how a broader public can become engaged in the fabrication of electronic products [8] (see Figure 2). Such studies shed light on the role of informal networks of expertise sharing, and they can also result in guidelines for the design of better future technologies that overcome hurdles that individuals makers and groups experience today.

THEME 2: ENVISIONING THE FUTURE OF MAKING: DESIGNING TECHNOLOGIES FOR MAKERS

Because of the institutional support for developing and evaluating novel, experimental technologies, academic makerspaces are also ideally positioned to push the boundaries of the hardware and software tools that are found in such spaces. Different engineering disciplines from Computer Science to Electrical Engineering and Mechanical Engineering are increasingly becoming interested in developing technologies that are tailored to makers as target users. Academic makerspaces can also help disseminate the most promising technologies through workshops and through developing and publishing documentation, tutorials, and example projects.

A. DESIGN SOFTWARE

One strand of recent research provides improved design software for existing digital fabrication equipment in such spaces. For example, in our own work we have developed design tools for modeling, routing and fabricating hollow tubes inside 3D-printed objects, which can then be filled with conductive materials to integrate electronic components or create interactive, touch-sensitive objects (released in Autodesk's Meshmixer) [9]. Others have developed algorithms to 3D print "wireframe" models an order of magnitude faster than solid 3D models [10], or computationally modify models to create tactile textures [11], or articulated figures [12]. One advantage of such software advances is that wide distribution is simple. However, making the transition from a research prototype to robust software with appropriate maintenance and support is at not always aligned with researchers' academic career incentives.

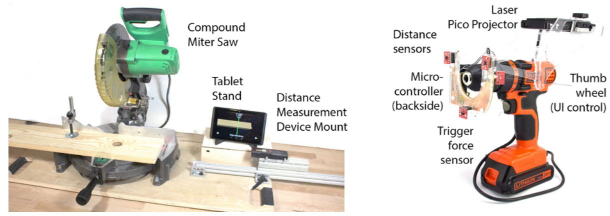

Figure 3: Augmented power tools by Schoop et al. [15] aim to deliver dynamic tutorials to tool users.

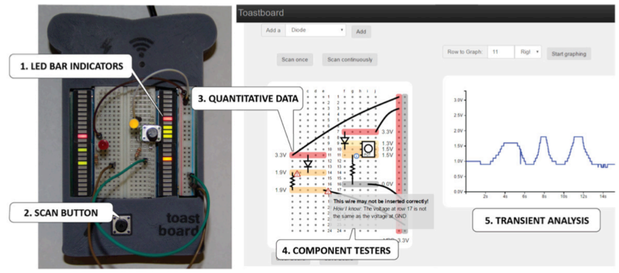

Figure 4: The Toastboard, an augmented breadboard for troubleshooting circuits by Drew et al. [20].

B. FABRICATION HARDWARE

Researchers are also developing novel hardware tools – from CNC felting machines [13], to actuated hand-held carving tools [14] and augmented drills and saws [15] (Figure 3). These explorations can most profoundly re-envision what future makerspaces will look like and how makers will interact with their tools.

C. EMBEDDED CODE AND ELECTRONICS

Many projects created in makerspaces include embedded code and electronics. Moore's law and the success of accessible microcontroller platforms such as Arduino have lowered both the price and expertise barriers such that adding computation and interactivity has come within reach even for novices. Research labs have produced embedded computing platforms aimed at makers, e.g. for interactive textiles [16], or for connecting sensors to smart phones [17]. Because of maker-oriented electronics distributors such as Sparkfun, Adafruit and Seeed, these research projects are increasingly available to the larger community. In our own work we have focused on making the new "stack" for Internet of Things devices – embedded, smartphone and cloud – more easily programmable for makers [18].

One of the key challenges going forward will be to support makers in understanding and debugging the complexity of the cyber-physical systems they build in makerspaces [19]. For example, to support novices in circuit construction, we are developing an augmented breadboard that continuously scans voltages across all rows and visualizes discrepancies between intended and observed circuit behavior in a web interface [20] (Figure 4).

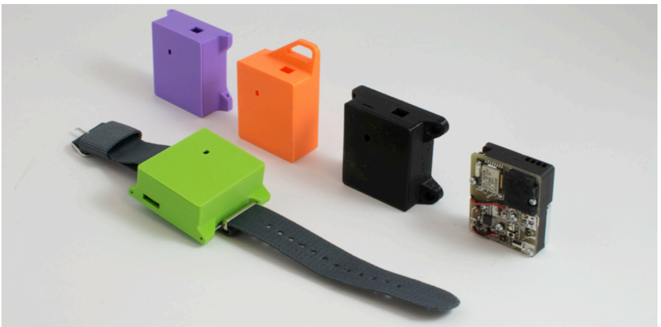

Figure 5: The MyPart wearable particle sensor research project by Tian et al. [23] was enabled by PCB milling, 3D printing and electronics equipment in the CITRIS Invention Lab.

THEME 3: MAKER RESOURCES AMPLIFY EXISTING RESEARCH

The equipment available in makerspaces, and the result-oriented, prototype-driven value system frequently found there, can support research in a wide variety of domains. While many scientific disciplines have developed highly specialized equipment, our experience has shown that the general-purpose fabrication tools in makerspaces have broad applications across many scientific fields. Furthermore, the relatively low expertise threshold for digital fabrication tools – when compared to traditional machining – means more researchers perceive working in a makerspace as within their reach.

For example, our labs have seen researchers build automated RFID rodent trackers, novel haptic actuators, spherical tensegrity robots, laser-cut water treatment devices, 3D printed microfluidic devices, pressure ulcer sensors, domed LED arrays for mobile microscopy [21], robotic floats that study the ocean's carbon cycles [22], and low-cost, wearable air particle sensors [23] (see Figure 5).

While such research is often federally or industrially funded and access fees are of little budgetary significance for PIs, we have found that merit-based fellowships that give free access to our makerspace are a very effective vehicle to raise awareness of our makerspace among graduate students. In addition to the resulting research itself, the mixing of highly trained doctoral students from various disciplines with undergraduates who are getting their first exposure to hands-on design is a tremendous positive for our lab culture.

Ideas that arise in graduate research groups can also serve as the basis for undergraduate student projects. A fundamental insight or discovery can be further explored, or moved towards a translation into a concrete product or service. Several project ideas that teams developed in the Jacobs Institute and Invention Lab originated as research projects in the medical school and medical center at the University of California, San Francisco. For example, a student group created pressure-sensing insoles for patients with sensory ataxia (loss of feeling) in the legs. The idea first arose in medical research; students in a class hosted in our makerspace then contributed engineering expertise to build a wireless prototype. Additional class projects based on medical center needs have included liquid tracking for nephrology patients, and methods to counteract patient delirium.

METRICS

Documenting the integration of research can be helpful in arguing for appropriate resources for makerspaces, and in showing how making activities connect to the core academic mission of knowledge production. In addition to examples and anecdotes such as the ones listed in this paper, we suggest that documentation should, at a minimum, comprise descriptive statistics on fundamental metrics such as:

- The number of research artifacts or instruments that were built in a makerspace.
- The number of papers published that were enabled by a makerspace.
- The number of research grants or gifts submitted and funded that leveraged a makerspace.
- The number of graduate, postdoctoral or professional researchers served.
- The number of undergraduate makerspace students who were involved in the research and were trained in research methods.

CONCLUSION

We have described three separate but complementary themes how research activity can be integrated into academic makerspaces. In addition to the intellectual value, research integration can also contribute to important pragmatic and operational goals, for example ensuring that makerspaces receive appropriate institutional attention, credit, and funding. Finally, the community benefits of creating spaces where both novices and experts cross paths are significant. We encourage other makerspaces to consider attracting and growing research engagements in their facilities.

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Using makerspaces to develop didactic models for mechanical engineering

ISAM 2016 Paper No.: 09

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INTRODUCTION

Mechanical engineering learning of concepts requires the knowledge and understanding of the function of different mechanical elements through the career. Gears, mechanisms, bearings, pulleys, among others, are analyzed through the curriculum. Learning styles studies have shown that visual style, and visual in combination with auditory or kinesthetic, are the preferred by mechanical engineering students [1]. So, to have didactic models that show how different mechanical elements work, is very useful.

Since sometimes, a high investment is required to get these models, finding opportunities to build them with students is helpful. Not only for the economic reason but for the possibility to involve students in the use of the makerspace, its tools and equipment, which results in a deeper learning experience [2].

So, with this in mind, in the first semester of 2014 *Mechanical Engineering Department at Universidad del Valle de Guatemala (UVG)* proposed to *The Student Association of Mechanical Engineering (AMEC)*, the project of transforming a Toyota Hilux 1998 pickup truck that was out of service into different mechanical didactic models in order to use them in different courses, working the project in the makerspace of the department.

Five students from *AMEC* directed the project. They planned all of the activities, designed the three models, raise funds and managed them. With the help of three additional mechanical engineering students and the supervision of the makerspace technician the project was executed. Along the way there were several decisions to be made regarding the best way to present mechanical components in each model, what equipment to use for each task, what colors to use, how to raise funds. All of this and other challenges presented were decided upon as a team, taking into account all of the students involved.

METHODOLOGY

Students started the project in July 2014, establishing that three didactic models were going to be built in one year: transmission, rear section (braking system, differential and suspension) and engine. The process to make them followed these activities: defining goals, making a plan, identifying requirements and manufacture.

A. DEFINING GOALS

Provide a visual and kinesthetic experience to the learning and understanding of mechanical elements, by transforming out of service pickup truck components into didactic models. These models would enhance the learning experience of the students of mechanical engineering. The didactic models should keep the structural strength of components such as the transmission and engine but allow windows of observation in key elements such as the gears in the differential, piston travel in engine and gears in a manual shifter.

B. MAKING A PLAN

First of all, the magnitude of the project required a plan to be completed in the most effective fashion. Students established this plan, considering different aspects, as number of students involved in the project, time available and equipment. The working team consisted of five students from *AMEC* and three voluntary students. This team agreed in the setting of dates and times of activities during the week that better suited their schedule. Usually the time designated to work on the project was early in the mornings so it would be possible to attend classes in the afternoon. Having established this, the university provided the pickup truck, equipment, tools, maker space time and technical support to work during the whole project. The Gantt chart of the final schedule of activities can be found in Appendix 1.

The project would need funds for items such as paint, screws, degrease, wheels and others appeared. So, as a student´s association initiative, key chains were made with the 3D printer for Valentine's day sale as well as organizing two food sales where around US $150. 00 were raised. These activities helped to develop qualities like leadership, entrepreneurship and teamwork between team members and authorities of the university.

C. IDENTIFYING REQUIREMENTS

For each model several requirements were established. In Table 1, requirements for the engine are summarized as an example.

D. MANUFACTURE

The process for manufacturing this project required the use of the UVG Mechanical Engineering Makerspace. This facility is equipped with all the machines, tools and parts for a project of this magnitude; such as welding, painting, milling and cutting machines (Fig.1).

Table 1. Engine model requirements summary

Code *	Description	Priority
S01	The model should be safe for student use, transportation and storage	High
S02	The model should not have cutting edges exposed	Medium
S03	The model should be adequately secured to the mounting	High
S04	Moving parts should pose no risk to user	Medium
D01	The motor should have internal mechanism exposed	High
D02	All four pistons, valves and camshaft should be at least partially visible	High
D03	The different components should be differentiated by color	Low
D04	The model should be easily transported	Medium

*Code: S=safety, D=display

Fig.1 UVG Mechanical Engineering Makerspace

With the correct tools and equipment, the project was completed within a reasonable time frame, and accomplished that the whole project would be produced entirely *in-house*.
Different manufacturing strategies, tools and equipment were used through the development of the project. In every single stage of the project, security was the first priority. Guaranteeing safety gear was used accordingly and the safety regulation in the maker space was respected. The students participating had already approved previously courses for the use of welding, machines and tools.
Main equipment and machines used for the project are detailed in Appendix 2. Initially the pickup truck was taken by an external junkyard who removed seats, windows, and other scrap metal. This left the pickup truck´s chassis and mechanical elements mounted on it as a starting point. First, a general cleaning process was needed. Some elements like the gas tank and spare tire were removed, for safety purposes and to make working on it easier.
After that, the chassis was cut by the half (Fig.2), in order to make it easier to store and transport.

Fig.2 Cutting of chassis by José Valdez, mechanical engineering student

Starting with the rear section, the left wheel was removed for taking out the braking system (Fig.3). This was disassembled, cleaned and cut on the drum for the mechanism to be visible. The cuts were made with the milling machine and a lathe was needed to remove rust on the external face. With the suspension and differential, a similar process was followed, but because of the length of the differential system a milling process was not possible. Instead, those parts were cut using the polisher with a cutting disk. After this, everything was painted with different colors for easier identification and reassembled. The chassis was polished in certain places to prevent accidents and equipped with wheels for an easier transportation.

Fig.3 Original condition of braking system

Next on the list was the transmission system. This one was particularly difficult to cut because of the irregular shape, however the milling machine was used to make the openings

(Fig.4). Two cuts were made in different areas so that part of the transmission and the four wheel drive gears were visible. This one was thoroughly cleaned and painted. For the transmission to be aligned with the rear part and for easy mobility, a wheeled bench was built, that supports the whole transmission, maintaining the transmission relative position. This support was mainly built using arch and autogenous welding as seen in Fig. 5.

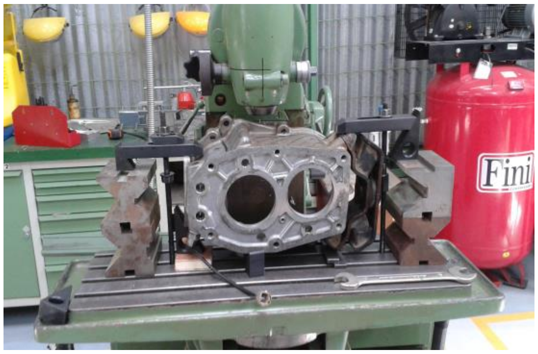

Fig.4 Gearbox milling process

Fig.5 Autogenous welding of transmission support, by Roberto Rossino mechanical engineering student

Finally, the engine was disassembled and all of its components cleaned: pistons, transmission chain, bearings, crankshaft, valves, etc. (Fig.6).

Once the block was empty, cuts were made for the pistons and valves to be visible. This last part was the most difficult. Because of the irregular shape and size of the block it couldn't be milled completely. It required drilling, milling, use of the polisher and other processes. The block was painted and reassembled for its display.

E. RESULTS

Fig. 7, 8 and 9, show photographs of the final didactic models for the rear section, transmission module and engine module, after finishing the project in May 2015.

The models have been used for different purposes on different courses such as: Introduction to Mechanical Engineering, Materials, Mechanisms, Mechanical Engineering Design and Internal Combustion Engines. Also, students from high school visit UVG, and the didactic models are shown to them during tours to the laboratories and maker space. They serve as an interactive way for senior students and professors to explain what the career is about.

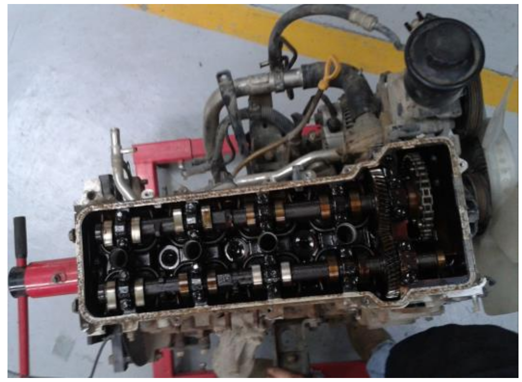

Fig.6 Engine during cleaning process

Fig. 7 Back part finished model

Fig.8 Transmission finished model

Fig.9 Engine finished model

Table 2 shows the number of students that have used the models during 2nd semester of 2015 and 1st semester of 2016. Additionally, the rear section and transmission models were placed in exhibition three days at the University's main plaza (fig. 10 and 11). The main purpose was to share the project with students from different careers, giving them a glance of what mechanical engineers do, as well as promoting the *AMEC*´s work. Jonatan, one of the students who worked on the project summed the learning experience as: *"I learned and understood about mechanisms that once seemed alien to me."* While other student, Byron added: *"I liked that the project was practical and hands on type of learning, I learned a few pair of tricks you can't learn from books or classes."*

Table 2. Number of students using the didactic models (2nd semester 2015 to 1st semester 2016)

Introduction to Mechanical Engineering	31
Materials	220
Mechanisms	69
Mechanical Engineering Design	90
Internal Combustion Engines	14
High School visits	105
Total	529

The exposition reached more than one hundred students. Some students said *"I got to learn about parts I didn't even know a car had."* The models were permanently there during the exposition, with a banner explaining the different stages of the project including the engine (which at the time was a work in progress). During specific periods of time there were *AMEC* members present explaining the project, the mechanisms and answering questions. The most common questions were: "*Wow! How did you guys did it?", "What does this part does?", "Do all motor vehicles look like that?"*

Professors from the Mechanical Engineering Department have also noticed the importance of these models. *"When you can touch and see something, is easy for you to remember it"*, said Prof. Andrés Viau, who have used the models to teach the mechanical elements of them. Prof. Rony Herrarte teaches the mechanical design course and said *"some things were understood until my students watched them in the models"*.

Since these didactic models were successful, as a future project next year's student association is planning to build refrigeration didactic models, from cooling systems that the University no longer uses with the aim to have a more practical experience in this type of classes.

Finally, total costs for each didactic model project are presented in Tables 3, 4 and 5. A total of US$.4,959.68 was required for the preparation of the three models, where the highest part corresponds to the use of the equipments of the makerspace.

Fig.10 Visitors during exhibition

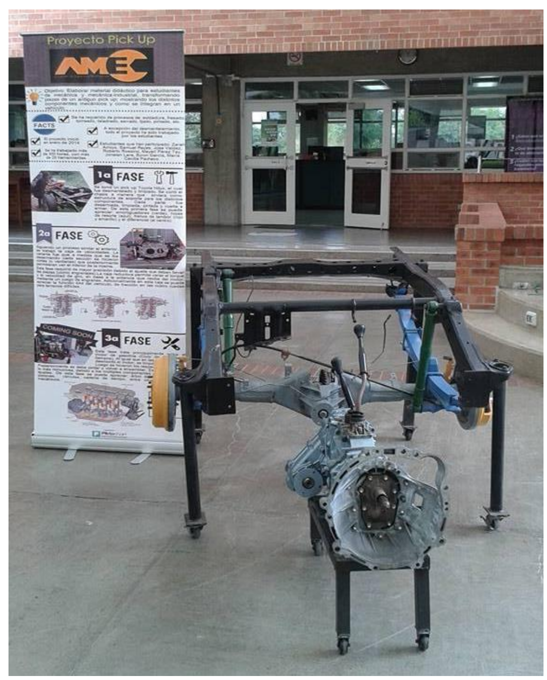

Fig.11 Exhibition of didactic models in UVG´s plaza

Table 3. Final cost, back section model

Process/Material	Cost (US$)
Welding	$547.11
Milling	$241.67
Turning	$169.17
Materials and supplies	$314.99
Technical supervision	$458.33
Total	$1,731.26

Table 4. Final cost, transmission model

Process/Material	Cost (US$)
Welding	$.556.00
Milling	$.834.00
Materials and supplies	$.104.53
Technical supervision	$.213.89
Total	$.1,708.42

Table 5. Final cost, engine model

Process/Material	Cost (US$)
Milling	$.1,158.33
Materials and supplies	$.86.67
Technical supervision	$.275.00
Total	$.1,520.00

APPENDIX

Appendix 1. Gantt chart for the project

Year	2014				2015				
Month	Jul	Aug	Sep	Oct	Jan	Feb	Mar	Apr	May
Planning	X								
Dismantling		X							
Cut and separation			X						
Funding activities			X						
Rear section				X	X				
Transmission module						X	X		
Engine module								X	X

Appendix 2. Main equipment and machines used

A	Milling machine
B	Lathe machine
C	Arc welder
D	Pedestal drill
E	Polisher
F	Autogenous cutting equipment
G	Wrenches
H	Arch saw
I	Hand drill
J	Compressor
K	Security gear (gloves, glasses)

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Building community around a student-run makerspace: Project-based social and educational events

ISAM 2016 Paper No.: 10

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INTRODUCTION

Opened a little over a year and a half ago, MIT MakerWorkshop* is a new student-run engineering space on MIT's campus. One of the central goals of the space is to foster a student community in a hands-on learning environment where modeling, prototyping, and validation resources coexist. MIT MakerWorkshop provides space and equipment for a community of innovators that focus on deterministic designing and problem solving. In order to achieve the goal of fostering a student community in this space, MIT MakerWorkshop hosts social events, runs student-led weeklong workshop courses, and hosts shop cleanups that are social events and highlight ownership and buy-in over the space. All of these are discussed in this paper.

MIT MAKERWORKSHOP

MIT MakerWorkshop is supervised and maintained by 40+ student volunteers known as "Mentors." The student Mentors are responsible for the maintenance and operation of, and the training of Users on all machines in the space. To facilitate these tasks, Mentors are divided into teams responsible for a specific area of the shop or group of machines (e.g. Mill Team is responsible for the upkeep of and training of Users on the mill). Each team has a Machine Master, a Mentor who coordinate the other team members to ensure tasks are accomplished. Furthermore, the Mentors elect students to serve on the executive committee, who in turn make major decisions about topics such as policy, purchasing, and membership, in conjunction with the space's faculty advisor, known as the "Maker Czar." Currently, the facility has over 800 trained Users comprised of undergraduate students, graduate students, faculty, and staff.

FAB. FRIDAYS

One way in which MIT MakerWorkshop aims to strengthen the community of the space, while furthering the mission of a hands-on learning environment, is through social events known as Fab. Fridays (where "Fab." can be considered an abbreviation for "Fabrication" or "Fabulous"). These events often incorporate working on a small-scale project and are open to both Mentors and Users.

A. FAB. FRIDAY LOGISTICS

Fab. Friday events are run by a Social Chair and a Social Team. The Social Chair is a member of the executive committee and is selected based on election by the student volunteers who have supervisory and management roles as "Mentors". The Social Team is comprised of a mix of Users and Mentors. The Social Chair is responsible for arranging the event, obtaining funding, and advertising. The Social Team handles theme and idea generation, some advertising, and set up of the event.

Most Fab. Fridays events require 30 minutes of preparation. This includes time for the Social Chair to meet with the Social Team to determine activities and food offered at the event, develop flyers and announcements about the event, as well as order items to arrive for the event. The event itself runs from 1-1.5 hours, depending on the project. Finally, clean up generally requires 15-20 minutes, with extra help from the Users and Mentors who attended the event. The events are held every two to three weeks with a plan to have around five events every semester and are offered at 4PM on Fridays. The advertisement of the events is organized via emails and fliers distributed a couple of days prior to the event.

B. BUDGET

The budget for each event is approximately $200-250 for the first event of the semester (which usually has the most food and activities), and continuing with $75-100 for all other events of the semester. The budget is mainly used for food, materials required to make projects, and prizes for contests. It is controlled by the Social Chair and MIT MakerWorkshop executive committee.

C. EVENT PLANNING

Each Fab. Friday is connected to some making or building event. Thus, planning requires determining the build project, ordering either tools and materials, games, or prizes. Some themes have been:

- National Holidays (Christmas, Halloween, National Worship of Tools Day, National Dessert Day, etc.)
- Lecture/master class/learning oriented event (Office Hours, Portfolio Workshop, Flexure Lecture)
- MIT and Boston event oriented (de-stressing event after the first wave of midterms, MIT's prospective undergraduate Campus Preview Weekend, Race for Boston marathon, tours and hands-on activities for MIT 100 years in Cambridge anniversary)
- Co-sponsored events with other MIT groups (FSAE formula racecar team, Mechanical Engineering Graduate Association of Women, Lemelson-MIT Program)

* Formerly named MIT MakerWorks

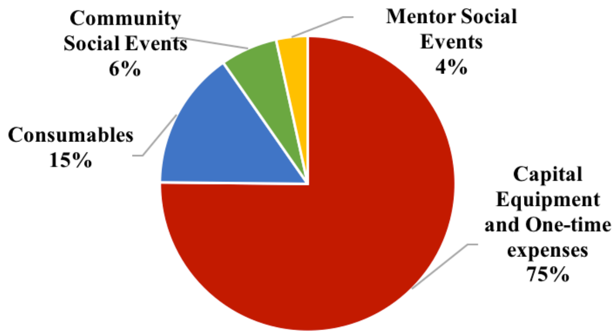

Fig. 1 The breakdown of the Y1 spending of the MIT MakerWorkshop. Note that Y1 refers to dates between July 2015 and July 2016. This demonstrates that Fab. Fridays (shown here as Community Social Events) only account for about 6% of the spending of MIT MakerWorkshop.

Fig. 2 MIT MakerWorkshop community member using a reciprocating saw to carve a pumpkin during the Halloween Fab. Friday "Pumpkins and Power Tools"

To date, our most popular events have been:

- **Make-Your-Own Cookie Cutters out of sheet metal**. At this event, people made their own cookie cutters in shapes of tools and Christmas symbols by bending aluminum sheet and fastening using rivets. It was attended by 25-30 people.
- **Pumpkin carving with Power tools**. At this event, attendees carved pumpkins using power tools such as reciprocating saws. Last year, 25 people participated in this event. When it was offered this year, approximately 15 attended.
- **Fab. Froyo Friday for National Dessert Day.** This event was an early Fall term social event at which frozen yogurt was served. Those who attended constructed their own sundae. It was attended by over 25 people.
- **Flexure Lecture**. A short lecture was offered by one of the Mentors as an introduction to the physics and applications of compliant mechanisms. The event also featured snacks such as coffee and cookies. It was extremely well received and attended by ~20 people.

Fig. 3 MIT MakerWorkshop Mentor giving the Flecture Lecture, a short introduction to the physics and applications of complaint mechanisms. It was attended by 20 people.

D. CONCLUSION

Fab. Fridays have proven to be a great way to engage with MIT MakerWorkshop community, both Mentors and Users alike. The theme and project-based events further emphasize the community focus on hands-on learning. The challenge in offering Fab. Fridays is the inability to gauge student interest prior to the event. Student attendance to these events often decreases the weeks when classes have midterms, finals, or projects due. Attendance can vary from 30 people at one event to 4 people at the following event, both of which had project-based activities or skills transfers and were further incentivized with food and/or prizes. One solution could be reaching out to the greater membership through a survey to determine the kinds of events they would like to see offered during the term. This could also be resolved by asking members to commit in advance to attending the event (reserve a spot) and comparing commitments to actual attendance.

CNC SHORT COURSE

Another way in which MIT MakerWorkshop works to build a student community focused on hands-on learning and engineering is through student-led workshops that aim to teach basic design, fabrication, and validation techniques. The first of these such courses offered was the Computer Numeric Controlled (CNC) machining short course. It was taught by MIT MakerWorkshop Mentors with the goal of going over the basics of CNC machining through the fabrication of a working centrifugal pump. On the mill, students learned to use Computer-Aided Manufacturing (CAM), with software such as HSMWorks, to generate G code, CNC program conversationally at the ProtoTrak interface (including creating conversational events from a DXF of part geometry), set up and run machining operations, and learn more advanced fixturing and locating techniques. Students fabricated additional motor interfacing and housing components using the 3D printer and laser cutter with options for customization. At the end of the course, participants showcased their pumps and all the students were able to keep their pumps.

A. COURSE LOGISTICS

The CNC machining short course is taught by a team of Mentors including one team leader (who serves as the main point of contact), and three to six instructors.

The course is broken down into two sections of two lectures and one recitation each, two days of machining time, and a last day of assembly and a project showcase, for a total expected time of 15-17 hours of time for the weeklong course.

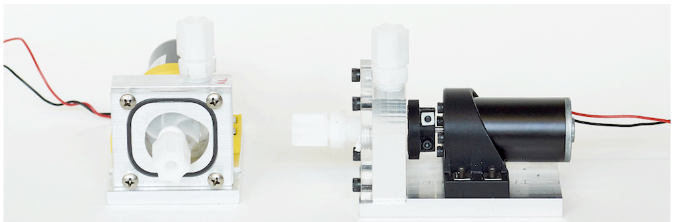

Fig. 4 Example of final centrifugal pump fabricated as part of the CNC short course.

B. BUDGET

The course was offered January 25-29, 2016 and August 15-19, 2016. The budget included paying for components and raw materials required to make the centrifugal pumps such as motors, magnets, and aluminum, as well as food for the final project showcase. Fig. 5 details the change in the budget between the two times the course was offered. All participants are asked to pay $15-25 to help cover the cost of the pump raw materials.

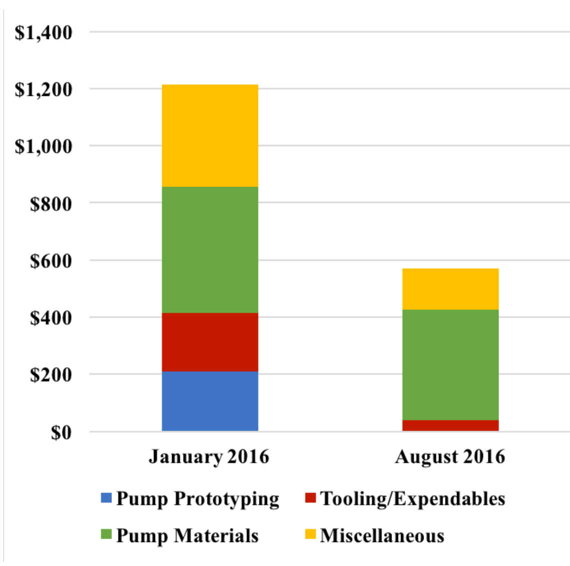

Fig. 5 CNC short course budget when offered in January 2016 and August 2016. The reduction in cost in August 2016 is due to iteration on the course material from January 2016, allowing for a more cost-effective design and hence a reduction in the pump prototyping costs as well as the tooling/expendables costs.

C. COURSE PLANNING

Preparation for the course requires approximately five meetings between the course team that take place during the month before the course is to be offered. This time is used to plan and test out design updates to the pump, make changes to the course material, ensure every member of the course team is well versed in the topics of the course, all materials are ordered in a timely fashion, and the course team has run through the fabrication of the centrifugal pump as well. Applications are solicited from MIT MakerWorkshop community (both Users and Mentors). These applications are then vetted by the course team based on whether the individual is a member of the community, has been mill trained, their availability to take part in the entire course, and their interest in the course. In total, the course offered in August 2016 required a 162 person hours for both planning and instruction.

D. CONCLUSION

The CNC short course is a valuable offering by MIT MakerWorkshop, as evidenced by the great amount of interest each time the course is offered. Costs have decreased since the first offering of the course, likely due to iteration on the pump design and fine-tuning of the pump prototyping. The first offering of the course (when the material and pump design were put together for the first time) is the most time intensive and subsequent course offerings require fewer person hours since a bulk of the course material is already complete. Unfortunately, the course still currently requires a great deal of planning, organization, and actual instruction, and can only accept a limited number of students each term. Moving forward, August is more of the "steady state" case in terms of required funding (potential further reductions in cost with additional offerings, but likely will level off). A future goal is to make the course completely free for students, and waive the $25 materials fee. The course would be an ideal candidate for corporate sponsorship, which would allow the ability to recruit more student instructors for their time, increase the offerings each term, and thereby increase the number of students who can take part in the course.

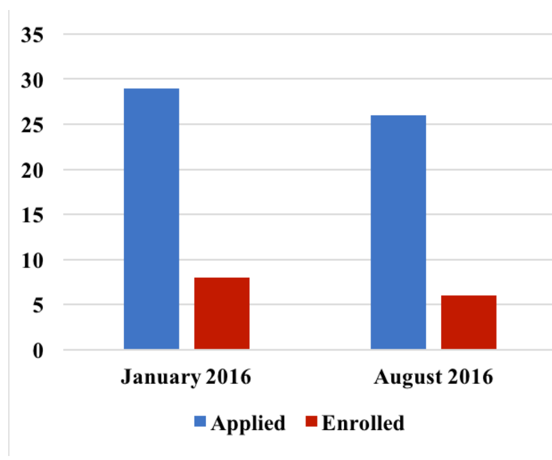

Fig. 6 CNC short course number of students who applied and were enrolled in the course. On average, for both offerings, approximately 25% of those who applied were accepted and enrolled in the course. The slight decrease in the number of students applying to the August 2016 section is likely due to the summer being a time when more students are travelling and away from campus than in the winter.

SHOP CLEANUPS

MIT MakerWorkshop also uses shop cleanups as a way to build community among the student volunteers who maintain the space. These shop cleanups are organized to include a Mentor social event (usually dinner) after the work day, while also increasing student ownership of the space through the improvement projects that students work on during the cleanups.

A. CLEANUP LOGISTICS

The cleanup team is led by the Vice President, who puts together a detailed list to determine what projects need to be accomplished by the end of the cleanup (e. g building a shelving unit, building a wall for electronics tools, etc.). The Vice President also selects a date, clearly details a project list to be accomplished, and ensures materials for the projects are available. The Vice President works with a few Mentors during the cleanup who take charge of specific projects on the list and coordinate other Mentors to help.

The cleanup itself lasts 2-3 hours, during which time Mentors are organized to help on various projects. Afterward, the Mentors helping out are treated to a dinner, usually lasting another 1-2 hours. The entire event is meant to be not only social, but a way to give back to the space.

B. BUDGET

The budget of the cleanup varies depending on the specific projects to be completed. Some projects require advanced purchase of raw materials or equipment, while others can be completed using scrap and hardware around the space. After each cleanup, the Mentors who helped out are treated to dinner, which further incentivizes participation in the clean-up. At the first cleanup, approximately 20 Mentors joined to help and dinner cost <$500.

C. CLEANUP PLANNING

Given that specific projects must be completed during the cleanup, the event must be planned ahead of time. To do so, the Vice President meets with the other members of the Executive Committee as well as the Machine Masters to determine a list of pressing projects that should be completed during the cleanup. The Vice President also asks Mentors to RSVP with their availability for the cleanup so that they can plan projects based on the number of Mentors available.

D. CONCLUSION

With specific goals for each cleanup, proper scheduling, and incentivizing using food, the shop cleanups can be extremely successful. Multiple, small, infrastructure projects around MIT MakerWorkshop can be completed in a relatively short amount of time. Furthermore, the completion of these infrastructure projects by Mentors of the space gives them a larger sense of ownership over the shop and greater buy-in over the way that the space is run and operated. However, in order for a shop cleanup to be successful, prior planning is required on the part of the Vice President to ensure there are clear, detailed tasks to be completed, there is enough notice given to the Mentors allowing them to RSVP and plan ahead, and the materials required to completed all projects are available at the time of the cleanup.

CONCLUSION

Building a community around MIT MakerWorkshop, a place run by 40+ student volunteers and home to over 800 Users is extremely challenging. It is hard to cater to the desires of all of the membership, however MIT MakerWorkshop hosts events that further project-based learning, involve skills transfers, and increase Mentor ownership of the space. Some of the activities highlighted in this paper include User and Mentor social events known as Fab. Fridays, a skills transfer CNC short course, and successful shop cleanups.

Moving forward, additional initiatives are being developed to engage with the freshman community of MIT, various departments at MIT, the larger Boston community, as well as the greater national and international makerspace movement.

ACKNOWLEDGEMENTS

The authors would like to thank MIT's Provost Martin Schmidt, the MIT School of Engineering, the Martin Trust Center, the Richard H. Lufkin Memorial Fund, the MIT Department of Mechanical Engineering, Prof. Dennis Freeman and the MIT Project Manus initiative for providing support, encouragement and funding for the MIT MakerWorkshop. The authors would also like to thank Prof. Martin Culpepper for serving as an amazing faculty advisor (Maker Czar) for our space. Finally, the authors would like to thank all Mentors, past and present, for all their time and dedication into designing, building, and maintaining the MIT MakerWorkshop.

A BioManufacturing Maker Lab: The Future of the Academic Maker Lab at the University of Oklahoma, Stephenson School of Biomedical Engineering

ISAM 2016 Paper No.: 11

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INTRODUCTION

This paper proposes that the biological sciences, and bio manufacturing in particular, will be a major part of future maker space development. The paper describes the proposed biomanufacturing (biomaker) program at the University of Oklahoma's (OU) Gallogly College of Engineering, Stephenson School of Biomedical Engineering (SSBME) and the physical and intellectual resources being sought to support the program. It identifies the constituencies expected to be served by the new BioManufacturing Lab and what family of products might emerge from such a program. Importantly, it describes the amount of supervision expected to manage the facility, the type of training expected of each user, and how faculty, graduate students and undergraduate students will use the facility. Finally, this paper identifies the measurable attributes to be used to gauge the benefits of the facility over time.

BACKGROUND

The future of the academic maker lab is poised to rapidly extend the culture of *making* that has been a staple within programs at engineering schools. Long before the current maker movement, academic making in schools of engineering occurred informally as individual hobbyists or more formally as part of capstone projects or as club activities and competitions centered on things like concrete canoes, bridge designs, solar cars, robots, race cars, UAVs and many others. Many of these programs have enjoyed industry sponsorship. The range of projects and partnerships continues to expand and is increasingly including disciplines outside engineering. This expanding maker lab typology will be a key ingredient of individual programs across numerous fields including the social sciences, business, humanities, and the arts and will energize the academic community as a whole.

The maker movement and the associated network of tool shops, design studios and project spaces, including a substantial amount of existing space that is being rebranded, is having a cultural impact on the perception of what individuals can expect to create and make outside of a professional or skilled expert environment. Digital tool platforms from desktop to 3D printing have democratized the ability to make and traditional tools are being aggressively offered to a wider community [1], often guided by experts that provide some level of training in the use of hazardous or technically difficult equipment. Relatively inexperienced creators and innovators can realize the working prototype part of the engineering design cycle themselves, allowing a high degree of spontaneity and a lowering of the barriers to ideas being realized.

Innovative maker spaces are likely to continue to play an important role in higher education and research at both the undergraduate and graduate levels. Maker labs have become vital assets within graduate research facilities, serving as a useful proving ground for the next generation of product innovators. The maker facilities of the future will include both an expansion of the traditional features of the maker neighborhood such as:

-Traditional active learning classrooms plus spaces such as independent study rooms that create a sheltering academic atmosphere conducive to concentration.

-Collaboration and meeting areas with computer resource centers, training areas, and structured team rooms for presentations.

-Project and prototype testing spaces with dedicated areas for special research projects.

-Managed shop spaces with increased space allocations for rapid prototyping, traditional machine tooling, high-bay and even small-scale fabrication.

-Incubator and accelerator/developer spaces for public/private collaborations with space for start-up projects.

The possibilities of making now include biological products is evidenced by the DIYbio movement and iGEM. [2] Biomaker labs with biocontainment represent a relatively untapped field of making given the tremendous potential of new technologies such as BioRobotics, BioManufacturing / BioPrinting and promising biological tools such as PCR measured gene delivery, molecular therapies and and most recently gene editing using CRISPR/CAS technology.[3] This new area is where OU is attempting to press the future.

DEVELOPMENT OF THE BIOMANUFACTURING MAKER LAB

In the new program being planned at the University of Oklahoma's (OU) Gallogly College of Engineering, Stephenson School of Biomedical Engineering (SSBME), the maker concept is being pushed to embrace a significant amount of wet lab bioengineering capability in the form of a BioManufacturing Maker Lab. The goal is to extend the wet lab capabilities well beyond the expected range of engineered prosthetics or assistive-technologies and support bioengineering at the cell and molecular level within a maker environment. This broadens the scope of what is considered "making" and creates questions about the limits of wet lab activities in a maker space environment. Maker programs in colleges and universities around the country are only now starting to include some amount of wet lab space that can support biological science, but the scope is usually limited. [4]. For example, the Yale Center for Engineering Innovation & Design (CEID) has an extensive and well-developed program in innovation that includes a small amount of wet lab space that "has equipment designed to support chemical, environmental, and biological work, and provides a clean and isolated workspace for contaminant sensitive processing. The lab contains standard equipment such as incubators, refrigerators, ovens, microscopes, and an electrophoresis gel reader, in addition to a suite of tools to develop microfluidics. The lab is Biosafety Level 1 and special permission is needed to use the space. Both a project proposal and MSDS listing of chemicals used are required for consideration." [5] The scope of the maker lab at OU will be similar, but unlike the CEID at Yale, biological work will be a primary focus. Initially, the lab will not emphasize synthetic biology, but it will be capable of pivoting in that direction and will be equipped to operate at Biosafety Level 2 from the first day.

POSITIONING AND CONTEXT

The project development team is placing the biomaker lab within an entirely new School of Biomedical Engineering. Limited existing resources dedicated to biomedical engineering education were available at OU to guide the project development or test working concepts. However, the practice of engineering design teaching and learning at OU is well supported by the ExxonMobil Lawrence G. Rawl Engineering Practice Facility (REPF). This world-class facility includes 10,000 square feet of space that students use to design and build engineering projects and senior capstone projects. It includes high bay assembly space, machine shop and collaboration areas. The new Biomedical Engineering Building will be adjacent to the REPF and is expected to benefit by that proximity. Accordingly, the design team looked carefully at Stanford's Product Realization Lab (PRL) as a model for how resources from the entire campus were integrated into a coherent clearly identifiable branded system. The team made good use of the excellent videos made public by the PRL.[6]

Within the building itself and as part of a new biomedical engineering program, the maker lab context was influenced by several visits to Olin College where studio labs, innovation and design are a staple of the curriculum.[7] Two studio lab spaces will be located directly across from the maker lab at OU and have a direct line of sight. Although available for biomedical engineering, the studio labs will be used by all of the School of Engineering for incorporating proven studio methods throughout the engineering curriculum.[8] When programming the new school, the studio labs came before the maker space.

The new BioManufacturing Maker Lab will be prominently located on the ground floor of the new Biomedical Engineering Building currently in design and will be built within the Engineering Quad on the main campus in Norman.

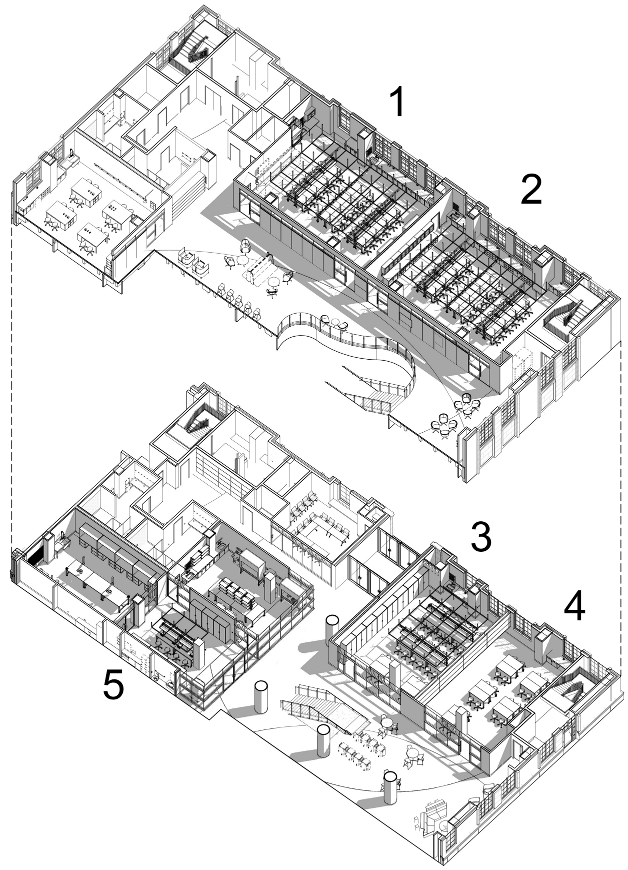

Fig.1: Diagram of Biomaker Laboratory Suite context within the new building at the University of Oklahoma, Norman

The Biomaker Suite Context

1 – Tissue Engineering Teaching Lab
2 – BioMechanics Teaching Lab
3 – Studio Lab #1
4 – Studio Lab #2
5 – Biomaker Lab Suite with BioManufacturing Lab

Occupying 2,000 square feet of the ground floor, the BioManufacturing Maker Lab will be an adjunct to other biomedical engineering teaching and research spaces within the new building, including the studio design labs and two biomedical teaching labs with instrumentation. The facility will become a part of a network of spaces supporting undergraduate and graduate innovation, engineering capstone projects, and a much broader movement that supports making and innovation across more disciplines throughout the student body in new types of maker lab spaces.

PRODUCT GOALS

Biomedical Engineering is a distinct discipline that focuses on the medical applications of engineering. Biodesign encompasses the making of products ranging from biomedical imaging devices to biomaterials capable of inducing bioactivity in cells that can be implanted by surgeons. Thus, a cutting-edge biodesign maker space must be capable of providing students with the physical resources necessary to implement ideas encompassing any of the wide-ranging subdisciplines which makeup the field of biomedical engineering.

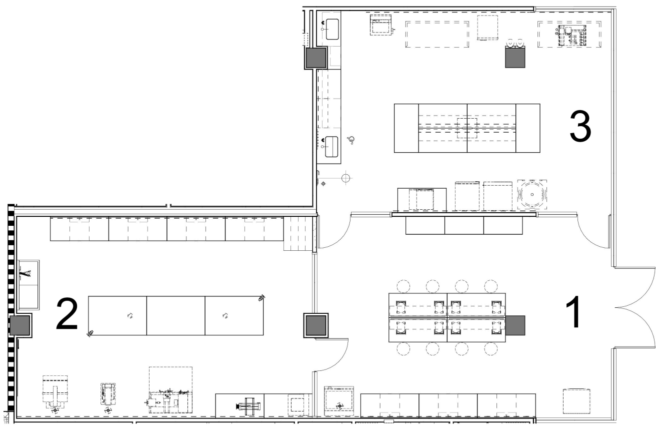

Fig.2: Diagram of Biomaker Laboratory Suite zoning at the University of Oklahoma

Zones within the Biomaker Suite

Zone 1 – Electronics (low noise, low dust)

Zone 2 – Prototyping – Machine Shop and Mechanical Testing (high noise, high dust)

Zone 3 – BioManufacturing – (low noise, clean, Biosafety Level 2 containment equivalent)

To accomplish this goal, the BioManufacturing Maker Lab is designed to accommodate projects requiring environments ranging from a noisy and high dust settings to sterile and low noise settings. The SSBME BioManufacturing Maker Lab was determined to need the physical resources to support three working zones as illustrated in Fig.1: Zone 1- an electronics manufacturing and assembly zone (a low noise and non-sterile zone), Zone 2- a machine shop and mechanical testing zone (a high noise and high dust zone), and Zone 3- a semi-sterile BioManufacturing zone for cell culture and organic material synthesis (a low noise and clean zone) designed to meet the CDC criteria of a biomedical lab at Biosafety Level 2 equivalent. Combined, these three zones will allow junior and senior SSBME students the physical resources to design complex biomedical products with electrical, mechanical, and biological components.

A wide variety of products are expected to emerge from this program, with aspirations for students to solve real-world problems and obtain patents from their designs. From the electronics work zone, products ranging from the biomedical imaging devices and health tracking devices are expected; from the BioManufacturing zone, products ranging from soft biomaterials to biomolecular assays are expected; and from the mechanical design and assembly zone, products such as hip implants and novel hospital bed designs are expected to emerge. Importantly, the design and testing of each product is expected to require at least two of these maker space zones, and more likely will require the use of all three zones. For example, a novel glucose health-tracking device would have both mechanical and electrical components, and would also require testing in the BioManufacturing facility.

OPERATION

Safety within this new facility will be of top concern, and all design students will be required to attend facility training sessions. The training sessions will serve a dual purpose to educate the students about safety as well as about what instruments they have access to use as part of their design process. All training will be completed during the first month of the fall semester (of the 2 semester senior design curriculum); pending approval from the laboratory manager, undergraduate or graduate student can also be granted access to use the facilities if they complete the same training Any high risk and high cost instruments such as the benchtop CNC lathe, laser etcher, and 3D printer will require instructor supervision until students have demonstrated consistent, proper, and safe use. Special attention will be given towards training students to use the semi-sterile BioManufacturing zone as well as the high-risk machine shop zone. Some preliminary BioManufacturing training will already be completed as part of the prerequisite junior year BME lab curriculum, including sterile biohood usage and basic cell culture techniques; however, students will be required to demonstrate proficiency in these techniques before being granted access to the maker space biohoods and cell-culture incubators. For high usage instruments (primarily including the 3D printer, laser etcher, biosafety hood), scheduling will be completed using a standard lab scheduling software.

In many respects, this BioManufacturing facility will resemble a core facility within a research facility; however, its purpose is primarily to serve the undergraduate program. Access for graduate research projects will be allowed but will not have priority. Although positioned for visibility and access by undergraduates, the maker lab will not be completely stand-alone. Operation of the space will require the research expertise and facilities located on the upper floors including support areas such as autoclave and glassware washing.

Beyond physical resources, a critical component to the undergraduate curriculum is the intellectual resources necessary for biomedical design. Each senior design team will be allowed to choose from a pool of real-world challenges facing industry and physicians, which is being created by the course instructor based on direct talks with companies and physicians. The pool of challenges will be updated each year. After selecting a challenge, teams will be assigned industrial or physician mentors who can help define the design solution parameters and ultimately provide feedback on proposed design solutions. Accordingly, new industrial collaborations with OU SSBME are currently being established, with many already underway.

Experiences with industrial and physician mentors will allow design students to develop technical and problem solving skills to solve current biomedical design issues, and these skills will prepare the future engineering workforce beyond the capabilities of a solid academic background. Many SSBME students go on to medical school, and for those students, the design course experience will provide communication and collaboration experience, so that future physicians may effectively describe needed solutions to clinical problems as well as be cognizant of the steps needed to implement and bring their own designs to the market.

PURPOSE AND VISION

The facility will be designed to serve the larger science and engineering-oriented undergraduate campus-wide community, including students ranging from engineering to chemistry and biology. The location of the maker space is intentionally high visibility within a new building intended specifically for biomedical engineering, but importantly, the facility also houses entry level biology and chemistry teaching labs, creating a steady stream of freshmen past the maker space and suites of other spaces supporting the BME department. Freshmen will be encouraged to participate in undergraduate research and design projects, and programs are being designed to make this possible. Equally important and a key vision for the overall facility, the maker space is directly adjacent to the university's expanded Diversity and Inclusion program in Engineering. This program is meant to facilitate the outreach, recruitment, retention and overall success of underrepresented minorities, including African American, Native American, Hispanic, women, first-generation college students and students with disabilities.[9]

The SSBME department plans to fit-out the facility with top tier equipment such as a high-end Bioprinter, Makerbots, and quality machining equipment. The goal over the next 5 years is to focus on cutting edge biomanufacturing, bio printed tissue, biomedical devices, PCR measured gene delivery, molecular therapies and potentially incorporating new gene editing technologies.

The facility will encourage linkages between business students and engineering majors and seek collaborative public/private initiatives that emphasize the several hundred companies with a bioscience focus in the region. Product ideas and development in joint collaboration with faculty and students can include items such as tissue-engineered products, prostheses, electronic components and hardware.

There will be an emphasis on new venture creations. Students will learn both the business and the ideation/creating aspects to product conception and development. For example, if a company has an idea for a product but lacks the facilities and/or funds to bring it to the market, then the faculty and students can collaborate in its development, thereby mutually benefiting both the public and private sectors that will help to grow the regional economy.

MEASURABLE ATTRIBUTES

The benefits that derive from invention and creation as a result of the productivity of the Biomaker Facility at OU will be measured by the numbers of patents, by the numbers of students that are listed as co-inventors, and by the numbers and types of products brought to market and their utility and success.

The public/private partnership benefits can be measured by the numbers of industry partners, donations of money and equipment. The benefits can also be measured by job placement for graduates of the program by industry sponsors.

On the academic side, the benefits can be measured by the number of students from all walks of life that participate in hands-on making activities across multiple departments and also by the numbers (citations) and quality of articles that appear in academic publications. Ultimately the recognition that the facility receives from national design competition awards and from positive feedback from graduates and alumni will be a fundamentally important measure of the value of the facility.

The facility is an integral part of the design course in the BME program to encourage creative thinking and hands on learning by doing. Students, even freshman, will be encouraged to use the facility to get an early introduction into the full spectrum of design, from idea to prototype. They will learn to engineer bioproducts and to solve problems. By the time they get to the 4th year, and they have an opportunity to practice what they have learned, the program hopes to have produced better engineers and infused them with a spirit of hands-on experimental learning.

CONCLUSION

The goal is to create a biomaker lab of the future that can accommodate a much wider range of activities through careful planning and zoning of both accessible and managed space types (from noisy and dusty to quiet and clean biocontainment capable) while building on the maker philosophy that inspires creativity, innovation, and camaraderie. In this way the next generation of maker facilities will continue to build an energized academic scientific community of thought-leaders and doers and be a tremendous vehicle to realizing applications along the spectrum from basic to applied science for many disciplines.

This project documents the programmatic outcomes of the SSBME's vision for the biomaker lab of the future. It is a vision that links undergraduate and graduate research initiatives by including, as a first step, the biological sciences and associated support spaces including some specialized ones that require training in not only equipment usage but also biosafety protocols. As more disciplines engage with a maker approach, the range of maker lab and lab support spaces needed for research and discovery, testing and fabricating will dramatically increase. Expanding 'making' into the biological realm requires a direct facility response in the form of appropriately designed, equipped and positioned biomaker lab space. This is now part of the DNA of the next generation of academic maker labs.

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ACKNOWLEDGEMENTS

Permission to present the Gallogly College of Engineering, Stephenson School of Biomedical Engineering (SSBME) at the University of Oklahoma was granted by Dr. Michael Detamore, Founding Director of SSBME and Stephenson Chair Professor and Dr. Thomas Landers, Dean, College of Engineering, AT&T Chair and Professor. The authors also wish to thank them for important details that pertain to the BioManufacturing lab suite.

ISAM 2016 Paper No.: 12

Why to make (almost) anything: A human-centered learning approach

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INTRODUCTION

Although CNC (Computer Numerically Controlled) machines have been in use since the late 1950s, digital fabrication laboratories and maker spaces have only recently been installed in educational institutions and community spaces. These CNC machines were originally described by their MIT creators as the "perfect slaves" [1], because, their creators thought, they would free makers from much of the manual drudgery required in constructing designs. Nowadays, once students are trained in the technical skills necessary to use these digital tools, they are expected to begin creating immediately. However, many students find it difficult to move beyond executing such simple technical tasks as laser cutting a key chain or 3D printing it. Whether in a design studio or an engineering class, teaching methods have not yet successfully addressed the integration of digital fabrication machines into the curriculum. Moreover, instructors tend to focus on the finished product rather than on the process of making it.

In this paper, we argue that the focus on teaching technical skills in maker spaces leaves students under-prepared to design and create on their own. To help remedy this problem, we introduce a human-centric learning process in which the instructor guides students in learning-to-make and making-to-learn. We define *making* here as a process that unites the *mental action* of designing with the *physical action* of construction.

A. MAKING IN ACADEMIA

Following the creation of the first Fabrication Lab at MIT by Neil Gershenfeld, many makerspaces and fabrication laboratories have been integrated into academic and community spaces. An ideal Fab Lab is a place where a person can make almost anything; it includes CNC machines, hand tools, and electronics benches. Today Gershenfeld's MIT course, "How to make (almost) anything," is being replicated in different departments within MIT and beyond. The class focuses on learning the technical skills required to use a new machine for each assignment in order to make a "thing." The course does not address the design or creativity aspect of this process, but rather focuses on the technical skills required. Other universities have followed MIT in developing Fab Labs (or what some call "Makerspaces") on their campuses, including the Design School in Stanford University, The School of Engineering in New York University, and The Swiss Federal Institute of Technology in Zurich. However, there has not been any research on finding an effective method for teaching students how to improvise and create on their own using tools in these makerspaces.

B. LEARNING THROUGH MAKING

In a recent paper, the first author introduced a human-machine interaction process in making and learning called I^3 for its three layered operations of *Imitation, Iteration and Improvisation* [2] (Fig. 1). This process is based on the constructivist learning approach of learning by doing [3]. It is inspired by how we learn a craft, and how imitation -- or what the first author call here "mindful copying" -- is important for learning making skills. In the first phase, *Imitation*, the instructor guides the student to make something that has already been built. What the student builds does not have to be an exact copy of what s/he sees, but it should involve building following the same concept, or building part of the "thing." Instead of spending time designing and constructing something from scratch, the student can go straight to the hands-on interaction required in making. This activity of making something that already exists helps the student to focus on acquiring the necessary technical skills to use CAD/CAM software and operate digital fabrication machines and tools. The student also starts to learn about material behavior and properties, and how all the elements come together. In the second phase, *Iteration*, the instructor guides the students in producing several iterations of the project, but restricts the student to making only one change per iteration. These iterations are guided by certain constraints, such as the instruction to change only the material or change the scale of the object in-the-making. For example, the student might change the geometry or material of one element, which might entail also changing whatever depends on that element. In the third phase, *Improvisation*, the student uses the technical, design, and making skills gained in the first two phases to improvise and create something new on his or her own.

C. THE ROLE OF THE INSTRUCTOR

While there has been great deal of focus on how fabrication machines can empower students to be creative, there has not been enough emphasis on the role of the instructor in this empowerment. Much of the problem lies with the method of instruction. Instructors tend to focus on the finished product rather than on the process of making it.

Skillful makers have acquired both the design skills and the experience to bring their creations to life. They think about materiality, about how things come together, and understand which tools or machines will be used to produce the parts of the artifact and how to bring them together. They know the capabilities and limitations of each machine, and how to tweak them to serve their purposes. Instructors of future makers thus need to focus not only on the product itself, but on the process of making it. They must address both issues of how to design and ways to use these new machines to realize their designs. Beyond providing instructions on the technical aspects of these machines, instructors need to guide the students through what the technologies can do and when and where they can be best employed.

In addition to guiding students during each phase, the instructor should give relevant mini-lectures and invite speakers to talk about their making process in their projects. The instructor should ask students to present their work at each session and moderate the conversations that these presentations give rise to. The aim is to increase the students' abilities to judge and criticize work, and to learn from each other.

D. CREATIVE MAKING

In Spring 2015, in consultation with Professor Terry Knight, the first author used I^3 as the curriculum structure in an MIT course called *Computational Making: Light and Motion*. In this course, students built interactive lighting units that changed or moved in reaction to their surroundings. Although the course was not primarily a digital fabrication course, it relied heavily on learning and using digital fabrication machines. The course consisted of twelve weekly sessions and several recitations. Students came from different departments, including graduate and undergraduate students in architecture, computer science, civil engineering and mechanical engineering. At each session, we gave students an assignment for the following week. Because reflection on the action of design and making is important for learning [4], students were required to document their making process and use visual rules to describe the changes they had made (Fig. 6& 7). We then asked students to present their designs to the class. Observations the first author have made outside the academic world in community Fab Labs and "Maker Faires" have shown the importance of the community itself in helping makers to develop their skills. When students present in front of their colleagues, they begin a conversation that leads to feedback and suggestions (Fig. 1). In our classes, we observed these conversations, moderated them, and eventually provided our own feedback. We also asked students to read relevant materials, including Lisa Iwamoto's book *Digital Fabrications: Architectural and Material Techniques* [5], from which we asked students to choose some digital fabrication techniques they were not already familiar with and analyze them.

In this paper we present the students' progress during the course, but also focus on the importance of the role of the instructor. We began the course by giving the students a small exercise in describing a making process. We asked the students to introduce new ways to make an origami piece. Some students changed the opacity of the paper to show folded layers, some used visual illustrations of hand motions and folds, and others integrated verbal and visual information directly onto the paper to be folded. This exercise became more helpful when we later gave them the *Imitation* assignment. For this assignment, we asked students to choose five lighting units they liked from anywhere, and then select one unit to analyze and build. We had already given them technical workshops on operating the digital fabrication machines and software. However, the idea here was to direct them toward focusing on gaining design thinking and technical skills through building a lighting unit without having to worry about how to start a design from scratch. As they started building, they began to focus on the details, materials, structure, and considered which machines to use and how the elements would come together. Students brought their lighting units to class, and we had a discussion on their making processes and what could be done to improve their units (Fig. 2).

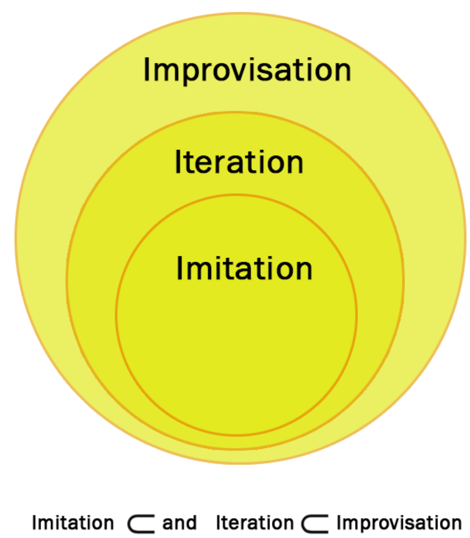

Fig. 1, I^3 is a multilayered operation of Imitation, Iteration and Improvisation. Improvisation includes both Iteration and Imitation, and Iteration includes Imitation.

Fig. 2, Students present their work to the instructors and their colleagues to receive feedback. In the above photo, Jacquelyn Liu presents her early Improvisation stage of her lighting unit.

Fig. 3, Students present their work in every session. In the above photo, June Kim presents her early Iteration of lighting unit.

In the next four weeks we had students do four guided Iterations. (Fig. 3 & 5) In the first Iteration, we asked students to change any one element other than material in the lighting unit they had made. This element could be geometry, structure or even scale. In the second Iteration, we asked them to change the material of one element and whatever depended on that change. In the third Iteration, we asked them to change the lighting source and pattern. The idea here was to direct them toward thinking about the intangible such as light and motion as well as the physical thing. In the fourth Iteration, we asked the students to add motion to their lighting unit. This motion could involve a physical change or a change in the light pattern, using electronics and sensors. The students used microcontrollers (primarily Arduinos) and distance and sound sensors (Fig. 4). In the *Improvisation* phase, we gave students the option of developing their units as a product line or making entirely new lighting units. At this point, students were able to use the tools and machines to produce new functional units without direction (Fig. 8 & 9). When it came to using electronics and programming for interaction, they were able to build on their skills and try to enhance their codes, even though some of them did not have any prior programming experience. In the full paper, we will explain the progress of two students as they progressed through the three phases of *Imitation, Iteration and Improvisation.*

E. DISCUSSION

Making activities for learning are embodied. They depend heavily on the direct interaction between the maker, the object-in-the-making, and the tools that are used. In this course, we wanted to introduce a new process to help bridge the gap between the machine and the novice maker. Such teaching methods are needed in order to help novice makers cope with new technologies and tools. The process we introduced enhances the learners' sensory experiences with making and encourages them to overcome their fears of interacting with digital machines.

Fig. 4. June Kim's Imitation and Iteration stages.

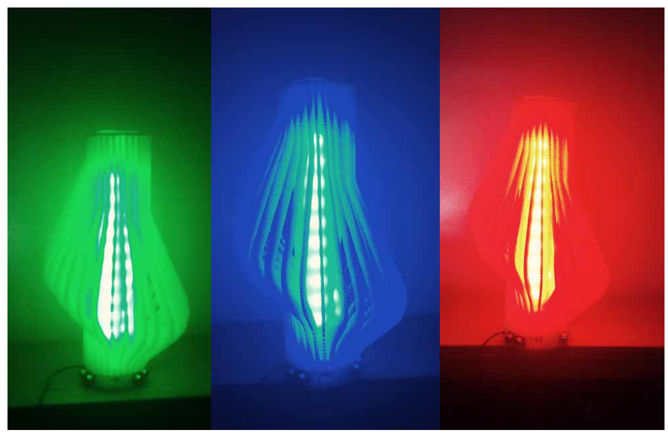

Fig. 5, June Kim's fourth Iteration. The unit changes in color as people move around it.

Fig. 6, Estelle Yoon's Imitation and Iteration stages.

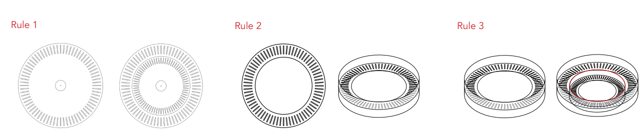

Fig. 7, Estelle Yoon's visual rules for assembling her lighting unit.

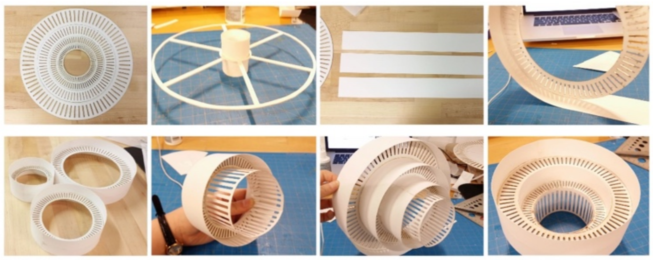

Fig. 8, Estelle Yoon's making process for assembling one of her lighting unit.

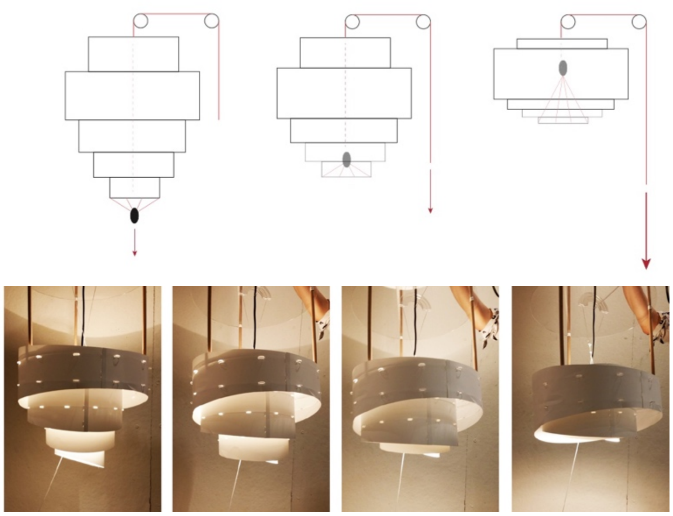

Fig. 9, Estelle Yoon's Final lighting unit in the Improvisation stage.

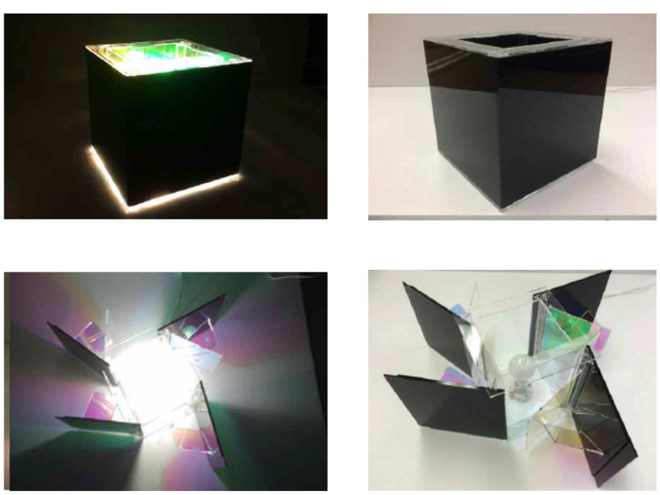

Fig. 10, June Kim's Final lighting unit in the Improvisation stage.

The question before us now is how we can gauge the effectiveness of this process. How can we know whether students can really improvise and create on their own after the course ends? In an attempt to answer these questions, we gave the students questionnaires to answer before and after they had taken course. We asked the students to rate their skills in using manual tools, operating several digital fabrication machines, and programming. We also included a small design and making problem and asked them how to solve it. For example, we asked them how to build a cylinder with certain dimensions without printing it in 3D. We also asked students to do open-ended tasks such as defining the concept of improvisation, criticizing their own projects, and questioning themselves as to how they might improve those projects.

By comparing the questionnaires from before and after the course, we learned that all students felt positively about their learning experience. First, they felt much more confident in their technical skills. When asked to rate their digital fabrication knowledge after taking the class, 90% of the students rated their skills as "very good." Some architecture students rated their programming skills in Arduino from none before the course to above average after the course. Students were also able to provide a description for several making processes for a simple making problem. When we asked them the question, "If you were given a new project to design and build, what would you do?," they described a process similar to the one they had gone through in the class. We saw that not only were they able to transfer their technical skills to other projects in other classes, but that they had emerged from the course with a making process they could apply in the future. As course instructors, we consider the students' success in the non-guided *Improvisation* phase as a good indicator that they were now able to utilize the machines to make on their own. In our paper, we discuss our results more thoroughly and present future steps to develop and improve the I^3 process.

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Development of an Educational Program Using Capabilities of (Academic) Makerspaces

ISAM 2016 Paper No.: 13

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ABSTRACT

This paper describes the development of an educational program for the academic Makerspace at Graz University of Technology (FabLab Graz). It is based on a comparative investigation of Fab Labs in the United States of America and the European Union as well as on a survey of the potential users of the existing Makerspace at Graz University of Technology. The first step to develop a comprehensive educational program is the establishment of a course dealing with product development, rapid prototyping and entrepreneurship based on identified customer requirements. The findings can easily be transferred to other academic Makerspaces worldwide.

I. INTRODUCTION

Digital fabrication is currently spreading swiftly around the world. Makerspaces are one of the main drivers in this movement. They enable individuals to invent and build hardware products. This was nearly impossible in the past without traditional organizational backing. In 2014, Graz University of Technology started the first university-based Fab Lab in Austria. Since the opening of FabLab Graz many persons made use of the tools and equipment provided for prototyping their ideas, fabricating products for lectures, or just to make fun stuff. Fab Labs are a special type of Makerspace. The first Fab Lab (fabrication laboratory) was established by Neil Gershenfeld and a team from CBA (MIT) in 2003 with the intention of creating a prototyping platform for learning and innovation [1]. Fab Labs provide innovative, easy-to-use and mostly digital production machines for local entrepreneurship and hobbyists. The success of the Fab Lab initiative appears in the impressive and rapidly rising list of more than 700 registered labs worldwide [2].

A great community assembled within a short period of time made it necessary to think about increasing the available space at the FabLab Graz, which was only 50 square meters until then. But very soon it was realized that merely expanding the floor space and considering the Makerspace isolated from its environment is not an adequate approach. To foster the innovation strength of such a space it is essential to connect the capabilities of a Makerspace with other relevant institutions. The authors are thus in the process of developing an education program for an academic Makerspace to foster hands-on activities in line with entre- and intrapreneurship. This paper provides insights in the approach, first steps and learnings towards an extensive educational concept.

This research work is structured in three main segments: market research of existing Fab Labs, identifying customer requirements and development of an educational program.

The first deals with a web revision of registered Fab Labs in the EU and USA to gain insights into the commonalities and differences of the educational services of Fab Labs. This paper provides an in-depth and comprehensive view of more than 400 Fab Labs. 988 courses and events are analyzed and evaluated. The results show that all Fab Labs have commonalities, but slight differences regarding services and tools provided for different user groups, making every lab unique and able to determine its own identity, thus a user-centered approach regarding education in Fab Labs is recommended.

The second gives insight into a survey involving the main user group of FabLab Graz namely students of Graz University of Technology. With the aim to obtain a better understanding of the desired equipment and knowledge 187 students are questioned.

The third describes the development of an academic course for the main user group – the students. This research introduces an academic course concept with the objective to foster the innovation capabilities of students. This course is the initial step towards the overall aim of a comprehensive educational program for users of the FabLab Graz.

II. METHODOLOGY

The development of the course is based on a comparative investigation of Fab Labs at the USA and EU (internet search) as well as on a survey of user-groups of the existing Makerspace at Graz University of Technology.

Section III shows the results of the internet search. All official Fab Labs are registered at www.fablab.io [2]. Based on this resource the research was conducted on all listed labs in the USA and EU. In case of a misleading link at www.fablab.io, a metacrawler was used to track down the missing website of the Fab Lab by using the name of the facility as keyword. The research was conducted from February 2016 to May 2016. Section IV describes selected results of the survey conducted at Graz University of Technology (187 responses from May 2016 to September 2016).

III. MARKET RESEARCH OF FAB LABS IN THE USA AND EU

The research was conducted for the EU plus the USA and covers all officially registered Fab Labs. A total of 433 labs were examined including 324 labs situated in Europe and 109 labs in the USA. Only 109 registered Fab Labs in the USA despite the fact that the movement originated in Cambridge, Massachusetts, whereas in Europe there are now 324 labs. At the time of the research, only 80% of Fab Labs in the EU and only 60% of Labs in the USA had an accessible website and of these, only one third of all official registered Fab Labs offered more than three courses or events to their community. Based on these restrictions, only 129 Fab Labs are finally investigated.

The objective of this Internet search is to show the substantial variances between Fab Labs in terms of courses and events they offer. In sum, 988 courses and events are analyzed and evaluated. Typical offered courses aim to give a brief insight into specific topics/ machines in order to provide the participants a brief overview. An operational part concentrating on specific equipment takes place immediately to ensure the participants can get started on their own project fast. All the events and courses mentioned differ slightly from lab to lab but as stated, a typical course characteristically has a theoretical part and a hands-on part in which the process steps of the operation are explained directly on the specific equipment involved. The two most popular courses overall are 3D printing (offered in over 70%) and laser/ plasma cutting (proposed in 55%), as shown in Fig. 1.

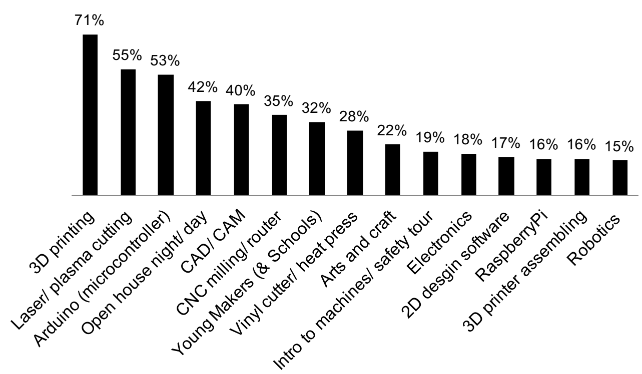

Fig. 1 Topics of top 15 courses and events offered in Fab Labs in the USA (28 Labs) and the EU (101 Labs).

Fab Labs in the USA and the EU have the same origin but this research shows that there are significant differences in respect to educational services, as illustrated in Fig. 2 and Fig. 3. In the USA "Laser/ plasma cutting" is the most popular course with an occurrence of more than 70% while in the EU only 51% of facilities offer such courses. "3D printing" has a prevalence of 64% in the USA while 73% make it the most popular course in European Fab Labs. Courses on "Vinyl cutting/ heat press" with 54% is ranked third in the USA while only 22 % of all European labs offer such courses. "Arduino" (56%) is at the second rank in EU while only 43% in the USA offer courses in that field. Differences emerge when comparing CAD/ CAM courses (EU 44%, Rank 4 vs. USA 29%, Rank 9). "Lab and Safety Tour" is offered at 43% of the Fab Labs in the USA but failed to make it in the top 10 in the EU (13%, Rank 16). "Open House Nights" have very similar ratings in both regions (EU 43% vs. USA 39%) as well as "Arts/ crafts" (EU 22% vs. USA 25%). Events dealing with young makers and schools are popular in the EU (36%) while in the USA only 5% of the labs offer particular events in this field. Courses dealing with CNC milling/ router are at rank 7 in both regions with a prevalence of 35% in the EU and 39% in the USA. "Electronics", like soldering or electronic board design, is relatively popular in the USA and almost one third of all labs offer at least introduction courses on the topic while only 15% of the EU labs do so. 20% of all EU labs offer a course in which the participants can assemble their own 3D printer. A prevalence of 20% is remarkable since such a class can last over several days and it costs more than 100 U.S. dollars.

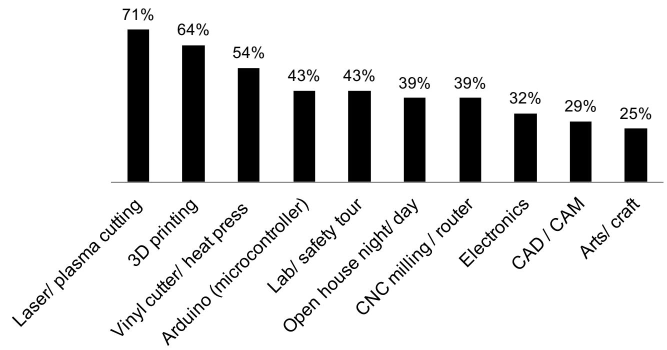

Fig. 2 Topics of top 10 events offered in Fab Labs in the USA (28 labs).

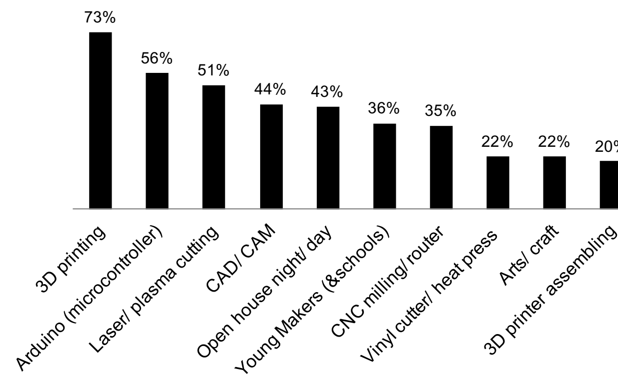

Fig. 3 Topics of top 10 events offered in Fab Labs in the EU (101 labs).

IV. IDENTIFIED CUSTOMER REQUIREMENTS BASED ON A SURVEY OF POTENTIAL USERS

It is clearly apparent that the Fab Lab community and the whole Maker Movement is constantly changing and adapting to new opportunities and challenges. Consequently, every region, country and continent emphasizes different issues, a situation which is crucial for maintaining a certain diversity within the movement. No two Makerspaces can ever be alike, because the communities around a Makerspace are never exactly alike. Based on these thoughts it is crucial to include the user community in the finding process of a matching educational program.

The main user group of FabLab Graz are students of Graz University of Technology. In total, 187 students – 56% bachelor's degree programs, 38% master's degree programs, and 6% doctoral programs – are questioned with the aim of obtaining a better understanding of the desired equipment and know-how. Selected results of this survey are shown in Fig. 4 to 8.

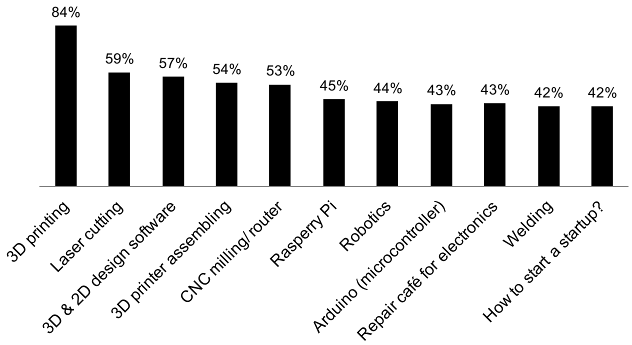

Fig. 4 Top 12 topics of courses and events (187 responses).

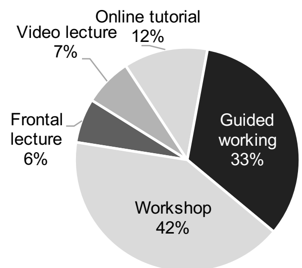

Fig. 5 Preferred course and event-types (187 responses).

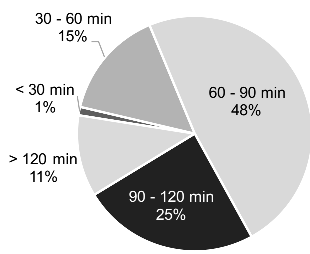

Fig. 6 Ideal duration of courses and events (187 responses).

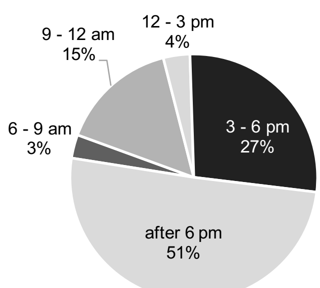

Fig. 7 Preferred time of day for courses and events (187 responses).

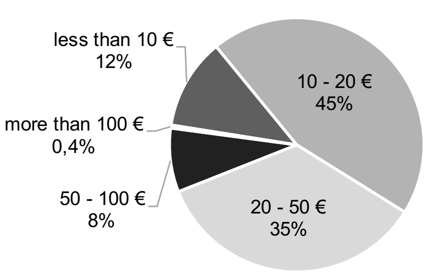

Fig. 8 Acceptable price for courses and events in Euro (187 responses).

V. ACADEMIC TEACHING AT MAKERSPACES AND DERIVED EDUCATIONAL PROGRAM

This section discusses potentials of Makerspaces in education, existing university-based Makerspaces and their course-concepts plus the developed “Design Thinking & Rapid Prototyping” course for FabLab Graz.

A. POTENTIALS OF MAKERSPACES IN (ACADEMIC) EDUCATION

Caine & Caine (1990) proposed principles influencing the learning process. Makerspaces are promoting those basic principles, e.g.: stimulating both the experiential and theoretical learning in an appropriate combination is important; an empowering, supportive and challenging environment fosters understanding; interdisciplinary content and embedding prior to learning in a superior context foster overall understanding. [3]

The authors of the study “Learning Styles and Learning Spaces” state that adequate learning spaces are important for education. The challenge is to create an optimal learning space, which meets the needs of each learner. A more student-centered learning environment is needed to foster the learning capacity of learners. The results of implementation are increased teaching effectiveness and learning outcomes. [4]

The American Society of Engineering Education noted that curricula focus primarily on theory. By contrast the National Research Council (2004) reports in “The Engineer of 2020” that creating, inventing and innovating are essential skills for technology graduates. For this reason hands-on and active learning are increasingly in the focus of technology education. Many universities are in the process of changing their course program by increasing hands-on and active learning as a means of fostering media creation, design and entrepreneurship. In the USA, 153 universities and colleges were already committed to support the Maker Movement in education in 2014. [5, 6]

Georgia Institute of Technology conducted a survey regarding their digital fabrication laboratory (“The Invention Studio”). The following statements of this study attest the positive reception of the facility by the students: [7]

- serves as cultural hub and meeting place
- provides access to hands-on, state-of-the-art prototyping technologies
- supports extracurricular activities
- motivates students to seek careers involving design, innovation and invention
- enables students to work on real-world problems

Furthermore, 90% of the students reported a significant impact on their design skills. Additionally 80% of the respondents confirmed that the fabrication lab had a positive impact on their manufacturing skills. Supplementary to these comments the authors of the study “Fab Labs in Design Education” stated that digital fabrication laboratories empower students to accelerate their ideation and invention processes. [7, 8]

The influencing factors on the learning process, the theory of adequate learning spaces and results of different studies concerning Makerspaces in education support the assumption that such laboratories bolster innovation capability. Makerspaces offer tools and learning experiences for engineering educators to promote skill sets with applicable value through hands-on building and practicing critical thinking. [5, 9]

The NMC (New Media Consortium) Horizon Report: 2016 Higher Education Edition points out that Makerspaces are addressing future needs in higher education and that their impact on universities will increase within the following two to three years. [6]

B. EXISTING ACADEMIC MAKERSPACES

At universities around the world students from different academic fields are starting to learn by making and creating [9]. An internet search in a former study of the authors was conducted with the aim of acquiring insights into the courses at academic Makerspaces [10]. This search considers the top-ten universities in the field of engineering and technology according to the "Times Higher Education World University Rankings 2015-2016" [11]. Information regarding the availability of academic Makerspaces as well as of existing courses involving these spaces was evaluated.

8 out of 10 of the universities investigated provide Makerspace-like laboratories. Two main differences regarding the utilization of Makerspaces at those universities can be described: (1) Makerspaces are part of the course program and (2) Makerspaces are open to students for extra-curricular activities. 6 out of 10 labs combine these services. Five of the identified spaces are not used actively in education. [10]

Evaluating the duration of the different course concepts shows that a majority of the courses are held in a timeframe from four to six months. These courses in particular apply individual projects where students work on their own and in their free-time. In addition, the courses include two hours of theoretical input per week. All of the courses identified are project-based. Furthermore, 70% of the courses provide real-world problems for the students packed into individual projects. The remaining 30% of the course concepts promote project-based learning through assignments given on different production machines or topics. Corresponding with the literature findings 80% of the existing courses combine experiential and theoretical learning. For example the "How to Make (Almost) Anything" (MIT) course comprises a two hour long lecture every week, a weekly assignment related to a manufacturing process or technology (e.g. laser cutter, molding or electronic board design) and an individual project covering the entire content area during the six months course duration. The results regarding the duration and characteristics of existing courses involving Makerspaces are shown in Fig. 9.

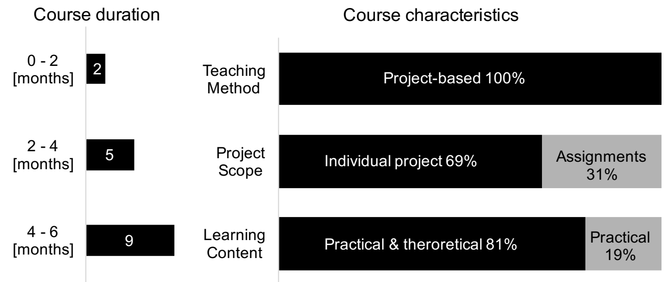

***Fig. 9** Course duration in months and characteristics of existing courses in Makerspaces at top-rated universities (Times Higher Education World University Rankings 2015-2016 [11]).*

Four main topics are in the focus of each evaluated course concept:

- digital production tools
- hands-on design experience
- rapid prototyping
- interdisciplinarity

Additionally, 3D-modelling techniques and electronics are partial learning objectives in the existing courses. Besides the general courses with an interdisciplinary setting more specifically focused courses are also available. In courses of this kind, the topic is related to a specific field or technology, e.g. "flexible part design" at Stanford University where students focus on the development of elastomeric part design.

C. IMPLICATIONS OF THE CONDUCTED SURVEY AMONG FABLAB GRAZ USERS AND THE INFORMATION OBTAINED FROM THE CONDUCTED INTERNET SEARCH

A new course takes the demands of the users and the internet search of existing Fab Labs in the USA and the EU plus university-based Makerspaces into account but some restrictions have to be made. The FabLab Graz restrictions for a course are the set maximum of 20 participants and a limited timeframe of five consecutive workdays due to the curriculum at Graz University of Technology.

A modern course should consider the different study-backgrounds of users. The aim is to address users from all academic fields. The fact that interdisciplinarity is part of each evaluated course-concept of top-rated universities supports this approach.

A new course thus includes design tasks addressing users from different academic fields. Further, mechatronic tasks are part of the concept with the aim of addressing students with computer science, mechanical and electrical engineering backgrounds.

The majority of the FabLab Graz users either prefer workshops addressing specific topics or guided working, which refers to guidance of a user's own project as outlined in section IV. Moreover theoretical input in the form of a frontal lecture is not in demand. This fact is in contrast with the situation for existing courses at top-rated universities. Most of the courses (81%) at top-rated universities at a Makerspace combine theoretical and experiential learning. However, all of those courses are project based. The scope of the projects varies between individual projects and assignments.

The implications derived from this are thus: (1) project-based course, (2) combination of theoretical and experiential learning with an emphasis on the practical parts and (3) provide freedom for individual ideas.

Based on the restriction of a maximum timeframe of five consecutive workdays, a course concept must balance the time limitation factor so as to still provide a feasible project task with the appropriate scope for design in order to gain students interests.

D. DERIVED LEARNING OBJECTIVES AND CONTENTS FOR THE DEVELOPED "DESIGN THINKING & RAPID PROTOTYPING" COURSE

The course is part of master programs at Graz University of Technology. The overall learning objective is to foster the innovation capabilities of students in higher education. The key topics of the course are product development based on Design Thinking [12], rapid prototyping and entrepreneurship using the Business Model Canvas [13].

The course concept focuses on student centered- and hands-on learning as well as on critical thinking. Hands-on learning and critical thinking is enhanced by working on individual ideas and projects. As a consequence the project task must be both challenging and feasible.

Due to the limiting timeframe of five consecutive workdays the course appears to be very short. Most comparable courses, however, are held in the scope of a two-hour class once or twice a week. Theoretical input and operation instructions for the different production tools are taught within these two hours. Individual projects are carried out by the students in their free-time. Handling such time consuming individual projects is not feasible within a five-day course. A pre-defined project with a scope for creativity is thus in the center of this course concept to balance the advantages of an individual project and the limiting timeframe.

The student teams design and manufacture a functioning prototype of a radio-controlled car. The car is controlled using a Bluetooth connection via a smart phone. The power train consists of an Arduino, two DC motors, a Bluetooth-transmitter and a motor control module. The power supply is provided by a battery pack. Electronic parts and software for the Arduino and the smart phone are provided by instructors to support the project feasibility.

The development is based on the theoretical inputs of the course. Feedback-rounds after a concept presentation and a first prototype presentation are important milestones. The advantage of this project is a guaranteed feasibility and an interdisciplinary approach. The project task combines mechanical-, electrical- and software engineering. Grading focuses on design, applied functions plus digital production tools, functionality of the prototype, appearance and participation during the course as well as documentation of the results.

A first test run of the course developed indicates that the existing Makerspace enhances academic education. Participating students report that it was to some extent their first experience in using electronic components, rapid prototyping and a practical application of a design process. The creative freedom within the given task and the collaboration among the student teams are issues of special interest according to the participants. FabLab Graz as a learning environment has a positive influence on the creativity and the learning outcome of the students. Furthermore, students suggest additional laboratory exercises with a similar setting.

VI. CONCLUSION AND OUTLOOK

A Makerspace is a changeable environment, which must adapt to shifting circumstances. It is thus necessary to frequently investigate the needs of the users. It is useful to establish different course/ event pools for specific user-groups. The user-centered approach in the development of the course described was the key factor of success to develop a target-aimed course content supported by the capabilities of FabLab Graz.

The further goal of the authors is the development of a comprehensive modular course program for all user groups. The workshop-based educational concept of FabLab Graz should be suitable for easy transfer to other academic Makerspaces worldwide.

The potential of digital fabrication laboratories in higher education has by no means reached its zenith yet. Future research should clarify the impact of Makerspaces on education in all academic fields. In the light of the remarkable evolution of the Maker Movement, further studies on how universities approach this trend are suggested.

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SNU Idea Factory with Integrative Approaches: From Physical Space, Education, to Culture

ISAM 2016 Paper No.: 14

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ABSTRACT

SNU College of Engineering launched its new concept of-maker space, SNU Idea Factory, on March 17, 2016. SNU Idea Factory has provided students a 24/7 opening creative space for ideation, machines for prototyping, and mentoring to help students find ways toward realizing their visions. SNU Idea Factory aims to assume a physical pivot as a creative space, whereby it offers a variety of education and supports. Also, SNU Idea Factory has offered an engineering design course, prototyping support, start-up incubation and acceleration. SNU Idea Factory has been based on the *SNU Creative Space Project*, having been conducted with the following three areas; space design, engineering education, and cultural context. In this paper, we present the integrative approaches and those outcomes that we have undertaken to initiate and develop SNU Idea Factory. For the past one and a half year, SNU Idea Factory has been taking an exemplary academic maker space in South Korea.

INTRODUCTION

SNU Creative Space Project was suggested by students, along with a high level of student involvement in space design and development. This creative space project was initiated by an undergraduate engineering student, who with peer colleagues, wanted to build an urban disaster pre-warning system. After some time with the project, she fell on frustration because of difficulties in locating a suitable team space and supportive faculty with appropriate mentoring.

Instead of giving up on the project, however, she proposed a SNU creative space project to Prof. Kunwoo Lee, dean of engineering, SNU, in which student-oriented teams and productions spaces are provided with mentoring experts and staffs. With the strong support of the engineering dean, she formed a new team for the project and started research on a college creative space.

The project was conducted through cross-college and faculty-student collaboration for more than an entire year. After eight months, the team published a 200-pages creative space guideline on Sep 2015. Finally, the guideline has been realized as SNU Idea Factory with the support and donations of Ministry of Trade, Industry and Energy, Korea Institute for Advancement of Technology, and Haedong Science and Cultural Foundation.

Fig. 1 Overview of SNU Idea Factory

This paper presents the flow of motivation, concept and realization in SNU Creative Space Project. Then, we introduce how to manage the space and what pedagogy we are pursuing to facilitate the space. The contribution of this paper is to share our experience for building an academic maker space in SNU, which can give a hint for student-initiation and high-involvement in making an academic maker space.

A NEW CONCEPT OF SPACE

First question for designing an academic creative space in this project is what is a space which can stimulate creativity and cooperation among the space users? What kinds of behaviors do we wish to encourage among the space users? How can we make a resonant and sustainable space? Finding answers to these questions was the first step that we were trying to take.

To design and specify the space for the objectives, we have pushed this project forward with the following three methods: 1) field trip, 2) space programming, and 3) space experiment.

Firstly, we have visited several great maker spaces in Korea such as Idea Factory in KAIST, Daejeon Creative Economy and Innovation Center by Korean government, and Seoul Fab Lab by Tide Institute, Samsung C. Lab, Naver Green Factory, Realization Lab., D. School at Stanford and MIT Stata center.

Secondly, we conducted several times of space programming. For the conceptual work, we defined required spaces, their functions, and flows among those spaces. Fig. 2 is an example of space diagram. In this diagram, hive and intersection spaces are classified as an open, collaborative space; whereas labs are defined as closed team-based space.

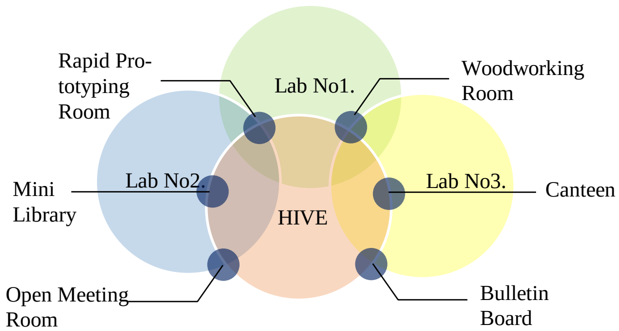

Fig. 2 Space Diagram According to their Functions and Flows

Finally, we have conducted space experiments according to the requirement and curriculum of the *design engineering* course. We applied the design thinking approach for the experiment. Since a critical lesson of design thinking is to consider viewing the issue from the perspective of users, we tried to consider the views of the space-users and applied their feedbacks and our own observations into the space experiments. Beginning with the minimum suppliers, we intended to fill spaces gradually, while observing the responses of our space-users [1].

Insights drawn by conceptual space programming and space experiments have been reflected on the real space layout (Fig.3). Those insights helped student-driven space supporters reason their opinions, when it contrasted to those of faculty. While faculty members preferred an easily manageable wide space; they designed space with small home-based rooms. Approaching the problem with user perspectives and supporting their opinions with previous survey and experiments, they reflected their thoughts on the space. The current result shows their observation was right.

Rapid prototyping studio has been equipped with the following fabrication machine: 3D printer (22EA), 3D scanner (2EA), vinyl cutter (1EA), laser cutter (4EA), and sewing machine (1EA). Woodworking studio is comprised of CNC router and CNC machine. The equipment in machining studio has not been described yet.

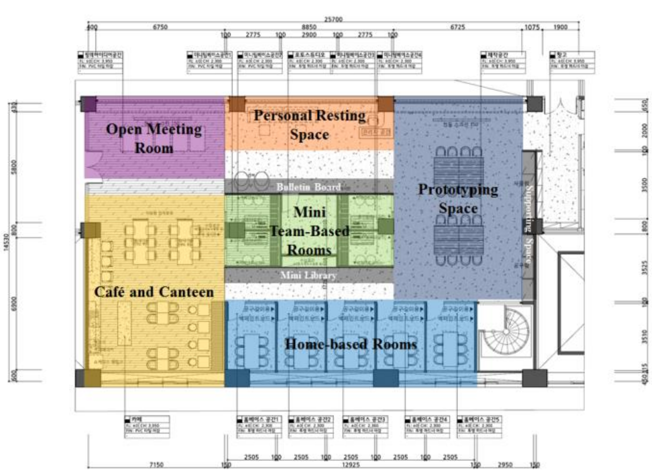

Fig. 3 Studio No1. Layout (provided by LG Hausys)

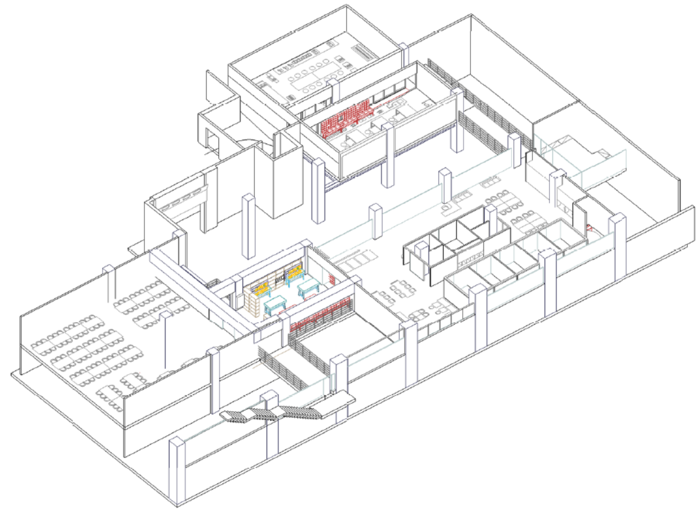

Fig. 4 Axonometric projection of SNU Idea Factory

The number of registered users were nine hundred in May and have increased up to one thousand at this point (August 12, 2016).

The space is only provided for registered members before and after the regular hours (9am – 6pm). To register and to use rapid prototyping studio and woodworking studio, students must have completed online course in environmental protection and safety.

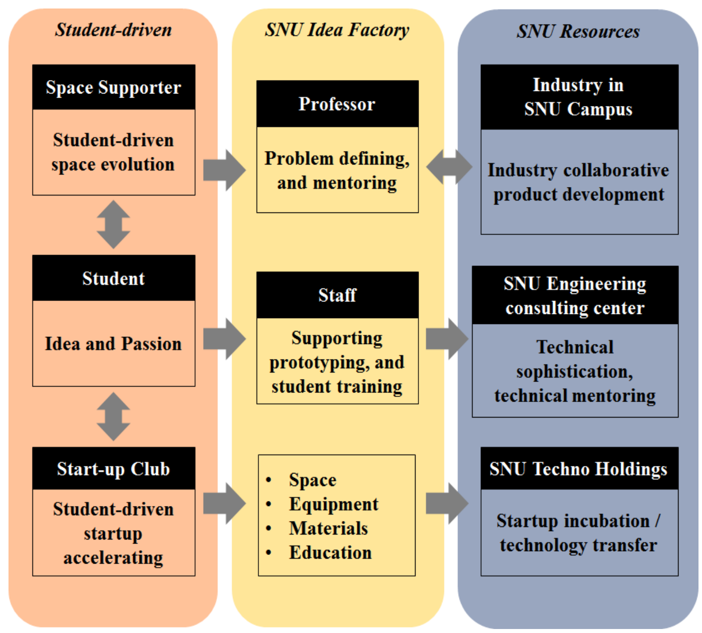

Fig.5 Operating System

ENGINEERING EDUCATION COMBINED WITH A NEW PEDAGOGY

An education and learning system is necessary to facilitate an academic maker space.

A. Regular Course

Simultaneous with the creative space project, founding faculty members launched a new interdisciplinary capstone design course for creative product development to fertilize and evolve the space. In this design course, students are requested to seek and define a useful problem that never existed before, and to design the corresponding engineering solutions. The course has been globally extended through collaboration with Hong Kong University of Science and Technology, Beihang University and Tsinghua University, Fall semester

B. Workshops

Machine workshops on high-demand subjects have been provided for the public. The workshops included: 3D printing; 3D modelling; 3D scanner; laser cutter; lathe; milling machine; CNC router; CNC machine; woodworking machine; and physical computing. After one semester of experience, the *Digital Fabrication and Manufacturing* course, which combines all those workshops in one academic curriculum, will begin in the upcoming Fall 2016 semester. This practice-intensive and experience-oriented course aims to familiarize students with *learning-by-doing* and *learning by failure*. This course is expected to increase the utility of this space.

C. Supports and Training

The recent, growing needs for design skills for engineering students is in line with increasing interests in student entrepreneurship activities [2]. Both the product design course and the hands-on workshops have provided skills to realize ideas that students could come up with during or after their education.

For students who already have an idea and want to develop it for their startups, SNU Idea Factory also offers supports and training programs. Those students who have been submitted their ideas and business plan and received the approval of the space manager can use space and materials 24/7. Also, various start-up education components such as an incubation/acceleration program, product/service usability evaluation, and visual sketching are available to students.

CONSIDERING CULTURAL CONTEXT

A. Encouraging Student-driven Projects

Though there are potentially many spaces where people are able to work together, we anticipated that the SNU creative space could have a particularly meaningful role as a physical pivot. However, in order to achieve this goal, it was necessary that we consider 'how' to connect students and 'how' to connect ideas. We attempted to make our space 1) unique and 2) a pivotal location which demonstrates SNU's collective intelligence. To achieve this goal, we have attempted to provide an education program which continues to inspire and motivate students.

B. Collaborative Place Nationwide and Beyond

Openness and collaboration are the two main important factors that can drive further creativity and innovation in this space [3]. The SNU Idea Factory should be distinguished from the conventional spaces which have been exclusively available for the college enrolled students. Based on this thought, SNU Idea Factory has attempted to advertise its place as open to everyone who has the passion to realize their dreams. It also has taken the initiatives to gather universities' maker spaces and to provide a collaborative program.

Also, beyond the national level, the newly launched *Global Product Design* course was initiated by SNU Idea Factory. During this course, students and instructors will meet both online and offline for three hours per week. Students will work collaboratively in Shenzhen for prototyping, in SNU Idea Factory for idea development, and in Beijing for the final presentation. As an initiator and provider of the educational system and resources, SNU Idea Factory has been planning to advance this course with universities in Singapore and in Japan.

OUTLOOK

A. General View

The potential of SNU Idea Factory is expected to be high. Since January, 2015, when the creative space project was initiated, its vision, philosophy, and various achievements have driven huge interest from both academia and industry. This rising interests in SNU Idea Factory has proved the fact that more and more people have a high regard for the value of interdisciplinary collaboration and for investment in well-equipped lab spaces [4].

Having a positive view of the SNU Idea Factory will lead to further steps as an initiative for academic maker space, as an interdisciplinary education studio, and as a student-driven startup incubator. As an academic maker space, SNU Idea Factory will keep providing advanced engineering education that will satisfy the current demands of a design approach in engineering. Also, as a startup incubator, it will be distinguished from the existing government-driven and corporate-driven startup incubators in promoting student startup and student-driven projects.

To reach its full potential however, a few things should be considered.

B. Design Thinking Approach

Though maker space generally focuses on hands-on experience, a precedent question should be answered first. The question is, "what to make?"

The design thinking approach would be useful as it is based on human needs and experience. It could fuel students to focus their desires and passions on what they want to realize [2]. Considering this, we have been implementing the design thinking approach for the creative engineering design course. Yet, the resources are limited as they are mainly provided by the engineering school. Also, as the Fig.6 shows, enrolled space users are dominated with students form architecture and mechanical engineering who conventionally have demands and skills in hands-on working. SNU Idea Factory should be able to offer interdisciplinary courses with collaboration between the design school and the business school.

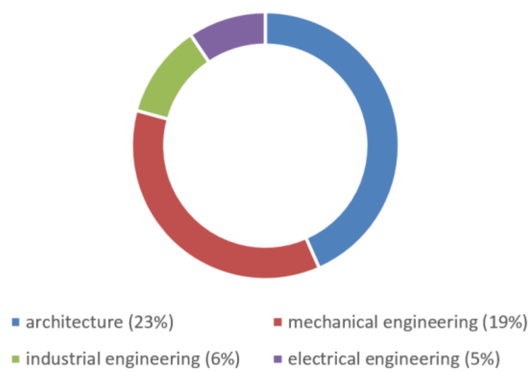

Fig.6 Percentage of Enrolled Students Classified with Majors

C. Creating Social Value

Maker space is a place where disruption happens: disruptive space, disruptive education, disruptive engineering, disruptive products and business models, and finally, disruptive practitioners. Given its tech lineage, maker space tends to contain a startup spirit with various new attempts and fast expansion, which drive those disruptions [4]. Considering these merits of maker space, leading academic maker spaces should always have social aspects in mind. The current philosophy of design for social innovation and the ethos of maker space should be considered and discussed.

D. Documenting, Sharing, and Patents

Documenting for sharing is the most important factor in accelerating the impact of maker space [5]. Accumulated practical knowledge and creative, collaborative, and collective intelligence are only possible with well-established platforms. With regard to this, an integrative online platform and cloud where participants can collectively document their experience and failures should be developed shortly.

However, such documentation will be partly distinct from the current open source concept. Skills and practices can be shared publicly; newly developed technologies and products should be protected legally. Therefore, SNU Idea Factory will provide further education on intellectual property and patents to protect and support students' work.

CONCLUSIONS

For the past one and a half year, SNU Idea Factory has been taking an exemplary academic maker space in South Korea. Its successful stories have been explained as various ways; yet the most important factor is based on a consensus on their vision from the onset. The creative space has been identified with a grand vision. 1) Connect ideas, 2) collaborate with people, and 3) cultivate creative culture, i.e., 3C.

Around this vision, the creative space has been designed, education and program have been developed, and institutional stability has been established. With a holistic approach on academic maker space, SNU Idea Factory has kept aiming for accomplishing their visions.

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Enabling Student Projects: Orientation to Tools and Techniques

ISAM 2016 Paper No.: 15

Invited

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An important educational opportunity provided by academic makerspaces is for students to learn how to make their own informed decisions in the complex open ended projects they pursue. However this requires that they first understand the landscape of resources available to them. Some may have previous machining experience, others may never have used a hand drill. Some may have experience with embedded processors, others may not know what a microcontroller can do and may never have written a line of code. Many will have no idea what thermoforming or vacuum casting could do for them. We can't teach them to be experts in everything they might need, but we also do not want to paint their project for them by telling them the techniques they will need; how can we enable them in this?

Core to our approach at Dartmouth is the use of small-group hands-on Tools and Techniques ("T&T") experiences in the first few weeks of a course. For example, our keystone project course starts with an evening overview tour where groups of 6 students travel station to station through our buildings taking some small role in a 5 minute demonstration, meeting the staff who can later help them, and accumulating a part (e.g. a laser-cut chassis, a thermoformed body, a PCB into which they solder a resistor, a measurement of motor speed with and without a gearhead); after an hour of this each sub-group of three students spends 20 minutes assembling these parts into a line-following robotic car and racing it against others.

That's just a first level orientation; it is followed by a series of hands-on 2-hour sessions run in small project groups (~5), covering for example foamcore mockups, CAD, machining, RP, plastics, microcontrollers with sensors & actuators, and making measurements. In the embedded controllers T&T session, for example, each student pair invents, wires, and codes their own product involving at least one sensor and one actuator which they choose from more than 80 in stock; they then demonstrate their working invention to others in the lab.

In a similar way, our introductory materials science course starts with small group T&T sessions learning from the very mentors and using the very equipment they may need in their open-ended term projects (e.g. heat treating, electron microscopy, manufacturing materials and techniques, strength and other property testing.) These guided T&T sessions are not enough to qualify students as solo users of some of the equipment they experience, but students do gain an appreciation of what they could do. Once a group has made decisions on their needs, students are typically asked to watch a training video, then work in more depth with a qualified TA or staff person. I will present further examples of T&T sessions and of the dramatic impact they have made on the quality and sophistication of our students' projects over the past decade.

While this T&T model is widely applicable, it is particularly useful at Dartmouth, where our audience is interdisciplinary. Not only do our users come from a variety of departments (sciences, studio arts, music, …), but the engineering school is by design, non-departmental – we have no EE, ME, ChemE departments, and our students come in with a wide variety of backgrounds. The T&T sessions help bring all students to the common baseline understanding they need to work effectively together, discovering, designing, developing, and making things.

The Hybrid Lab and the Open Collaboration Lab at CCA: Making Space for Makers at an Art and Design School

ISAM 2016
Paper No.: 16

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INTRODUCTION

The Hybrid Lab at the California College of the Arts (CCA) is a makerspace and classroom space open to students across the college. The Hybrid Lab and the initiatives it houses, specifically the Open Collaboration Lab (OCL), work at a critical intersection of art, design, and engineering to engage diverse audiences in technology based practice across art and design disciplines. The Hybrid Lab is unique in that it is based at an art and design school and seeks to attract students with a technical background and inclination, the "inverse" of the typical problem of attracting art and design students to an engineering makerspace. We run workshops and hold classes in the space using a pedagogy focused on interdisciplinary collaboration between technical and non-technical field. These classes and workshops bring 10-15% of our total undergraduate population each year into active use of the space; about half of these students have a technical background or are enrolled in a program with a substantive technical component.

MAKERSPACE ORIGINS AT CCA

For the past 17 years CCA faculty have been engaged in introducing students to emerging technologies used in art practice. CCA's Hybrid Lab is the culmination of years of experimentation and observation in incorporating technology into the work of artists, craftspeople, and designers. In contrast to the academic makerspace that originates from the experiences of technical DIY-ers, the Hybrid Lab comes from the experiences of art and design based DIY-ers and seeks to attract the technically- and non-technically inclined alike. Cross-disciplinary practices have been a tradition at CCA, and the Hybrid Lab is no exception.

An Art and Technology track at CCA was created under the tutelage of Barney Haynes within the Media Arts Program within the Arts division and college wide. The first Art and Technology class was called Interface (1999). The physical space that the class occupied, the curriculum, and the collection of materials for use (including old computers and Bay Area military and industrial surplus) replicated avant-garde arts practices that embrace montage, the juxtaposition of divergent disciplines, materials and methodologies, and that break down the idea of art as a singular object. Separately, from within the Design division, Dr. Wendy Ju developed and maintained a "Gizmo Closet" at CCA. The Closet housed electronics and related materials for physical computing and prototyping to be used by students within the graduate design department.

Out of a desire to create a joint interdisciplinary space dedicated to supporting technology pedagogy, CCA sought and secured funding in 2009 to design and build the Hybrid Lab and then to further expand the lab and staffing.

In 2015, the Hybrid Lab increased by in size by 50% to address increasing demand, and last year, the Open Collaboration Lab (OCL) formed out of classes taught in the Hybrid Lab in order to further the development of technical expertise among our technically-inclined students and to explore the particular needs art and design students have in learning technical subjects. Housed within the Hybrid Lab, the OCL fosters STEM based learning through a range of types of collaborations. Those collaborations and other activities described here are on track to double the number of students making use of the space each year.

OPEN CULTURE

The OCL, as well as the workshops and information systems emerging under the tutelage of Hybrid Lab Manager Dena Molnar, fosters a makerspace that emphasizes deepened connections, deeper learning, and multiple pathways to information and knowledge.

We think of openness and accessibility on a number of levels: 1) openness of the entire lab to technical students as well as non-technical students who might be shy about entering such a technical space where "experts" seem to know what they're doing, 2) accessibility to tools and machines inside the lab, and 3) accessibility to information about tools and processes that the lab encapsulates.

A. ACCESSING EDUCATION

An ongoing question for the Hybrid Lab is how a makerspace at a non-technical institution can attract students from across the college. The Open Collaboration Lab's founders (M. Haughwout, M. Shiloh, J. Zamfirescu-Pereira) came together in 2015 with a desire to improve the technology-based pedagogy employed in the Hybrid Lab, much of which is grounded in the Science and Math program area of Critical Studies at CCA. The Open Collaboration Lab emphasizes collaboration in the classroom, based on research suggesting that students learn better when questioning and explaining problems and processes to each other [1]. The study and practice of collaboration makes fabrication, programming, and electronics accessible to broader sections of CCA's student body, and especially to students in programs less directly linked to technical subjects within the Fine Arts and Humanities; a key component of the OCL's mission is to facilitate collaborations across classes and programs. Anecdotal evidence suggests that mixing electronics and programming with craft materials, as we do in the lab, can also help break down gender barriers [2].

Larger project development is also a process that invites collaboration. Here, students can participate in contributing to a project that they would not be able to do alone. Students develop skills explaining how their contribution to a large project will be situated (thus developing meta-cognitive ability that is critical to quantitative learning), and learn to integrate other elements into the development of their part of the project. Anecdotally, we've found that the pressures of being obligated to peers, rather than exclusively to the teacher, increases student motivation. In this context, documentation plays a critical role: students need to make good documentation for peers who need to understand how to incorporate code, quantitative analysis, or physical computing elements, for peers who want to replicate or reuse the contribution in another context, and for overall documentation of the project as a course deliverable. The effect of documentation for the student collaborators is again to strengthen meta-cognitive ability. Strong meta-cognition allows for the understanding of definitions, step by step procedures and conditions regarding larger organizational structures of computation. When it comes to programming, students who have the larger conceptual picture of what code elements do will find it easier to program specifics [3]. As Gregory P. Thomas observes in [4], the development of meta-cognitive skills in science and math fields “also requires that students are encouraged and supported to talk with the teacher and each other about their science thinking and learning processes, that they are able to voice their views regarding the nature of the learning activities they are asked to engage in, and that they are increasingly given control over the selection and enactment of their preferred learning activities [4].”

Fig. 1. An “open lab” Hacker Hours session; students soldering and completing homework assignments.

Summer workshops, open-to-all faculty-sponsored "office hours" we call Hacker Hours, and digital and non-digital interfaces organized by the OCL help visualize collaborations and prioritize documentation. In the Summer of 2016, the OCL hosted workshops with faculty from various program areas across the college including Writing, Sculpture, Furniture Design, Social Sciences, Sustainability Studies, and others. In these workshops, faculty explore how a unit might be embedded in their syllabi to add a technical component or collaboration to non-technical classes, how students can be encouraged to use resources in the Hybrid Lab, or how to pitch ideas to technical students looking for projects. Indeed, a goal of the OCL is to help the entire CCA community (students, faculty, and staff) find others to collaborate with.

Toward this end, Hacker Hours were initiated in the Hybrid Lab in the Spring of 2015 as a way to share knowledge, collaborate on projects, get help, and to practice using industry-standard collaboration tools like Git and GitHub. These gatherings are also an opportunity for students to show what they have made, inspiring others to try their hands at these sorts of projects. By creating a safe and fun environment we can attract students who might not otherwise take a class or attempt a project in this field.

Finally, in addition to the pedagogical methods described above that help keep students in the lab and returning to the lab, the Hybrid Lab also houses classes that satisfy college-wide learning outcomes. Thus students who might otherwise never visit the Hybrid Lab are introduced to the tools, materials, and learning therein.

B. ACCESSING TOOLS, MATERIALS, AND INFORMATION

The Hybrid Lab is a shared space for work, which we acknowledge as essential to a creative community. The “lab” format of engineering schools looks much like the "studio" format common in the context of an art and design school. Half of the Hybrid Lab is often used for classes (though not restricted at other times), and the other half is an open lab available for student use. On the perimeter of the space lies the Hybrid Lab's digital fabrication equipment and machines, soldering areas, etc.

The lab is primarily run by student monitors. Each monitor is trained on the equipment generally, but expected to own a domain of expertise specifically. That is, all monitors are expected to know how to operate the equipment in the lab, but each is trained to acquire knowledge about a specific process or domain as directed by their interests. This dynamic creates a sense of ownership for both the student monitor and the enquirer.

Hybrid Lab monitors also produce content for tutorials, educational posters, and maintain the Hybrid Lab website and activities. A main component of a monitor’s job within the Hybrid Lab is to foster the sense of community and accessibility to information.

The Hybrid Lab employs a variety of methods to create accessibility to tools and machines inside the lab. In designing the lab, we explicitly chose equipment that could be used without significant training and without requiring strict supervision. An individual coming into the lab does not need advanced training or the assistance of staff to begin using or experimenting with a given piece of equipment (though that help is available if asked for). In addition, a large set of commonly-used low-value components are designated as "consumables" and can be used for projects in the lab or taken home, no questions asked, eliminating what is often a frustrating barrier for first-time users of a makerspace.

In addition to tools typically seen in an engineering-focused makerspace, the Hybrid Lab houses a substantial diversity of 2D and 3D equipment and materials across a range of art and design disciplines with the goal of engaging different audiences in the production of technology based work. For example, the lab houses conductive inks, paints, and fabrics, for the production of paper based electronics as well as to engage students in Fine Arts in both technical and non-technical production; also on offer is an electronic knitting machine for the exploration of computational fashion and fabric-based sensor creation, exposing unconventional processes as opportunities for technological intervention; desktop 3D printers and milling machines, offered as opportunities for both electronics prototyping and PCB production, but also for jewelry and mold-making. Such hybridization of materials employed, use cases for equipment, and divergent applications in electronics projects opens up the question as to who owns the domain of technology.

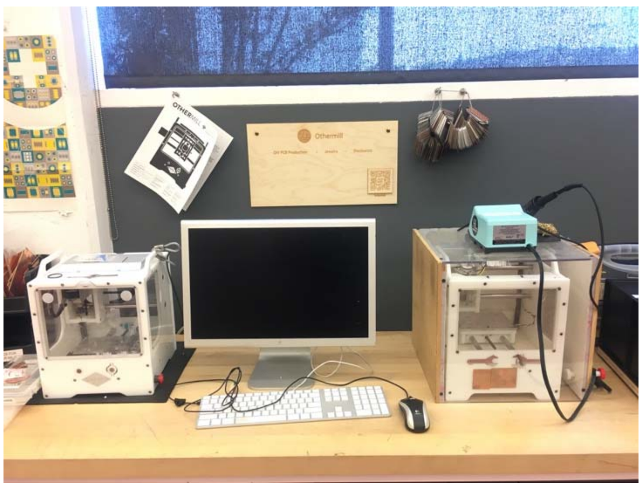

Fig. 2. The "Othermill" PCB milling station; the QR code laser-etched into station placard leads the scanner to a page guiding use of the tool.

Each machine in the Hybrid Lab is given a devoted "work station", with relevant materials, components, tools, examples and tutorials around the machine, facilitating the understanding of possible workflows and outputs. A recent addition being tested is the creation of tutorials accessed via QR codes above each machine. QR codes can also be found on and in the drawers that house the Hybrid Lab's non-consumable electronics, such as Arduino boards and shield, Raspberry Pi boards and capes, sensors, motors, and other actuators. Students can scan QR codes to access tutorials and use cases for each item.

TOPICS, APPROACHES: CLASSES IN THE HYBRID LAB

In our experiences teaching at CCA and within other art and design programs, we have encountered technically-inclined students as well as many students who tell us that they were never good at math, and that they feel overwhelmed, for example, when looking at a page of code. As a result, our programming and electronics pedagogy, and our educational materials more generally, differ from curricula that might typically be found in Computer Science or Engineering departments. What follows are a few sample strategies we have used for teaching art students who are easily intimidated and with little or no background in the field, but that also hold an appeal to students with substantial technical background.

A. CONCEPTUAL ART, CODE AND ELECTRONICS

In a programming and electronics class, students learn to engage in a creative and technical practice through studying and then conducting a conceptual arts practice. This practice is rooted in the work of Sol LeWitt, whose instructional based pieces were realized by artists other than himself. The assignment has three parts: students first write out a description of a dynamic painting and hand it off to a fellow student. Next students work to realize the 'painting' in the programming environment Processing. Students then trade off their code again, and work to have the dynamic elements of their code effect mechatronic activity through the serial port using Arduino [5].

B. SCULPTURE AND ELECTRONICS

Collaboration between students across classes is a key type of collaboration supported by the OCL. Our students are unlikely to go on to me principals in technical fields; any technical work they contribute to is highly likely to be collaborative in nature, as part of a team that includes technical collaborators. Our goal is thus to help prepare students for collaborations in which they can feel like they are contributing to something greater than themselves, and producing something they could not produce on their own.

One example collaboration experimented with grouping students with distinct skills from a sculpture class focused on 3D modeling with students from an introductory programming and electronics class. Given a few parameters (laser cut a sliced 3D skull from an online compendium; animate it somehow; finish the surface), students met in their groups to decide together what combined project spoke to their mutual interests as artists and designers. The resulting works exceeded our and our students' expectations in scope and originality; more than half the students responded affirmatively when asked whether their project was something they could not have completed without their collaboration partner, suggesting that our experiment achieved its goal of producing something uniquely producible through collaboration.

C. AN ADVANCED ELECTRONICS ASSIGNMENT

A module of a recent class involved reviewing a number of art pieces that relied on technology. In a class discussion, students attempted to understand how technology was employed to achieve the observed appearance and behavior. One result was creation of a block diagram identifying key hardware and software components, or building blocks. Students were then assigned to understand a building block, using a combination of individual research and assistance from the instructors. At the end of this process each student wrote a tutorial and built a prototype which was demonstrated to the class along with a summary of the tutorial. This process was repeated, so that each student became an expert in a number of building blocks. For their final projects in the class, students could then draw on this pool of building blocks, knowing that they could rely on in-class expert support (along with other material). Through collaboration, these technically-inclined students gain a broader understanding of the technical building blocks they can use in their own work.

As a matter of principle, we embrace the practice of sharing information, as exemplified by the Open Source movement. We believe that students benefit greatly from information others have shared, and so it is incumbent upon them in turn to share what they learn with others as discussed in the previous section. This has the further advantages of developing their writing and critical thinking skills, as well as deepening their understanding of the material.

In addition to the examples above, classes in the Hybrid Lab directly serve the Sculpture, Fashion, Industrial Design, Interaction Design, Architecture and Science and Math programs through collaborative projects, wearables, electromechanical interfaces, and explorations of the liminal space at the boundary of art and science. Many of these programs house a few students with a technical background, and by offering classes within those programs we are able to attract the technical students therein.

EVALUATION

The undergraduate population at CCA is about 1500 students. Through our classes and other activities, we bring 10-15% of those students each year into active use of the lab. Of those students, about half are technically inclined or in a program with a substantial technical requirement.

Use of the Hybrid Lab has been growing since its creation. The implementation of the collaborative approach described here has accelerated that growth by attracting technically-inclined students from across the college, notably including technically-inclined students from programs which, like many in the Fine Arts division, do not have a technical requirement. Student usage of the lab is on track to nearly double as a result of these activities. Additionally, a new advanced class that we piloted in Fall 2016 enrolled to capacity; these students are technically-inclined and previously attended introductory-level classes, speaking to the strength of our approach in keeping those students engaged with the lab from year to year.

Not everything we have tried has been equally successful. For example, we hoped that the QR codes would reduce friction and increase the number of new students willing to try using a work station or electronic component by eliminating the need to wait for help from a member of the staff. Preliminary results suggest more work remains to be done: few students use the QR codes and many are even at a loss for how to scan them; of those that do, the tutorials we link to are not always at the right level.

CONCLUSION

The Hybrid Lab provides a vital place for Art and Design students of all majors to learn about and work with technology including electronics and programming. By drawing on legacies of studio practice and avant-garde arts practices, and through collaborations, we introduce electronics resources and fabrication tools to students who otherwise may not visit the lab. The Hybrid Lab community provides mentoring and support for students and faculty who are engaging in projects of this sort. Equipment of the space using tools that have a low barrier to entry makes it relatively easy for students to get in and start making.

The Open Collaboration Lab increases student involvement by developing new ways for students to collaborate across disciplines, to work on projects bigger than they would have been able to do on their own, and to document their work for the benefit of future students and collaborators. These activities provide an avenue for technically-inclined students to develop their abilities within the context of their chosen programs of study, and have encouraged a larger percentage of the student body to make use the Hybrid Lab facilities and support.

ACKNOWLEDGMENTS

The Hybrid Lab is supported in part by a generous grant from Intel. The Open Collaboration Lab is supported by a generous grant from Intel, a generous grant from the Humanities and Sciences division of the California College of the Arts, and by a CCA Curricular Development Grant. The Open Collaboration Lab would also like to thank Humanities and Sciences Dean Juvenal Acosta and Design Dean Leslie Roberts for their enthusiastic support. The views and findings contained in this material are those of the authors and do not necessarily reflect the views of Intel or of CCA.

We appreciate the work of the ISAM program committee and reviewers in suggesting revisions for this paper.

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Yale Center for Biomedical and Interventional Technology (CBIT)

ISAM 2016 Paper No.: 17

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INTRODUCTION

The Yale Center for Biomedical and Interventional Technology (CBIT) was founded in February 2014 by Drs. Peter Schulam (Urology) and Mark Saltzman (Biomedical Engineering) to catalyze biomedical innovation and improve patient care. CBIT achieves its mission by promoting active collaboration among clinicians, engineers, business people, designers, administrators, students, staff, and faculty members through **strategic connections**, such as those between Yale School of Engineering and Applied Science (SEAS), Yale School of Management (SOM), Yale School of Medicine (YSM), and Yale-New Haven Hospital (YNHH). Notably, many CBIT initiatives are amplified by its close partnership with the Yale Center for Engineering, Innovation, and Design (CEID), an impactful design studio and collaborative makerspace, as the CEID provides physical resources as well as technical guidance to prototype and test medical innovations. The broad goal of CBIT is to **promote an inclusive spirit of creative innovations to improve patient experiences and outcomes**. Operating on the talent-rich Yale University campus, CBIT aims to provide clinical pulls for many of the available technologies and resources.

PURPOSE

A. MISSION & ACTIVITIES

CBIT functions as an interface that matches clinical questions, often arising from YSM and YNHH, with technical and business solutions, usually developed within the framework of Yale SEAS and SOM, respectively. Many of CBIT's functions mirror those of CIMIT: Center for Integration of Medicine & Innovative Technology[1], a non-profit consortium of Boston-area universities and teaching hospitals, especially as the Executive Directors of CBIT are also members of CIMIT Executive Committees. With a focus on creating medical device, health IT, diagnostic, and data solutions, **CBIT first identifies clinical pain points and sources ideas around which to organize multifunctional teams**. CBIT occupies an important place in the Yale entrepreneurial ecosystem, engaging all stakeholders to develop viable solutions for validated unmet clinical needs. That is, CBIT focuses on identifying areas for improvement in the current healthcare system, primarily through direct interactions with clinicians (physicians and nurses), hospital staff (purchasing and sterilization decision makers), and patients. Twice a month, at least one CBIT team member attends a Patient and Family Advisory Committee (PFAC) meeting at YNHH, in which approximately twenty passionate people who have been patients and/or caregivers provide ideas for improvements or feedback on current projects. **Project ideas are first vetted for clinical desirability by engaging clinicians and patients** before the economic feasibility is assessed through discussions with reimbursement specialists and/or insurance partners.

Once an important healthcare problem is identified and due diligence is performed, CBIT facilitates team assembly, either through direct connections of people with appropriate expertise, courses, or events. CBIT supports three courses: MGT/MD 657, Creating New Ventures in Health and Life Sciences (cross-listed in the Schools of Management and Medicine), MENG/BENG 404, Medical Device Design, and Medical Software Design. In each of these courses, teams form around clinician-identified problems to create business, device, or software solutions.

CBIT-led events include Healthcare Hackathons and Clinician Pitch Nights, in which physicians and nurses present pain points to form multifunctional teams to solve these problems. **We have found that events in which diverse groups of people congregate for focused discussions (often around free food) provide a fertile ground for team formation**, and therefore we aim to frequently bring together clinicians with students and faculty members of many backgrounds.

Healthcare Hackathons are CBIT's signature community-building and team-forming events, the most recent of which drew 125 participants to the medical school for 3 days during a blizzard. These hackathons are an excellent example of the **partnership model** that CBIT employs; the planning committees consist of people from MIT Hacking Medicine, neighboring universities, Patient and Family Advisor Committees, and YNHH in addition to Yale University. Attendees of the most recent hackathon, Patient Experience and Provider Engagement, selected from 370 applications, represented 38 institutions and corporations and formed 19 teams to create both physical and digital solutions; 7 teams continued to work on projects months after the hackathon, belying the sustained impact of these events. Even attendees who did not work on teams that continued projects reported that they enjoyed this energizing, inspiring event, and they left with new friends, professional mentors, and ideas.

[1] About CIMIT: http://cimitcolab.org/web/cimit

B. STRUCTURE & PARTNERSHIPS

Taking no equity in ventures created, CBIT provides an inclusive framework and resource for the entire Yale community, as it is not housed or owned in a single department, and its activities occur in many locations. While some CBIT staff offices are located in the medical school, others work in the engineering school, and one splits her time between the university and the hospital. A diverse, multidisciplinary research and clinical practice community, CBIT advances projects via education, team formation, guidance and mentorship (prototyping, regulatory, and business planning), collaboration among distant yet important stakeholders, and funding. To enable these activities, **CBIT has created key partnerships with the CEID**, as well as YEI and Yale Center for Clinical Investigation (YCCI). CBIT's advisory panel consists of leaders from YSM, SOM, SEAS, CEID, YEI, and Yale School of Public Health. Furthermore, **CBIT has created connections beyond campus**, most notably with the local Medtronic site; CBIT has developed an educational Clinical Immersion program that provides Medtronic engineers with didactic lectures, ranging from anatomy to hospital purchasing, and surgical observations. Entering its third year, Clinical Immersion Program participants report that exposure to Operating Rooms and discussions with surgical staff enable them to perform better at their jobs, and Medtronic staff have given training sessions on proper device use to YNHH employees, leading to better patient outcomes and experiences. Given CBIT's focus on measurable clinical impact, CBIT engages biomedical innovators at every phase to enable relevant design of products, including Voice of the Customer (VOC) feedback studies with patients, surgical staff, and medical device and sterilization specialists.

C. MAKERSPACE TIES

The close partnership between CBIT and the CEID enables a **unique opportunity for the entire Yale community to develop and actualize ideas** in an academic makerspace equipped with full machine and wood shops, 3D printers, a laser cutter, electronics equipment, wet lab, and other useful equipment and materials for prototyping. Anyone in the Yale community can become a member of the CEID, after which they are granted 24/7 access and the ability to attend workshops and events ranging from bacterial transfection to Clinician Pitch Nights. The CEID has built a thriving community centered on innovation and entrepreneurship, partially due to its well-executed courses, events, and workshops. When assisting project teams, CBIT frequently points to CEID resources for prototype design, development, and bench testing.

Additionally, MENG/BENG 404, Medical Device Design and Innovation, represents a synergistic partnership between CBIT and CEID. Currently in its fourth year, MENG/BENG 404 is co-instructed by the CBIT Engineering Director and the Assistant Director of the CEID, Dr. Joseph Zinter. This is a particularly impactful course (that resembles courses at Stanford[2] and MIT[3]) as it requires students to work with clinician clients to identify unmet needs and prototype solutions in the CEID to address those needs. Students also receive lectures from medical device experts ranging from surgeons to FDA employees. MENG/BENG 404 selected 20 undergraduate students from nearly 50 applications in Fall 2016, conveying the high demand for design-based coursework that solves real problems.

D. LESSONS LEARNED

Of the approximately 200 projects brought to CBIT, about 80 remain active. Therefore, by considering the varying successes of projects, several lessons have been learned. We have found that **thoughtful team formation is critical to a project's success**; generally, successful teams result from matching a clinician, engineer/programmer, and business person. Often, teams may start as two people (for instance, a physician guiding a Mechanical Engineering student in her senior design project), and grow to include a person with business expertise, such as an MBA student, as the project moves beyond proof-of-concept to proof-of-value. A success theme we've observed is **that a team must contain at least one passionate, motivated champion**; in our experience, these champions are either clinicians (mostly surgeons) who submit a project via the CBIT website or participate in a CBIT event, or students who enroll in CBIT-supported classes. While these initial project screening and team match-making activities are time-intensive, we've found that the upfront effort is a worthwhile investment for project sustainability.

Next, **a project must be sufficiently desirable, feasible, and valuable to succeed**. To assess each of these metrics, CBIT works directly with patients and clinicians to estimate desirability, and continues to engage these end-users through the development process. Feasibility is often assessed in partnership with CEID staff, who have expertise in design for fabrication, machining, manufacturing, and assembly, and project team members frequently use the CEID makerspace resources to prototype. Finally, potential value is measured by several mechanisms, including discussions with potential industry partners, market and business plan analysis in the context of MGT/MD 657, engagement with mentors and investors, or workshops.

Like many accelerators, CBIT assigns a mentor to each project team, either by leveraging the CBIT network or reaching out to contacts at the Yale Entrepreneurial Institute (YEI) or CEID, and **regular contact with mentors tracks with project sustainability**. Following the CIMIT model, a numerical score of Technical Readiness Level is assigned to projects upon intake such that progress can be measured. While current offerings and partnerships have been effective in terms of design, prototyping, market analysis, and business planning, **we've found that a gap exists in terms of software development and regulatory planning**. CBIT Leadership is therefore working to raise funds for regulatory strategists and software developers, such that the development of healthcare

[2] http://biodesign.stanford.edu/programs/stanford-courses/biodesign-capstone.html

[3] http://web.mit.edu/2.75/

solutions may be accelerated.

MENG/BENG 404 provides a useful case for pedagogical insights and development of best practices. The **teaching staff expends significant effort to source clinician projects prior to the semester**; this year, a Request for Proposals (RFP) was emailed to physicians, nurses, and other relevant hospital staff members in July, and interviews were held with clinicians who submitted potentially suitable projects. The teaching staff chose projects partially based on scope, with the goal of keeping a team of four undergraduate students busy while allowing them to reach significant milestones and feel successful by the end of the semester. The course aims to include a diverse range of students to promote creative problem-solving techniques, and thus 1/3 of students are Mechanical Engineering majors, 1/3 are Biomedical Engineering, and 1/3 are non-engineers. This year, the non-engineering majors include Computer Science, Molecular, Cellular, and Developmental Biology, American Studies, and Economics. While student project preferences were considered, the teaching staff structured teams around clinician-sourced projects to ensure that sufficient expertise existed on each team. For example, one team that is redesigning a primary care tool includes a Biomedical Engineering student, two Mechanical Engineering students, and an Economics student.

Finally, an important lesson from CBIT's experiences is that **an effective way to form partnerships with industry is by focusing on education**. Initially, people from Medtronic and Yale were hesitant to interact because of potential legal complications, and thus the first two years of the CBIT/Medtronic partnership was exclusively educational. Now that relationships and trust have been built, and each partner understands each other's policies, the CBIT/Medtronic relationship has evolved to allow for co-creation of biomedical solutions.

E. IMPACT

Bridging engineering, medicine, and business, CBIT has enabled numerous successes over the past 2.5 years. Over 200 projects have been proposed to CBIT, and 5 of these teams recently received $30,000 grants through a partnership with Connecticut Innovations.

Examples of projects in which CBIT team members have participated include:

- Acantha is a team led by two undergraduate engineering students that is developing a better device for central venous catheterization; they won a $15,000 VentureWell Debut Prize (2016). They have been supported by a CEID Fellowship and by CBIT mentoring on product development, intellectual property, and regulatory strategy. This group played a central role in the CBIT-led course, Creating Healthcare Ventures, in the Spring of 2016.
- Wellinks, founded in 2013, is a company started by three Yale students who worked with CEID, YEI, and CBIT. Wellinks has created a smart scoliosis brace that automatically adjusts and interfaces with software. This company recently closed a ~$1M seed round for manufacturing. With CBIT, Wellinks worked on grants and intellectual property strategy.
- VIP Transplant is a project that developed from the Medical Device Design course in which four undergraduate students worked with a physician (the Chair of Transplant at YNHH) to develop a telehealth platform for transplant patients. They were supported primarily by CEID in device design and prototype development. CBIT contributed some support by connecting them with medical industry professionals and corporate advisors. This team is currently testing its software prototype and collecting clinical data.

Educational successes include the high class ratings and competitive applications for inclusion in CBIT-supported courses, in addition to 4 undergrad teams winning national and international prizes and 9 publications/poster presentations. Currently, at least 6 CBIT-supported teams have received external funding to commercialize their innovations.

The Growth of Making in K-12 and the Expectations for Maker Resources at Universities

ISAM 2016 Paper No.: 18

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INTRODUCTION

Maker-spaces are the hottest thing in STEM education. They are effective spaces for people to learn, experiment with new tools, develop skills, collaborate, have fun, and become innovators and entrepreneurs. As part of his commitment to promoting STEM education, President Obama declared a National Week of Making in 2015, and in June 2016 the White House announced [1]:

"More than 1,400 K-12 schools, representing almost 1 million students from all 50 states, are committing to dedicating a space for making, designating a champion for making, and having a public showcase of student projects."

In 2014 researchers at Dartmouth College estimated that there were some 1,500 maker-spaces worldwide. [2] Popular Science confirms that estimate and reports a 14x increase in the number of maker-spaces worldwide between 2006 and 2016[3]. Male and female students alike are joining this new culture. In the 2015 MIT Undergraduate Enrolled Student Survey, 30% of Class of 2018 respondents identified as "maker", with similar rates for both men and women who responded.[4]

Students are enjoying the intellectual freedom allowed in maker-spaces to discover and explore their passions and become empowered learners. There is no standardized test for these valuable maker skills, and they may go unnoticed or unappreciated in traditional high school student evaluations. How can students be identified based on their maker experience in high school and valued in the selective college admissions process? How can colleges and universities create maker cultures on their campuses that attract high school makers and provide them with more extensive and advanced maker opportunities, benefiting both the students and the residential college experience?

THE EVOLVING EDUCATIONAL LANDSCAPE

The relationship between high schools and colleges is complex. The mission of a high school is to prepare their students for a productive life whatever educational path the student takes, and our culture and workplace strongly value a college education. Colleges want a well-rounded student with a variety of skills as well as the academic ability to be successful in college curriculums, yet academic scores are easier to evaluate than the well-roundedness of the student. Academic subjects in high school are most often taught in a book/computer format, with writing being the primary means to express thoughts and solutions. While reading and writing skills are clearly important methods to take in information and express a response, an empowered learner will also demonstrate the skills of critical thinking and self-direction. Experiential education, advocated by John Dewey over 100 years ago, is widely acknowledged as an effective way to learn and create critical thinking and self-direction. [5] Students are given opportunities to do and to direct their own learning, rather than simply be passive recipients of information and knowledge created by others. This type of learning could easily involve tools and materials other than paper and pencil. [6, 7]

A. K-12 EDUCATIONAL EXPERIENCE

The decline in hands-on or experiential learning over time in primary and secondary education is often caused by cuts to the arts, technical education classes, and home economics classes. Students in previous generations likely had opportunities to create things in their homes as tools and materials for building, sewing, and fixing household items were more commonly available. The prevalence today of computer-based devices, digital toys, and the sophisticated manufacturing of consumer products makes it much less likely that a child's play will meaningfully involve a knowledge of the workings of the toy or device, and it will be very unlikely that they can build or fix products they interact with daily. [8] However, high schools and communities are realizing the advantages of hands-on learning and are creating maker-spaces for use by students and other community members. There are maker-spaces in K-12 schools, in extracurricular programs, in summer camps, and in public libraries and museums. These maker-spaces are in multiple locations and are open day, evening, and weekend times, creating an ecosystem of maker opportunities. [9]

B. MAKING AS EXPERIENTIAL LEARNING

School maker-spaces and maker projects are a new version of an old idea – project-based learning. Teachers may incorporate maker projects into existing classes, for example creating a unit where the students define the problem and express their solution with the tools and materials available to them in the maker-space. Maker projects may be physical models or computer programs that show the relationships between parts of any system (biological, chemical, mechanical, electrical), or metaphorical models in their representation of ideas, structures, concepts and systems. A design or engineering teacher may have projects where the students identify and frame their own problems, then create solutions using the maker-space tools and materials. There are opportunities for academic study, market research, and entrepreneurship in addition to all the tools and materials knowledge and skills.

Many schools have seen the benefits of project-based learning and are integrating maker projects into academic class. Examples from the Castilleja School in Palo Alto, CA:

- 8th graders design, construct and present their own monuments to important women in American history, appropriate for the national mall. [10]
- Students in a 12th grade Biology elective are challenged to design an interactive museum exhibit to educate visitors about some aspect of cancer biology [11]
- Algebra II students build physical models that demonstrate the "Law of Sines" and help them visualize the various types of solutions. [12]

The activities in a maker-space are engaging and educational in many ways. Students using their hands to build can develop fine motor skills, knowledge of various material properties, and use logic for an assembly process. Computers can be used for technical purposes other than reading and word processing - they may control machines, draw, design, or create computer code. A key feature for maker activities is that the tools, machines, and the things they create are fun! No matter the age, people stare with amazement at a 3D printer, laser cutter, or sewing machine as it whips through a task that would be painstaking and tedious if done by hand. Students stick with the learning because it is fun to use the tools, and even more fun to create something new that looks great, performs a desired task, or in some way solves a problem. A key tenet in experiential learning is that students are inspired to continue their learning in a direction of their own choosing. [13] After exposure to entry-level maker tools and skills, many students will be inspired to learn the principles and techniques for more sophisticated tools and materials, or take their technical acumen and spatial reasoning skills into any other field.

C. IMPLEMENTATIONS OF MAKING IN K-12

There are a variety of programs available in high school settings for both formal and informal making. In the early 1990s, FIRST (For Inspiration and Recognition of Science and Technology), pioneered an extra-curricular project-based learning experience in high schools based on an introductory class taught at MIT. [14] FIRST was a pioneering hands-on program that engaged students in a creative and open-ended challenge to design and build a machine to play a game against other teams' machines. Other examples of maker-style activities include VEX Robotics [15], FabLabs [16], local TechShops [17], Lemelson-MIT InvenTeams [18] and others. There are also numerous schools and school districts that are implementing making as part of their curriculum. [19]

COLLEGES ARE RECOGNIZING THE VALUE OF MAKER-STUDENTS IN THEIR ADMISSIONS PROCESS

Colleges and universities utilize a selective admissions process to identify and admit students to their campuses that are both academically prepared and also mature enough to be ready for the less-structured learning environment provided by post-secondary education. Grades and test scores are quantitative and often students are overly focused on these metrics, such as number of AP classes. However, other factors can give admissions officers valuable information about students. MIT's Dean of Admissions, Stu Schmill, wrote about how admissions views a maker-style program like FIRST [20]:

A residential college experience is about the education of the whole person… We don't want students who do things because they have to, or because they think it will look good on their résumé. We want students to do things because they find true enjoyment and personal growth from them… I understand why those students from California might see participation in FIRST as a risk. It is a great example of an activity

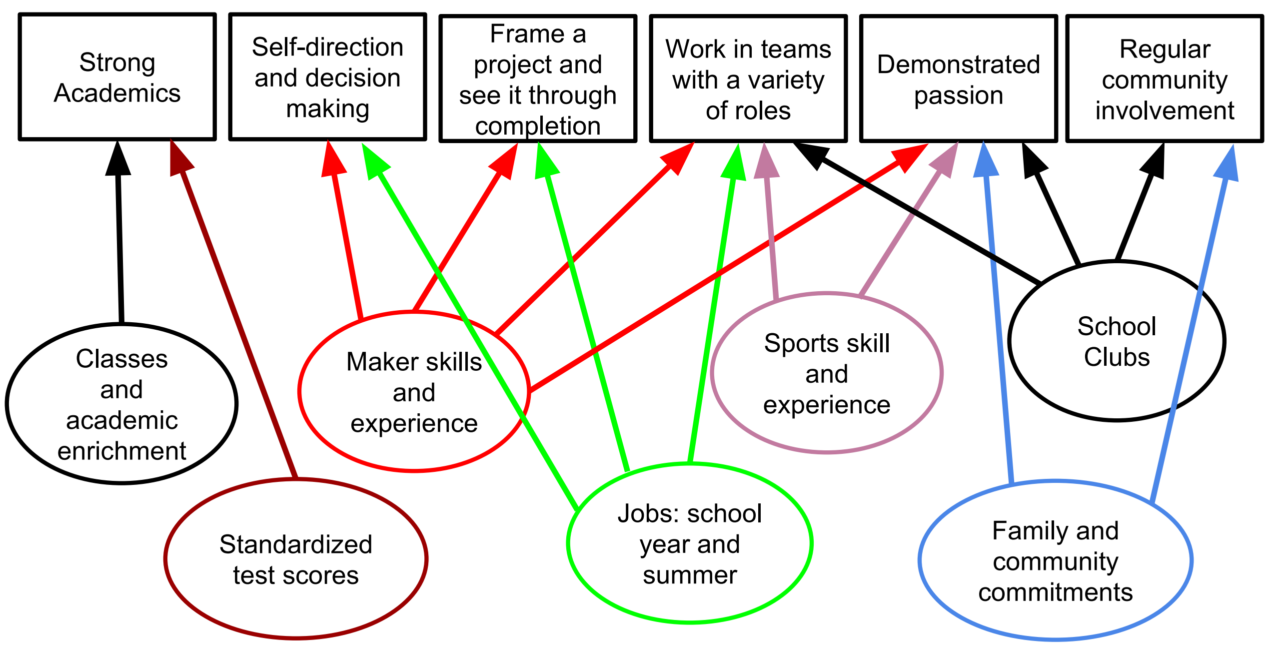

Figure 1: What makes a good college applicant? Rectangles represent holistic skills and experiences evaluated by admissions offices in the selective college admissions process. Ovals represent the spectrum of activities that are a part of a student's K-12 experience. Arrows indicate possible ways that the activity can show up in one of the evaluated areas, indicating the many ways in which making can help admissions identify a strong student candidate.

where you put in a huge amount of time and effort and you may not succeed with anything tangible. Your robot may not work and you will not receive a grade. But that risk is a telling one. It shows an understanding that it is the experience and not the trophy that is the reward.

Experience in making can give the student valuable skills in creative thinking, self-directed learning, and collaboration which are desired by colleges and universities. Making provides ways for a student to demonstrate these skills, especially for students who are not as interested in or lack resources to participate in other extracurricular activities such as music or sports. Figure 1 summarizes how maker experience can contribute to many parts of the holistic view of a student in the college admissions process.

One of the challenges with considering student's maker experience in the college admissions process is how to appreciate and evaluate the experience. MIT implemented a Maker Portfolio option in 2013 [21] that follows a similar evaluation done by expert faculty and staff as their Music, Art, Architecture, and Research portfolio options. The Maker Portfolio has allowed MIT Admissions to value the students' experiences without changing the admissions procedures already in place. Several other universities now include maker experience in their admissions process and can serve as examples for implementation. Indiana University has created an open-access Open Portfolio Project for high school students to utilize in documenting their making. [22] Over 150 colleges and universities have joined a consortium of Make-Schools [23] committed to supporting a new generation of Americans who make, and the numbers continue to grow.

SUPPORTING MAKERS IN COLLEGES & UNIVERSITIES

As high school students take advantage of the maker opportunities available to them in school and in their communities, colleges and universities should continue to recognize the skills that these students have developed through their projects. Making gives students a new educational perspective and demonstrates self-directed learning and project management skills that are often missing from more traditional exam-based education. Colleges and universities should be prepared to offer these students expanded opportunities for making, creating, and innovating on their campuses. For some campuses, this is implemented in a centralized way, such as the Invention Studio at Georgia Tech [24, 25] and the Center for Engineering Innovation and Design at Yale University [26]. Other campuses have a more diffuse network, such as the loosely connected Project Manus network at MIT. [27] Both of these styles of maker-spaces can work well at the college level and provide an extensive array of resources for student makers.

CONCLUSIONS

Together, K-12 schools and higher-education institutions can identify students who, through making, have acquired transferrable learning skills. The authors believe these students are better prepared to pursue their passions and challenge themselves in college. Universities can attract these candidates by valuing maker experiences in their admissions process and offering exciting making opportunities for college-level students that build upon their previous accomplishments. These students will grow to be innovators and inventors through their college years and beyond.

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A Control Banding Approach for Safety in Shops and Makerspaces

ISAM 2016 Paper No.: 19

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INTRODUCTION

Renewed interest in "making things" has led to a proliferation of small shops and makerspaces throughout educational institutions and public settings. In addition to traditional hand and machine tools, new technologies such as 3D printers, laser cutters, and small benchtop Computer Numerical Control (CNC) mills now make fabrication, rapid prototyping, and small-scale manufacturing more accessible and affordable than ever. As important as increased exposure to "making" is, bringing individuals with highly varied experience levels to such a diversity of tools can pose significant challenges to the safety and management of these facilities.

This paper describes a technique known as "control banding" for identifying, evaluating, and controlling hazards. Adopting such an approach can improve safety and increase consistency in makerspaces by providing the individuals who use them - and those who are responsible for them - with a common language and framework. The technique is sufficiently flexible to enable organizations to tailor controls and requirements to their specific needs and risk tolerance. While this guidance is provided from the higher education makerspace perspective, the concept of control banding is also applicable to K-12, community, and commercial makerspaces.

HISTORY

Control banding (as used in the health and safety field) largely evolved from work practices and engineering controls developed for handling highly hazardous materials. One of the earliest applications of control banding was by the US Centers for Disease Control and Prevention (CDC) for infectious organisms [1]. Under their system, the CDC established four risk groups of infectious agents, along with corresponding biological safety levels (BSL 1-4). Each BSL outlines progressively more stringent biocontainment measures to safely work with infectious organisms in research and clinical laboratories. The BSL concept not only defines the scope of work that can be conducted in designated BSL labs but also addresses many others aspects of working safely with biological agents.

Control banding has also been widely adopted by the pharmaceutical industry to address the protection of workers who manufacture, compound, or otherwise handle drugs with high biological activity or toxicity [2]. In the 1980s, the (United Kingdom) Health and Safety Executive applied control banding techniques to even wider workplaces [3]. Since then, the US Occupational Safety and Health Administration has also incorporated control banding into several exposure standards, including their lead and revised crystalline silica standards for construction. Several US educational institutions have also adopted control banding for chemicals used in certain research and teaching laboratories, creating "chemical safety levels" akin to BSLs [4].

Regardless of setting, control banding is designed to reduce or eliminate the time-consuming and often confusing process of performing case-by-case risk assessments for equipment, facilities, training, and procedures. The control banding concept provides a systematic approach to controlling hazards associated with groupings of materials or operations, by categorizing them and their applicable control methods into a manageable number of levels or bands.

Tools and equipment are a universal and defining feature of makerspaces. With the variety of traditional machine tools and fabrication equipment, coupled with an expanding array of new tools and equipment, the concept of control banding provides a mechanism for ensuring safety in makerspaces. This process relies upon a review of tool and machine hazards, classification into levels or bands based upon those potential hazards, and a range of additional characteristics driven by the classification. However, in addition to the specifics of control banding, it is essential to also address the role of culture, and specifically instilling a culture for safety within makerspaces.

TOOL AND MACHINE HAZARDS

The first step to applying control banding to a makerspace is to review and evaluate the intrinsic hazards within these spaces. Machines, tools, and equipment can pose a range of potential hazards to users, others nearby, and property. Some hazards have been long recognized, other hazards are less obvious, and for some new equipment, the inherent hazards are not yet fully understood.

The most obvious hazards posed by tools and equipment are acute physical injuries at the point of operation, i.e., where the tool and workpiece meet. These injuries may include lacerations, pinching or crushing, amputation, and even death. The cause of the injuries may include entanglement and unintended contact with the machine or tool, as well as flying objects from the workpiece or the tool itself.

Less obvious hazards are posed by inadvertent contact with moving components and with elements of the tool power transmission system(s). Heavy tooling or the workpiece itself can break or fall, resulting in crushed and broken fingers, hands, feet, and toes. Handling a workpiece immediately after processing may result in cuts from sharp edges or burns from friction-generated heat. Open flame use and many metal cutting/grinding operations can generate hot particles and sparks, creating hazards of burns and fire. Cutting, by both torch and laser, and welding operations also create intense infrared, UV, and other light hazards which can cause eye damage.

Often under-appreciated are the potential chronic health impacts that some tools can pose, such as hearing impairment (due to high levels of noise) and soft tissue injuries (resulting from repetitive motions and heavy lifting). Many machine actions also generate hazardous dusts, fumes, gases, or vapors. Certain workpiece materials themselves can produce hazardous emissions, such as vapors and dust from pressure-treated lumber, disturbances to lead-based paint surfaces, machining reactive metals, and thermal cutting PVC, acrylic plastics, and other materials. Preliminary studies on some emerging technologies such as 3D printing have also raised questions about chemical emissions and the creation of ultrafine particles [5].

In addition to the hazards to operators and nearby personnel, the concept of safety can also be extended to prevent damage to the tools and equipment. It is also important to review the hazards of the products that are designed and fabricated within makerspaces.

Equipment and tool hazards can be controlled through a combination of user training, machine safeguarding, and the adoption of a culture for safety within the working space. These three components are essential to the application of control banding within makerspaces.

MACHINE SAFEGUARDING AND SAFETY DEVICES

Machine safeguarding refers to purposeful steps taken to reduce or eliminate the hazards associated with a tool, machine, or other piece of equipment. These may be inherent in the design of a tool, installed during manufacturing, or added by the owner after purchase. Guards, covers, and enclosures are among the most common safeguards used to limit bodily access to hazardous machine actions. Additional safeguarding features include power controls, interlocks, as well as thermal, load, and power limitations/protections. Emergency stops, although secondary to safeguarding, provide a means to stop a machine in reaction to an incident or hazardous event. In essence, safeguarding features become a component of the tool.

Practices for tool and machine safeguarding have been developed by manufacturers, professional societies (such as the American National Standards Institute [6], National Fire Protection Association [7] and National Safety Council [8]) and government agencies (Occupational Safety and Health Administration (OSHA) [9]). OSHA machine guarding standards technically only apply to employers and employees, but it is common practice (and strongly recommended) that they be applied as minimum requirements for tools used by anyone. While OSHA's standards provide specific guarding requirements for a limited number of distinct tool types, their General Machine Requirements are applicable to almost all tools. The American National Standards Institute provides detailed guidance on the tool safeguarding process, and the National Safety Council offers specific recommendations on machine guarding and control. It is also recommended that makerspace tooling and equipment meet or exceed these applicable guidance criteria. In addition to publications and on-line materials, these organizations also sponsor machine and tool safety training courses and provide other resources.

While there is a substantial amount of information available on machine and tool operations and safeguarding, the coverage is not necessarily comprehensive for every piece of equipment. User manuals generally provide detailed safety information for new equipment sold in many parts of the world. But with robust international and used equipment marketplaces, safety features and the associated safety information can often be incomplete or missing.

A review of machine tool and equipment hazards is an appropriate backdrop for presenting the concept of safety control banding within makerspaces. The tool and equipment classification methods in safety codes and standards form the framework for a comprehensive hazard classification system that establishes collections, levels, or bands of equipment with similar characteristics of potential harm.

HAZARD CLASSIFICATION

Control banding is proposed as a system to classify machine tools and equipment within higher education makerspaces. The classifications are based on the hazards associated with each specific tool to the user and nearby personnel. Factoring into the classification for a specific tool or piece of equipment are the power of the device, the presence of safeguards (that cannot be bypassed), and possibly the operating modes of the tool or piece of equipment (and the reliance of those operating modes on enclosures and interlocks).

The concept of safety control banding is not only a classification mechanism for tools and equipment, but also serves as the driver for establishing features of the makerspace room environment, user training, access, and oversight. The classification categories are presented in this section, followed by a discussion of these other features.

Risk (defined as the product of the probability of an accident and the severity of the resulting injury) is actually a preferred metric for a classification system. For example, while severe injuries are rare, minor lacerations and punctures from razor knives, chisels, and screwdrivers generally account for a disproportionate number of accidents in makerspaces, due to their frequent but often incorrect use. Unfortunately, reliable statistics are not available for quantifying risks from the more than 40 different families of common makerspace tools. Furthermore, OSHA's machine guarding requirements are prescriptive, making the potential hazards the more appropriate metric using the severity of potential injury as the delineating factor between each safety control band classification level.

The presented safety control band model is suggested as a template for institutions to create their own guidelines. While the presented model uses four tiers of control bands, programs can expand or contract this number to best meet their needs. To operationalize the concept of safety control bands within an academic makerspace, each band must be associated with policies that guide user training, access, use, and oversight appropriate to each hazard level.

Based upon a methodology developed at Yale University on student use of machine tools and equipment, the safety control band classification system presented in Table 1 uses four levels to categorize machine tools and equipment (and their subsequent use) [10] .

The provided examples are generalizations for machine tools and equipment. In practice, a hazard review is required for each tool to ensure that each is properly classified. For example, most Fused Deposition Modeling 3D printers might be classified as "Hazard Class 1" while Stereolithography 3D printers warrant a higher classification level based on the composition of the photosensitive liquid resin used in a specific printer. Similarly, 3D printers capable of printing metals or requiring corrosive washing should also be classified at a higher level.

Appearing in multiple hazard classification categories, CNC versions of manually-controlled machines must be carefully evaluated since different manufacturers provide different features, many of which are embedded in the system's operating software. When classifying such equipment, it is critical to verify the presence and function of all guards, enclosures, interlocks, and emergency stops.

APPLICATIONS OF CONTROL BANDING

The concept of safety control bands is proposed within makerspaces as a guide for the training, access, oversight and use of machine tools and equipment. A summary of the safety control band approach within makerspaces that details how this classification extends beyond the tools and equipment is presented in Table 2.

The concept of safety control bands can also be extended to define the classification category for specific areas within the makerspace, with appropriate levels of access control then used to ensure that only qualified individuals can use specific equipment at prescribed times. Specifically, the hazard classification of tools into categories in turn determines the classification for those areas that house this equipment in the makerspace. This methodology also leads to the development of requirements for the room's safety infrastructure, user training, supervision and oversight, and accessibility.

Table 1. Hazard-based Safety Control Bands

	Hazard Class 1
Hazards:	Minor injuries, addressable with basic first aid kit or ice
Power:	Less than 0.25 HP, 2-4 Amp, 120 VAC or less than 18V DC
Type:	Low power hand and small bench tools
Examples:	Manual hand tools, small cordless drills, glue guns, palm sanders, soldering tools, heat guns, sewing machines, 3D printers, 3D scanner, vinyl cutter
	Hazard Class 2
Hazards:	As above, plus more significant first aid injuries, potentially requiring medical assistance
Power:	0.25 to less than 0.5 HP, less than 10 Amp, 120 VAC or 18 to less than 24 V DC, and specialized enclosed/interlocked CNC tools
Type:	Low to medium power tools
Examples:	Mid-range powered hand tools, laser cutters, pneumatic tools, small benchtop tools, self-standing manual tools (shear, brake, roller, press), low powered CNC mills, routers and lathes (interlocked/enclosed), thermal foam cutters, thermal formers
	Hazard Class 3
Hazards:	As above, plus potential for serious lacerations and minor amputations that require medical attention
Power:	Greater than 0.5 HP, greater than 10 Amp, 120 VAC or greater than 24 V DC
Type:	Powerful portable and light industrial tools
Examples:	Portable construction-scale power tools, medium power industrial tools (generally free-standing), 3D printers/processes with toxic chemicals/corrosive wash steps, CNC interlocked/enclosed equipment (mill, lathe, plasma cutter, waterjet)
	Hazard Class 4
Hazards:	As above plus potential for serious amputations and life-threatening injuries
Power:	As above, plus typically self-standing and hardwired (including higher voltages and/or 3-phase power)
Type:	Large industrial tools
Examples:	Powder-actuated tools, industrial-scale mills and lathes, table saws, large (open format) robots, powered shears, rollers, brakes & presses

Under this approach, the highest hazard tool(s) present within a specific room determines the overall classification of the space itself. However, if that tool(s) can be effectively locked out or otherwise rendered inaccessible or inoperable, the overall room classification can be "downgraded" to the next lower tool hazard class.

Table 2. Control banding approach for tools and machines

Tool "Hazard" Classes	Low → high (potential hazards, complexity, cost)
Examples	Manual → high power / industrial (lists of specific tools)
Access	Open 24/7 → restricted access space/tools
Supervision & Oversight	Solo work → buddy → formal supervision
User Training	Self-taught → extended training
Credentialing	By training → demonstrated competency
Supervisors	Student peers → professionals & faculty

Room Safety Infrastructure
All spaces must be designed and built to meet basic life and fire code requirements. Similar to laboratories, makerspaces must also provide additional features to control their potential hazards. While most of these features apply to virtually all shops and makerspaces, some are likely only necessary for spaces with higher hazard equipment, materials, or operations. Basic room infrastructure features for most makerspaces include:

- High degree of "visual porosity" into the space,
- Slip-resistant flooring,
- Adequate general and task lighting,
- Sufficient general ventilation,
- Posted rules and safety information,
- Multi-purpose dry powder ABC fire extinguisher,
- Landline phone with emergency contact numbers listed,
- First aid kit,
- Prominent personal protective equipment station, and
- Access to operating manuals and instructional materials.

Depending upon the tools, materials, and operations present, additional features may be necessary, including:

- Replacing dry chemical fire extinguishers with CO_2 or other "clean" agent devices where laser cutters, 3D printers, and other electronic or optical equipment could be damaged by powder,
- Additional ventilation and filtration for fumes and/or dust,
- Wider array of personal protective equipment,
- Room or individual tool access control(s) in the form of punch codes or identification card readers,
- One or more room-level emergency shut-offs,
- Tool out-of-service (lock-out/tag-out) station,
- Emergency eyewash where exposures to chemicals may occur (and deluge emergency shower if corrosive compounds are handled),
- Flammable storage cabinets,
- Hazardous chemical waste collection and signage,
- Binder or file for material safety data sheets for chemicals and chemical products.

User Training
The users of makerspaces often have diverse backgrounds. Some may have extensive and even professional machining or carpentry experience. Others may have very little familiarity with basic hand tools. Consequently, training requirements for those accessing a makerspace and using the tools within must be carefully thought out to ensure appropriate training is consistently performed. The intensity of tool-specific training should vary depending on the Hazard Class of the specific tool. These levels of training may include self-guided instruction, peer-based instruction, and hands-on training methods by professional staff. As with all safety training, documentation of each person's participation in each training session is essential. In addition to the initial training, a robust safety program will also include a qualification process (to demonstrate safety awareness and proficiency), as well as a certification process (to identify the tools each user is certified to use). The following examples illustrate a spectrum of training methodologies that span all of the presented hazard classification levels.

Minimum training requirements must be established for everyone accessing a makerspace, including those who do not intend to use tools. Typical training at this level includes emergency response procedures, familiarization of the space layout, identification of the approved activities, an understanding of activities that require additional approval, and an awareness of what tools may not be used without additional training. Specific training should be provided to address the Hazard Class 1 tools and equipment that are generally available within the space. This training may be performed in an orientation session and should be documented with a signed acknowledgement of the makerspace policies.

Training for Hazard Class 2 tools could include demonstrations by qualified peers, staff or supervisors, as well as self-education using equipment manuals, on-line training aids, and instructional videos. A qualification instrument needs to be administered to ensure the training was effective, with this qualification determined before a user is certified to operate the Hazard Class 2 tools and equipment.

It is expected that training for Hazard Class 3 tools and equipment would require hands-on work, with the training and oversight provided by a competent person as designated by the institution. Machine tool and equipment training within this hazard class would thoroughly address tool-specific hazards and safe operating procedures. The qualification process would demonstrate proficiency with the tools and equipment, as well as knowledge of the hazards associated with each piece of equipment or machine tool.

Training users to operate Hazard Class 4 machine tools and equipment would normally be conducted over a period of time, most likely in a series of sessions. Typical training for machines in this hazard class level would include instruction as well as hands-on experience with each user completing a specified project. The project may be used as a component of the qualification process. For many institutions, this training is delivered and the process is overseen by qualified shop managers, designated staff, faculty members, and post-docs.

Supervision and Oversight

Each higher education makerspace should be affiliated with a specific organizational entity, department, or school within an institution, and have a designated individual responsible for all operations within the space. That individual should have full authority over the space and its use. This individual should have experience with all of the tools in the space, and be accountable to the institution through the affiliated organizational structure. Wider oversight of the space can be accomplished through a steering committee or other administrative body.

At the day-to-day operational level, tool and equipment access would be a function of the specific safety control band practices and the supervision required within each hazard category. Using this approach, these parameters determine which tools and equipment are available for use at any time, depending on the prescribed levels of supervision for each tool (as well as pre-determined schedules of equipment and space use). For example, makerspaces providing access to the lowest hazard tools may permit solo use of specified equipment and tools, but require a peer escort and peer oversight for using Hazard Class 2 tools. Due to increased power and the associated increased potential for harm, however, the use of Hazard Class 3 and 4 tools would be restricted to periods when supervision by professional employees or faculty would be available.

Accessibility

The effectiveness of well-defined training and oversight requirements for makerspace users is highly dependent on the ability to restrict access to authorized users. The use of identification card access to limit access to authorized makerspace users is widely used as a control mechanism. Identification card access (and monitoring) systems afford institutions the ability to grant or deny access, limit operating hours and maintain a record of users accessing a space. Additional controls can be considered to limit access to higher hazard tools within a makerspace. Such systems have also been incorporated on specific pieces of equipment (such as 3D printers and laser cutters) to control access and record use.

Zones within a makerspace may also be used to provide a second tier of access controls to higher hazard tools (which by the classification system require higher degrees of supervision). For example, Hazard Class 3 and 4 equipment tools can be located inside a room within a makerspace. Card access to the inner room can be restricted to those authorized to oversee the use of the Hazard Class 3 and 4 tools and equipment in that space. Alternatively, equipment and machine tools with a higher Hazard Classification can be locked out to restrict access within the same space where lower Hazard Class tools and equipment are located. Lockable tool power disconnects and operational switches, along with the proper levels of controlling key access, are required for spaces exercising this option.

An additional method to limit access to higher hazard equipment is to power that equipment on a controllable electrical panel. Such a panel would only be activated using a keyed switch or card reader. Access to the power would only be provided to designated individuals (who are authorized to oversee work on that equipment). With this method, a makerspace containing equipment with a high Hazard Class can effectively be de-rated to permit users to utilize the space for activities using lower Hazard Class tools and equipment when the prescribed oversight is not available.

A CULTURE OF SAFETY IN MAKERSPACES

The concepts of community and culture are key to makerspaces. The term makerspace not only refers to a physical location and its equipment but also includes the people and programs that use and define the space. The community aspect of a makerspace is a factor that differentiates these spaces from other work sites, with the typical makerspace community being a collaborative and cooperative environment to learn, share and create in. These activities define the culture of the makerspace, and typically the culture is a permissive one (regarding freedom of work) as well as collaborative (regarding the exchange of ideas). In general, makerspace cultures are nurturing and accepting of makers at all levels of experience and interests.

Adopting a positive culture of safety is essential for safe operations within makerspaces. Key to this awareness is the recognition that safety is as important as every other aspect of making. A culture for safety establishes safe operating processes as the normally- expected behavior. It adopts a mindset within the community that safe operating practices are a collective responsibility, with members watching out for one another with respect to the safe operation of tools, equipment, and constructed devices.

The many challenges faced by makerspaces help justify viewing safety as an essential component of the community's culture (as opposed to the view that safety is a prescribed set of policies, with punitive actions resulting from noncompliance). These challenges include fluid membership and use, with new users continuously joining the community and the types of projects underway always changing. A culture of safety recognizes that not every condition can be predicted and prescribed, but is sufficiently flexible to embed safe operations in every activity. A culture of safety understands that created objects can have inherent hazards, and safe operating principles must be applied when using these objects.

Key to a culture for safety is the perspective that safety is practice-based and not enforcement-driven. With such a perspective, equipment is operated in a safe manner because it is the proper way of doing things as opposed to the view that safety is something that is done because of prescribed rules. Training, qualification, and certification by designated instructors is another attribute of an organization with a culture for safety, as are the concepts of space-bands and time-bands where access is provided to trained users at specific periods of time.

Essential to the culture for safety is the establishment of community-based practices that enforce personal accountability. In such communities, dialog about safety is commonplace as a means to establish norms, promote best practices, and improve systems. Where appropriate, lessons learned from accidents (and near-accidents) should be shared within the community to help prevent future mishaps. The cleanliness and order of the makerspace is another important aspect that often correlates with safety. Finally, with respect to higher education makerspaces, it is suggested that a safety review be part of every student project.

The measures of success within a makerspace include the observance of safe operating practices as well as the regular (self-motivated) use of personal protective equipment. A makerspace in the process of developing a culture of safety will likely see an initial increase in the accident and issue reporting as the community expands its dialog on this topic. As users learn and practice rules and norms, the community will begin to help each other with these and other activities. Frequent and engaged interactions between users and managers/instructors also mark a strong culture of safety. Risk is reduced by the collective actions of all to increase environmental and safety awareness, reduce hazards and exposures, and implement realistic control and operating processes.

CONCLUSIONS

The concept of safety control bands is presented as an operational framework within higher education makerspaces. This concept is based upon the classification of hazards associated with specific machine tools and pieces of equipment. The makerspace can be designed to group similarly classified tools and equipment in specific locations, with access to and use of these spaces managed by the makerspace's staff. Thus, the concept of safety control bands extends to the space's infrastructure, as well as the training, access, oversight, and ultimate use of each machine tool and piece of equipment. Four levels of hazard have been identified to classify tools and equipment, with examples of the levels of training and oversight needed for using the equipment. These guidelines are offered as a template for defining a system of safety control bands as one component to improve the culture of safety in higher education makerspaces.

Disclaimer: The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any institution or organization.

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Having Your 'Make' and Being Safe Too: Maker Advocates and EHS Working Together

ISAM 2016 Paper No.: 20

Invited

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INTRODUCTION

Many makers at universities think that their EHS staff don't know/understand making and are overly prohibitive. Many EHS staff at universities don't think that makers fully appreciate the safety, legal and regulatory issues that surround their making. This can lead to tension and contentious discussions. If everyone puts the students' best interest at heart, and makes decisions based off of known facts, disagreements generally are few and far between. This is important as it prevents makers from trying to 'hide from' or 'circumvent' EHS. Three key elements make a good collaboration between makers and EHS:

(i) Trust - Makers need to be able to trust that EHS staff will judge a making activity, method or machine based on facts vs. fears of what might go wrong. EHS staff need to be able to trust that makers won't hide or circumvent them.

(ii) Empathy - It is important for both sides to practice the ability to see the other person's point of view.

(iii) Willingness to experiment - Often, it's unclear how well a particular training method, maker program, or other activity will work. It is best to avoid being highly restrictive 'just in case.' This will only lead to hiding and circumventing. Starting small with experiments that enable both sides to learn is important. It is important for both sides to be able to accept positive and negative outcomes.

In this talk, MIT's main maker advocate - Maker Czar Prof. Martin L. Culpepper - and MIT's Director of Environment Health and Safety - Louis DiBerardinis - will share their observations and experiences working together to optimize safety while maximizing access to equipment and spaces. This collaboration has been key to enabling our students to innovate while minimizing risk/hazards and teaching student best safety practices.

They will discuss how they built a collaboration, and how they continue to collaborate and enable students to learn and make the objects they need in a safe, efficient and cost-effective manner. Our hope is that makers and EHS staff will be able to take several elements of this discussion back to their home institutions and create trusting, fruitful collaborations.

Safety in a Student-Run Makerspace via Peer-to-Peer Adaptive Training

ISAM 2016
Paper No.:
21

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INTRODUCTION

The Invention Studio at Georgia Tech is a free-to-use, student-run makerspace that serves the entire body of students and employees of the Georgia Institute of Technology. Campus makerspaces, such as the Invention Studio, provide a low barrier of entry to hands-on prototyping and fabrication experience relative to the classic machine shop model [1]. The student supervision of the space creates a unique environment that fosters campus community involvement in “maker culture”, which is shown to have a positive impact in the professional development of students in S.T.E.M majors [2, 3]. Despite the numerous proven benefits offered by student-leadership in campus makerspaces, student-run makerspaces are uncommon, due in part to skepticism over the ability of student oversight to maintain a reliably safe workshop environment.

Founded in 2009, the Invention Studio has grown consistently in terms of staffing, space, and impact on campus culture. Without existing procedures to accommodate rapid growth, the Invention Studio developed a series of policies to mitigate administrative concerns over safety and quality of service. After the implementation of the checklist training program in 2014, the Invention Studio saw a decrease in the occurrence of recordable work-related injuries, as defined by OSHA [4]. These policies, which are described below and packaged in the appendices, may serve as inspiration to readers who are facing similar challenges with the growth of their own student-led makerspaces.

HISTORICAL BACKGROUND

Reacting to growing industry demand for engineering students with hands-on experience, the George W. Woodruff School of Mechanical Engineering at Georgia Tech created the Invention Studio in 2009. Initially recruited to oversee a small prototyping facility for the Capstone Design course, faculty champions selected ten volunteer student instructors for their prior experience in a machine shop environment. This tightly-knit group facilitated student access to tooling through peer-to-peer instruction while offering opportunities for non-academic tool usage to a limited number of people [3].

At this initial time, safety policies were mostly divulged by word-of-mouth through instructor/user interactions. Due to the limited number of available instructors and minimal advertising, a small, yet highly engaged user base emerged. To continuously provide course support over time, this group acquired new members primarily through targeted recruitment of skilled and trustworthy members of the regular user base. The process was informal, guaranteeing safety only through the accountability of the limited number of highly invested volunteers. As the Invention Studio began to attract increased traffic, capital investment, and campus attention, the volunteer staff prioritized an increase in the availability of open hours. The rapid rise in staffing requirements led to a mass recruitment effort, where the previously utilized method of accountability through recommendation was no longer an option.

Following a brief period where tooling and procedural information was lost through graduation of key early members and an increased concern regarding the safety of operations, the student leaders of the Invention Studio recognized the need for more sustainable, methodological training solutions to accommodate the diverse user groups. The first attempt at student-generated policy to address this operational gap was introduced in 2014, and can be seen in Appendix 1. These policies and procedures, which are the primary focus of this paper, established and reinforced the current distribution pathways for knowledge, shown below in Fig. 1. Prototyping Instructors (or PIs) are student volunteers who maintain the space. Support staff includes professional staff hired by the Woodruff School. As can be seen in the Appendix 2, safety track record has been excellent. There have been zero OSHA defined reportable injuries since the implementation of the policies and First Aid Kit Usage shows that the worst injuries were small cuts requiring a bandage.

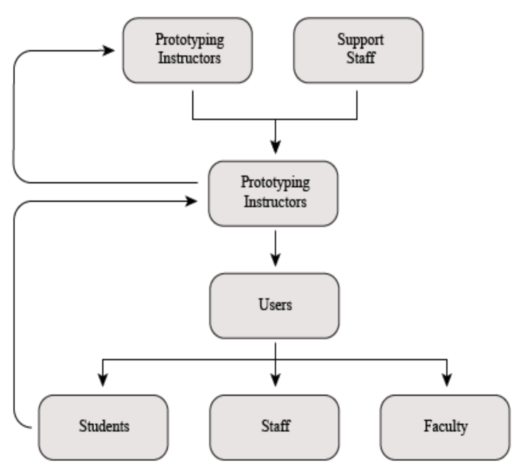

Fig. 1 Knowledge Transfer Pathways in the Invention Studio

A. Various Users, Various Needs, Various Equipment

Because the Invention Studio serves the entire population of the Georgia Tech campus, the user base is composed of individuals with various levels of hands-on experience, technical education, and project aspirations. Because of the need to minimize the barrier to entry for equipment access in the Invention Studio, users are not typically required to record demographic information, such as major, gender, or project type. The diversity of majors that participate in the space may be inferred by an analysis of the PIs. The Invention Studio's student leadership began keeping records of involvement since the Fall semester of 2012, despite operations since Fall 2009. In that time, over 230 students had served in an instructional or leadership role in the Invention Studio. Fig. 2 shows the majors of all recorded student volunteers in the Invention Studio over the past four years.

To date, student volunteers from 16 majors/disciplines have served as PIs. Note that abbreviations ending in "E" represent an engineering major, with mechanical engineering representing the most significant contribution of PIs. This can be attributed to the Invention Studio's location within a Mechanical Engineering building in conjunction with hands-on ME course requirements. Other strong sources of PIs include Aerospace Engineering, Biomedical Engineering, and Electrical Engineering. Members of other majors that do not teach CAD and traditional manufacturing methods - such as Chemical Engineering, Computer Sciences, and Human-Computer Interaction are also represented in the figure.

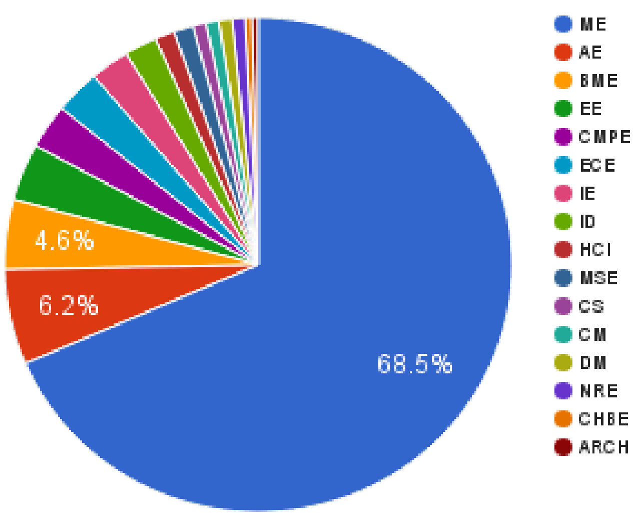

Fig. 2 Breakdown of Majors of All Recorded PIs

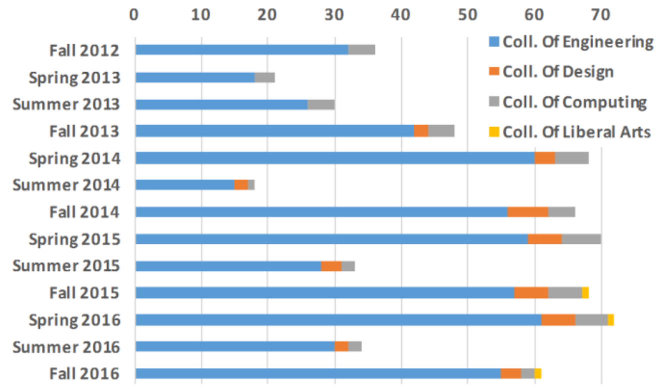

Fig. 3 Colleges of Active Prototyping Instructors per Semester

Fig. 3 illustrates the student involvement per semester by Georgia Tech. The number of active Prototyping Instructors fluctuates between semesters, with high turnout in the spring and fall, followed by a low participation in the summer, reflecting a campus-wide decrease in student presence. Four of Georgia Tech's six colleges have been represented in the Invention Studio's student volunteer base since Fall 2012, and participation of the College of Design and College of Liberal Arts is attributed to increased advertising and a campus-wide initiative for multi-disciplinary collaboration.

A wide variety of users require assistance with a broad range of projects - from holiday gifts to custom linear actuators. To successfully accommodate these project requests, the makerspace offers tools and equipment for processing many different methods and materials. As of the time of writing, the Invention Studio currently has six distinct categories of equipment, each with tools or features that require escalating levels of expertise and finesse. Examples of these categories and the tool offerings are shown in Table 1. Users are introduced to the appropriate tools and techniques for their projects as needed, but PIs generally train users on low-risk tools first. PIs who feel confident about the students' grasp of low-difficulty and low-risk tools provide additional training on higher difficulty tools, as listed below. Please note, the equipment list is not meant as an all-inclusive list of the available tools in the Invention Studio. Rather, it serves as an example of different training paths available.

Table 1 Equipment Available to Students by Difficulty Level

Tool type	Lowest Difficulty	Intermediate Difficulty	Highest Difficulty
Electronics	Soldering and Bread boards	Arduinos, Raspberry Pi programming	PCB milling machine
3D Printers	Afinia UP and UP mini	Makerbot Z18, UP box	Formlab, Hyrel
Waterjet	3 axis control	5 axis A-Jet technology	Advanced materials
Laser Cutter	Standard operating mode	Rotary attachment	Higher focal length lens
Wood-working	Handheld power tools	Planer, Table saw	Jointer, Wood lathe
Metal-working	Hand Tools	Metal Mill/Lathe	6 axis CNC

B. VARIED USER TRAINING OPPORTUNITIES

While access to equipment incentivizes participation of select users, the method of instruction delivery is key to creating a socially comfortable environment. Peer-to-peer learning has been shown to be beneficial in a classroom setting [5]. The Invention Studio takes advantage of the student-run aspect by creating a comfortable environment due to being taught by peers rather than traditional machine shop personnel. The comfort level is also increased by allowing the students to come and learn the equipment on their schedule. Rather than having structured and inflexible training times for students, the Invention Studio offers walk-in training on most of the equipment. To accommodate users who are not comfortable with the informal teaching methods, the volunteers in the Invention Studio offer structured training sessions on the equipment after normal studio hours.

Many times there are students who would like to learn the equipment but do not have a specific project in mind that they could use it for. For those students, the studio offers after-hours workshop events. These events serve to teach the students targeted equipment, ultimately working towards the same final goal of creating something they can take home such as a steel rose for Valentine’s day. There are also events held for specific groups on campus, such as the “Ladies Night in the Invention Studio” for female engineering students. [6]

SAFETY AND TOOL TRAINING

C. PROTOTYPE INSTRUCTOR BASIC TRAINING

The perks granted to PIs, particularly 24/7 access to the equipment, prove attractive to many regular users in the space. Many students are inspired to become Prototyping Instructors, and therefore contribute to the culture of safety. To become a PI, the checklist program must be completed by recruits. A full copy of the Invention Studio current checklist at the time of writing can be seen in Appendix 3. The goal of the checklist program is to ensure a baseline competency for new PIs on all major equipment in the makerspace. The checklist does not indicate mastery or advanced knowledge of the equipment, but it does guarantee an understanding of safety protocols among Invention Studio PIs. The process was designed as a hands-on training tool, where the students learn through practice as has been shown to work in other instructional labs [7]. For each of the sections of the checklist, the potential PI must follow guidelines to create a specific object using key equipment in that category. For example, the woodworking task is to build the GT emblem shown in Fig. 4 by utilizing the relatively low-risk wood shop equipment.

Ideally, potential PIs have already spent time using the Invention Studio’s equipment before attempting the checklist. However, if there is a tool they are unfamiliar with, they must get the appropriate training at least 24 hours before the start of that checklist item. This ensures that candidates do not simply copy what they have just been shown. In times of high machine traffic, students may seek supplemental information from the training videos created for the majority of low-risk tools in the Invention Studio. This “flipped classroom” technique exposes the students to an overview of safety guidelines and procedures, which allows for time in the studio to be focused on the details of practical machine use [8]. Because these videos feature the specific equipment available in the Invention Studio, students can draw directly from the lessons in the instructional videos when machine time becomes available. However, as Ian Charmas points out in his 2014 MakerCon presentation, videos can quickly become outdated [9]. Therefore, rather than solely relying on videos which require significant time, planning, and coordination to produce; an equipment and rules wiki-style site is monitored and populated by the Prototyping Instructors to serve as an up to date reference.

Fig.4 Woodroom Checklist Item

Once a potential PI feels confident enough in his or her knowledge, work on the checklist piece may begin. If they require help from the PI overseeing their room, the work done on the checklist task is discounted, and the recruit must retry that task another day. Following the completion of the task, the PI will compare the student's object with the sample object, and, if satisfied, he or she will sign off on that checklist item. The signature confirms that task was completed correctly, safely, and independently. Following completion of all checklist items and a brief culture-fit interview, the student assumes the role of PI, and begins overseeing the space, maintaining safety for the users and other volunteers.

D. *ADDITIONAL PROTOTYPE INSTRUCTOR TRAINING*

The training does not end once a person completes the checklist and is accepted as a Prototype Instructor. Because students are responsible for the upkeep and making equipment purchase recommendations, it is necessary to ensure specialized knowledge is transferred from one year's class to the next and is not lost when an expert member graduates. Each student has the option to specialize in any of the equipment in the studio to become a "master" of that tool. To do so, the student must complete the guided curriculum outlined by the current masters of their tool of choice (see Appendix 4 for example). The curriculum goes over how to repair the equipment as well as some of the nuances of the tools. Keeping with the theme of hands-on learning and makerspace culture, the apprentice student must complete a complex project using their newly mastered tool to prove their competency and finish their mastership training.

Another form of training offered to accepted Prototype Instructors is in an independent learning format called the "Maker Grant" program. Maker Grants are monetary grants given to any PI who wants to learn how to make a particular item using Invention Studio tools. The applicant PI must write a proposal outlining the budget, idea, and what he/she will learn from the experience. The premise behind funding personal projects is that if a student learns how to build a specific project, then they will be able to pass that knowledge on to the rest of the volunteer group and expand the library of knowledge that can be passed on to the users of the space.

RESULTS OF TRAINING

Efforts to appeal to as many different types of Georgia Tech students as possible have had outstanding success in attracting users and keeping them safe. As discussed previously, tools available in the Invention Studio are used by students and faculty from various engineering and non-engineering disciplines. As mentioned earlier, to keep the barriers to entry as low as possible, students are not required to sign in to use most equipment in the space, and this limits the ability to record demographic usage data. However, the professional printers and waterjet both require user input and therefore can be used to represent the usage of the studio as a whole. Fig. 5 shows the breakdown of unique users of the Professional 3D printers during last four years.

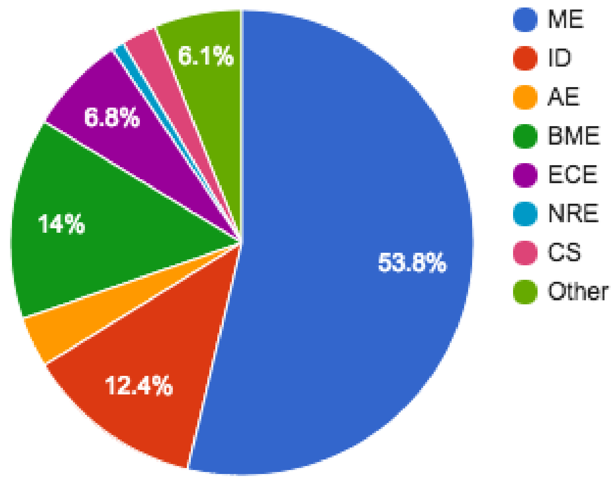

Fig. 5 Professional 3D Printers unique users by Student Major

As shown, approximately half of the total printer use comes from users outside the School of Mechanical Engineering even though the Invention Studio is housed in the mechanical engineering building. See Appendix 5 for a complete list of all majors and the amount of material used.

Besides accommodations for the user of any major, the Invention Studio prides itself on accessibility for a wide range of project possibilities. For diagnostic operations, one of the major tools, the waterjet cutter, requires logging of usage reasons in addition to standard equipment. Usage over the most recent semester, Summer 2016, indicates the diversity of usage in the Invention Studio. This data is shown in Fig. 6, and it provides a quantitative breakdown of the different uses of the Invention Studio. It is important to note that only 2% of the actual Waterjet use is for basic PI training. This exemplifies the impact the aforementioned training videos and other resources have to streamline the training process. Even during a semester with a low academic presence from decreased student population, equipment is still used regularly. Refer Appendix 6 for information on the daily usage of the waterjet from March 2016 to July 2016.

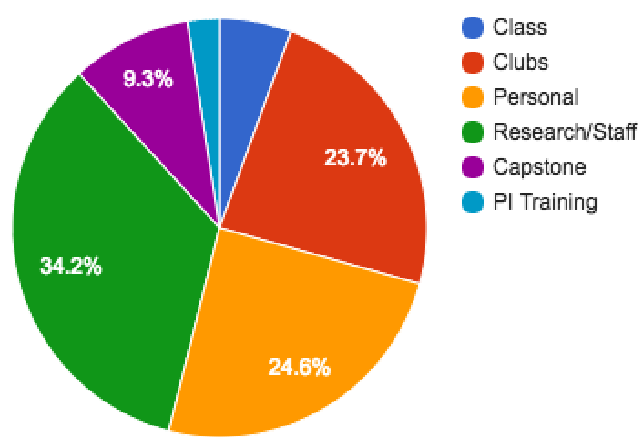

Fig. 6 Waterjet Usage by User Category

The instruction methodology of the Invention Studio seeks to enforce the diversity of projects and users that it naturally inspires. Through outreach events, space combats the pervasive issue of poor representation of females in STEM fields. Among the documented reasons for low female participation in STEM are a lack of opportunity, lack of role models, and a highly unbalanced male-to-female ratio [10]. Ultimately, those factors serve as barriers to hands-on familiarity by intimidation. Through the peer-to-peer training approach of the Invention Studio, some of that intimidation is mitigated. The Invention Studio has many strong female leaders who are Masters and PIs to serve as a role model. A biannual ladies' night hosted by the Invention Studio is specifically targeted towards women. The number of active PIs has doubled since 2013 due to these efforts.

CONCLUSION

The largest cause for concern in a student-run makerspace has always been safety. However, the case study of the Invention Studio shows that with the right training practices in place, a student-run environment can provide a genuinely safe and accessible learning environment. The student involvement and efforts of the Invention Studio have produced an open and welcoming culture for all Georgia Tech students ever since its conception. The specialized training for student volunteers keeps the equipment functional and mitigates the loss of knowledge from student graduation. The Invention Studio has been shown to be a safe environment through peer-to-peer adaptive training practices.

ACKNOWLEDGEMENTS

The authors of this paper would like to thank the following supporters of the Invention Studio and its mission:

The George W. Woodruff School of Mechanical Engineering - particularly School Chair, Dr. Bill Wepfer - for the continuous commitment to hands-on education, and for the belief in and support of the student-run makerspace model.

Dr. Craig Forest, for inspiring the founding members of the Invention Studio, reminding the space of its history and roots, and for the constructive advice and encouragement on this paper. The Invention Studio would not be what it is today without his invaluable input and creative vision.

Dr. Julie Linsey, for the advisement, resources, and time devoted to the Invention Studio and its student volunteers.

Mr. Clint Rinehart, for his expert guidance and mentorship on tool operation, repair as well as for generating the data from the Professional 3D printers reported in this paper.

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Appendix 1: Invention Studio Checklist V1.0

Georgia Tech Invention Studio
ULI Basic Skills Test
Version 1.0 (April 2014)

Name: ______________________
Date:______________________
GT Email: ____________________

Before you start the test:
1. Read this wiki article: http://inventionstudio.gatech.edu/wiki/ULI_Recruitment_and_Training
2. Find a ULI to check you off.
3. Perform the test tasks!

Hints:
-You can take each test separately.
-If you fail a section you will have to wait 24 hours to retake it.

3D Printer Test *Required: Standard .stl file.*	ULI Name: ______________________ ULI Signature: ____________________

1. Obtain the standard .STL file from the ULI training wiki article.
2. Use the slicing software that corresponds to the printer you want to use to slice the file and put it on an SD card. Use a raft and support material.
3. Print out the part.

Wood Room Test *Required: 2x4 board scrap.*	ULI Name: ______________________ ULI Signature: ____________________

1. Go into the wood shop.
2. Take a 2x4 board or another similar piece of scrap board and use the miter saw to cut off a 6” section.
3. Use the band saw to cut it in half.
4. Drill two holes in each piece. Use the drill press for one piece. Use the hand drill for the other.

Georgia Tech Invention Studio
ULI Basic Skills Test
Version 1.0 (April 2014)

Name: ____________________________
Date:____________________________
GT Email: _________________________

Waterjet Test *Required: Standard .dxf file.*	ULI Name: __________________________ ULI Signature: ________________________

1. Take the standard .DXF file from the wiki.
2. Import it into OMAX Layout.
3. Prepare the file for cutting. Use tabs and nesting to make two copies of the default part.
4. Export to OMAX Make. Set proper material settings.
5. Cut out the part.

Laser Cutter Test *Required: Standard .dxf file.*	ULI Name: __________________________ ULI Signature: ________________________

1. Use the standard .DXF file from the wiki.
2. Open the file using Inkscape, EngraveLab, or AutoCAD.
3. Edit the file for laser cutting.
4. Send the file to JobControl.
4. Cut out the part using proper settings for the material you're using.

Appendix 2: First Aid Kit Usage from Nov 1, 2015 - Oct 31st, 2016

Room	# Minor Injuries
Waterjet/Laser Cutters	29
Woodroom	29
Electonics and Metal	36
3D printers	45

Waterjet Room	
Date	**Item**
11/11/2015	Gauze
11/12/2015	Bandage
11/19/2015	Bandage
1/16/2016	Bandage
2/18/2016	Bandage
3/4/2016	Bandage
3/9/2016	Bandage
3/12/2016	Bandage
3/14/2016	Bandage
3/15/2016	Bandage/Antiseptic wipe
3/20/2016	Bandage
3/23/2016	Bandage
3/25/2016	Bandage
3/31/2016	Bandage
4/7/2016	Bandage
4/7/2016	Bandage/Antiseptic wipe
4/7/2016	Bandage
4/12/2016	Bandage/Antiseptic wipe
4/17/2016	Bandage
4/21/2016	Bandage
4/21/2016	Bandage
4/21/2016	Bandage
4/23/2016	Bandage
5/6/2016	Bandage
6/9/2016	Bandage
7/26/2016	Bandage
7/27/2016	Bandage/Antiseptic wipe
9/16/2016	Bandage/Antiseptic wipe
9/22/2016	Bandage

Woodroom	
Date	**Item**
11/4/2015	Bandage
11/7/2015	Bandage
11/9/2015	Bandage
11/17/2015	Bandage
2/4/2016	Bandage
2/12/2016	Bandage/Antiseptic wipe
2/16/2016	Bandage/Antiseptic wipe
2/16/2016	Bandage
3/18/2016	Bandage
3/26/2016	Bandage/Antiseptic wipe
3/26/2016	Bandage/Gauze
3/28/2016	Bandage/Antiseptic wipe
3/30/2016	Bandage
3/30/2016	Bandage/Antiseptic wipe
3/31/2016	Bandage/Antiseptic wipe
4/2/2016	Bandage/Antiseptic wipe
4/3/2016	Antiseptic wipe
4/21/2016	Bandage
4/27/2016	Antiseptic wipe
6/9/2016	Bandage
8/31/2016	Bandage
9/25/2016	Bandage
9/28/2016	Bandage
10/19/2016	Bandage
10/19/2016	Bandage
10/20/2016	Bandage
10/24/2016	Bandage
10/25/2016	Bandage
10/28/2016	Bandage/Tape

Electrolounge/Metal Room	
Date	**Item**
11/1/2015	Bandage
11/1/2015	Bandage
11/3/2015	Bandage/Antiseptic wipe
11/12/2015	Bandage
11/17/2015	Bandage
11/17/2015	Bandage/Antiseptic wipe
11/23/2015	Bandage
11/23/2015	Antiseptic wipe
11/27/2015	Bandage/Antiseptic wipe
12/5/2015	Bandage
1/20/2016	Bandage
1/28/2016	Bandage/Antiseptic wipe
2/10/2016	Bandage
2/11/2016	Bandage
2/15/2016	Bandage/Antiseptic wipe
2/25/2016	Bandage
3/1/2016	Bandage
3/8/2016	Bandage/Gauze
3/19/2016	Bandage/Antiseptic wipe
3/29/2016	Bandage
4/7/2016	Bandage
4/10/2016	Bandage
4/13/2016	Bandage
4/21/2016	Bandage
4/22/2016	Bandage
4/23/2016	Bandage
8/31/2016	Bandage
9/7/2016	Bandage
9/8/2016	Bandage
9/9/2016	Bandage/Antiseptic wipe
9/9/2016	Bandage/Antiseptic wipe
9/20/2016	Bandage
9/23/2016	Bandage
10/4/2016	Bandage/Antiseptic wipe
10/6/2016	Bandage
10/10/2016	Bandage

3D Print Room	
Date	**Item**
11/7/2015	Bandage
11/24/2015	Bandage/Antiseptic wipe
1/29/2016	Bandage
1/29/2016	Bandage
1/29/2016	Bandage
2/8/2016	Bandage
2/17/2016	Bandage
2/18/2016	Bandage
2/25/2016	Bandage
2/26/2016	Bandage/Gauze
2/26/2016	Bandage/Antiseptic wipe
2/29/2016	Bandage
3/5/2016	Bandage
3/7/2016	Bandage
3/9/2016	Bandage
3/12/2016	Bandage
3/17/2016	Bandage
3/20/2016	Gauze/Antiseptic wipe
3/29/2016	Bandage
3/30/2016	Bandage
4/6/2016	Bandage
4/16/2016	Gauze/Tape
4/18/2016	Bandage
4/18/2016	Bandage
4/30/2016	Bandage
5/1/2016	Bandage
6/13/2016	Bandage
8/4/2016	Bandage
8/31/2016	Gauze/Antiseptic wipe
9/13/2016	Bandage
9/16/2016	Bandage
9/20/2016	Bandage
9/20/2016	Bandage
9/21/2016	Bandage
9/29/2016	Bandage
9/30/2016	Bandage
10/17/2016	Bandage
10/19/2016	Bandage
10/26/2016	Bandage
10/26/2016	Bandage
11/19/2016	Bandage
11/25/2016	Bandage
11/28/2016	Bandage
11/28/2016	Bandage/Antiseptic wipe
11/29/2016	Bandage

Appendix 3: Invention Studio Checklist V3.1

Georgia Tech Invention Studio
ISPI Basic Skills Checklist
Version 3.1 (November 2015)

Name:______________________
Date:______________________
GT Email:______________________
GTID #:______________________
(If Applicable) SCC Team :______________________

Please note: If you are accepted as an ISPI or SCC team access holder, your information may be disclosed to other parties for the purpose of requesting access.

Before you start the test:
1. Read this wiki article: http://inventionstudio.gatech.edu/wiki/Recruitment_and_Training
2. Find an ISPI to check you off.
3. Perform the test tasks!
4. Do the 3D printer test last and drop off the checklist with the completed 3D printer part.

Hints:
-You can take each test separately.
-You have to wait 24 hours after getting trained to get checked off.
-If you fail a section you will have to wait 24 hours to retake it.
-You can keep your parts after you get signed off.

Wood Room Test *Required:* *Plywood Sheet* *2"x 4" Stock*	ISPI Name ____________________ ISPI Signature ______________________	Date:

Refer to the examples provided for how the completed product should look. Using only the tools in the wood room, complete the following tasks:

1. Cut out a 3" by 5" plywood rectangle on the Bandsaw. This is to be used for the base.
2. Cut a 7" piece of 2x4 stock using the Miter Saw.
    a. Use the template to draw GT logo on remaining piece of plywood. Then cut out the logo using the scroll saw.
    b. Using the Spindle Sander, smooth the inside curves of the GT.
3. Use the disc sander to round edges on the plywood base.
4. Use drill press to drill holes two holes in the plywood base. (These holes will be use in the next step to attach the plywood base to the 2x4 piece, so choose the location of the holes carefully.)
    a. Select an appropriate drill bit for the wood screws.
5. Use the hand drill to attach the plywood base to the 2x4 using two wood screws
    a. CLAMP!
    b. Create two pilot drill holes in the 2'' by 4'' to prevent wood from splitting.
6. Use whatever tools necessary to attach the GT logo to the 2x4 using two wood screws.
    a. CLAMP!
    b. Create pilot drill holes to prevent wood from splitting.
7. Clean up after yourself.
8. Have a PI compare your copy to the example copies.

Laser Test *Required:* *Plywood Sheet (in a box over banana)* *IS Logo in Vector Format*	ISPI Name ___________________ ISPI Signature ____________________	Date:

The goal is to engrave the IS logo using two different depths and cut out the design.

1. Demonstrate the laser shutdown and startup procedure.
2. Download and bring the IS logo from the recruitment page on a flash drive
    a. It is already in a vector format.
3. Change the Fill & Stroke of the existing lines to:
    a. Deep etch the gear
    b. "Invention Studio" and all shapes in the center are shallow etched
    c. "Design - Build - Play" is not etched
    d. Add a shape of your choice to cut out the design
4. Show the finished product to a PI to be signed off

Soldering Test *Required:* *Perforated board* *LED* *1k ohm resistor* *Wire and Solder*	ISPI Name ___________________ ISPI Signature ____________________	Date:

1. Find and set aside an LED, 1K ohm resistor, a spool of wire, and a spool of solder
2. Turn the soldering iron on and wait for it to reach its optimal temperature
3. Tin the iron using a dab of solder and either a wet sponge or the steel wool
4. Strip a small amount of wire and solder it to the perforated board.
    a. Strip it on both sides so one exposed end goes into the board and the other can be clipped to by an alligator clip
    b. Mark wire either with the color of the insulation or tape as the positive end of the circuit
5. Place the resistor on the board and solder the resistor.
    a. Make sure to place the resistor close enough to the wire soldered in step 4.
    b. Make a solder joint between the wire soldered in step 4 and one of the resistor leads
6. Paying attention to polarity, solder the LED to the board
    a. Create a solder joint between the resistor and the positive end of the LED (negative end will have a shorter lead or flat side)
7. Create another wire like in step 4 and solder it to the negative end of the LED
8. Tin and turn off the iron
9. Wash your hands!
10. Hook up the circuit to a 3.0V power supply on the bench and demonstrate the lit LED to a PI.
11. Desolder all parts from your board and clean up.

Waterjet Test *Required:* *Small sheet of aluminum*	ISPI Name ___________________ ISPI Signature ____________________	Date:

1. Demonstrate waterjet shutdown and startup procedure.
2. Take the test .DXF file from the wiki and put it on a flash drive.
3. Bring the file to the waterjet computer and import it into OMAX Layout. The .DXF file is in inches.
4. Prepare the file for cutting. Use tabs for both parts.
5. Export to OMAX Make and set proper material settings. Be efficient with space on the test material.
6. Note: The material you are cutting is fairly thin, so be careful on how you clamp it so it doesn't bow or shift during cutting. If this happens, your cut was not successful.
7. Test the placement of your cut by going to various spots on the path. Make sure it doesn't go off the edges or collide with any weights or clamps. Also, reduce the amount of material wasted by locating your piece near previous cuts.
8. Cut out the part. When finished, record your information and the pump hours in the logbook.
9. Keep both parts. They will be used to complete the metal room checklist.
10. Show the finished parts to a PI to get checked off.

Metal Shop Test *Required:* *Components from the Waterjet Test*	ISPI Name ___________________ ISPI Signature ____________________	Date:

1. Complete the waterjet test and keep both parts.
2. Use the shear to remove the extra flange on one side of the large plate. After you do this, all four sides will be the same height.
3. Remove tabs and deburr the edges using the belt sander.
4. Place the smaller GT plate on the center of the larger plate. Use a center punch to mark the locations of the two holes in the GT plate on the larger plate. (These holes will be used to attach the GT plate to the big plate later on.)
5. Use the drill press and an appropriately-sized drill bit to create holes for a ⅛" diameter rivet (provided). Drill these holes where you marked them. (Hint: Take the rivet to the drill bit box, and use it to find the right size bit, it should be larger than the rivet.)
6. Countersink the holes.
7. Using the sheet metal brake, bend the large plate into a box. Make sure you bend the box so that the countersinks are on the outside of the box.
8. Use two rivets to fasten the GT plate to the inside of the box. Use the countersunk ⅛" rivets that are provided. If there are none available, regular ⅛" rivets are acceptable.
9. Show the finished box to a PI to be checked off.
10. Have a PI compare your copy to the example copies.

3D Printing Test *Required:* *Example File from Thingiverse*	ISPI Name __________________ ISPI Signature ___________________	Date:

1. Unload filament from UP! Mini/Afinia.
2. Reload filament from UP! Mini/Afinia.
3. Complete and assemble propeller launcher build. Feel free to scale your parts, but all parts must be scaled by the same factor. http://www.thingiverse.com/thing:312971/#instructions The following steps must be displayed to a current ISPI for at least 1 part in the build:
    a. Print setup:
        i. Load a part
        ii. Orient a part (rotate the part so it fits on the platform)
        iii. Scale the part by .8
        iv. Print a part (including a walk-through of the print settings)
    b. Print cleanup:
        i. Remove part from printer
        ii. Clean up workspace
4. Show a PI that your completed and assembled part can fly

Appendix 4: 3D Printer Apprentice Checklist

3D Printer Apprentice Checklist (as of 08/20/2016)
You must complete all mandatory requirements for each printer

Apprentice Name:___________________________________

Masterpiece requirement

Each apprentice must complete a "masterpiece" to be fully considered for a master's position. The "masterpiece" must be of sufficient complexity as to showcase the benefits of 3D printing technology. For any composition to be seriously considered an adequate "masterpiece" the work is required to exemplify, at bare minimum, a singular advanced additive manufacturing characteristic from the subsequent index:

1. Made of more than one material
2. Kinetic or interactive
3. Obvious focus on practicality, usability, or personalization
4. Integrated electro-mechanical design
5. A downright stupendous work of art that makes our jaws drop due to the impossibility of how it actually printed

Mandatory checklists

UP! Mini/ Afinia Printer

- ❏ Unload and reload filament
- ❏ Full understanding of print settings & print procedure
- ❏ Calibrate the build platform
- ❏ Diagnose common print errors
    - ❏ "Clacking" print head
    - ❏ Not extruding filament
    - ❏ Jittering axis
    - ❏ Printer emits long, unending beep
    - ❏ Filament looks "squished" on the build platform
    - ❏ Filament peeling from platform
    - ❏ Filament printing in "thin-air"
- ❏ Disassemble printer head
- ❏ De-clog nozzle
- ❏ Clean gearhead

UP! Box Printer

- ❏ List major differences between UP! Box and UP! Mini

Makerbot Replicator Z18 Printer

- ❏ Unload and reload filament
- ❏ Full understanding of print settings & print procedure
- ❏ Calibrate the build platform
- ❏ Diagnose common print errors
    - ❏ Smart extruder errors
    - ❏ Not extruding filament
    - ❏ Filament peeling from platform
- ❏ Disassemble printer head
- ❏ De-clog nozzle
- ❏ Know rules for printing large parts

Hyrel Printer

- ❏ Unload and reload filament
- ❏ Swap printheads
- ❏ Level print bed
- ❏ Calibrate Z Height
- ❏ Create your own slic3r settings for ninjaflex
- ❏ Prepare bed for printing
- ❏ Diagnose common print errors and live repair if applicable
    - ❏ Not Extruding
    - ❏ Over Extrusion
    - ❏ Peeling from the layer or the bed
    - ❏ Starts building off the plate
    - ❏ Extruding in air

Formlab 1+ Printer

- ❏ Prepare Formlab for printing
- ❏ Print something to exclusive to SLA
    - ❏ Full understanding of optimal part positioning and support structures
- ❏ Post Print Clean-Up

Faro Arm Scanner

- ❏ Startup the Faro arm
  - ❏ Attach Laser Probe to the arm
  - ❏ Connect required cords
  - ❏ Startup the correct software
  - ❏ Ready the program to take a scan
- ❏ Calibrate the faro arm
  - ❏ Calibrate the touch probe
  - ❏ Calibrate the laser probe
- ❏ Demonstrate knowledge of the settings
  - ❏ What is scan rate
  - ❏ What is scan density
  - ❏ What are the proper setting to not fill holes
- ❏ Scan a "complex" object
  - ❏ Scan requires at least two separate scans to get all of the sides of the object
- ❏ Cleanup the file
  - ❏ Combine your multiple scans to create on part
  - ❏ Fill all the holes in the part so that it is a printable file
- ❏ Export your file in an appropriate format
- ❏ Shutdown the Faro arm
  - ❏ Properly pack up components
  - ❏ Turn off everything that needs to be turned off

MCOR Iris Printer

- ❏ Know how to load an .stl file
  - ❏ Know orientation tricks for optimal color reproduction vs model durability
- ❏ Full understanding of print settings & print procedure
  - ❏ Knife/Cutter calibration
  - ❏ Glue Wheel checks & cleaning
  - ❏ How to properly attach the base paper layer to the print bed
- ❏ Diagnose common print errors
  - ❏ Error 28
  - ❏ Error 29
  - ❏ Inkjet problems
  - ❏ How to get Mcor Support to respond promptly (Jeff trick)
- ❏ Know how to reload paper
- ❏ Know how to refill glue
- ❏ Know when the glue line is clogged
- ❏ Know how to purge the glue system

BIBO Printer

- ❏ Explain CURA software options/navigation
    - ❏ How you do move the head/platform using CURA?
    - ❏ How do you save material settings in CURA?
- ❏ How do you move the head/platform using the touch screen?
- ❏ How would you fix a melty goopy mess on top of a print?
- ❏ Unload/reload 2 different types of filament
- ❏ 3D print a vase (single layer wall thickness, spiral formation)
    - ❏ Prepare the platform for proper adhesion

3D Printer Basic Knowledge

- ❏ What are the 6 types of 3D printing techniques?
- ❏ When should stereolithography be used?
- ❏ What are limiting factors for 3D printing?
- ❏ What is the difference between ABS and PLA plastics?
- ❏ When should you direct someone to use the professional 3D printers? (i.e. Stratasys, Objet Eden etc.)
- ❏ What is bridging?

Optional Checklist

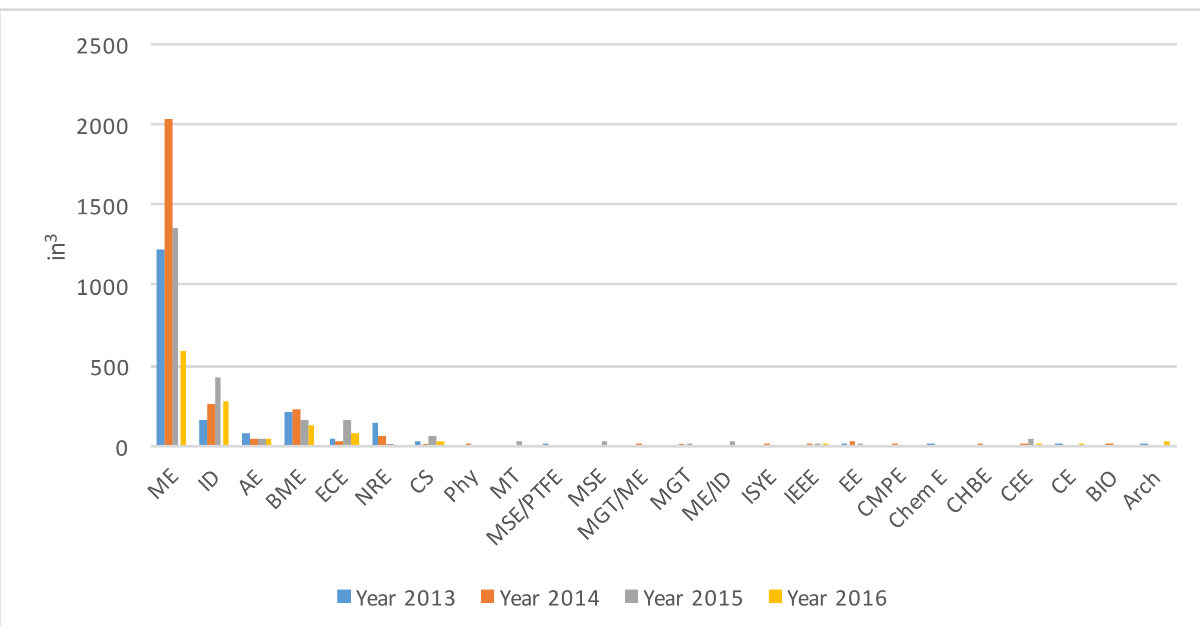
David scanner/ Next engine scanner

- ❏ Using the wiki/guide, scan an object
- ❏ Optional: Print your model in color on the MCOR

Appendix 5: Professional 3D printer material usage

Professional 3D Printers material usage in cubic inches by majors (as of 06/30/2016)

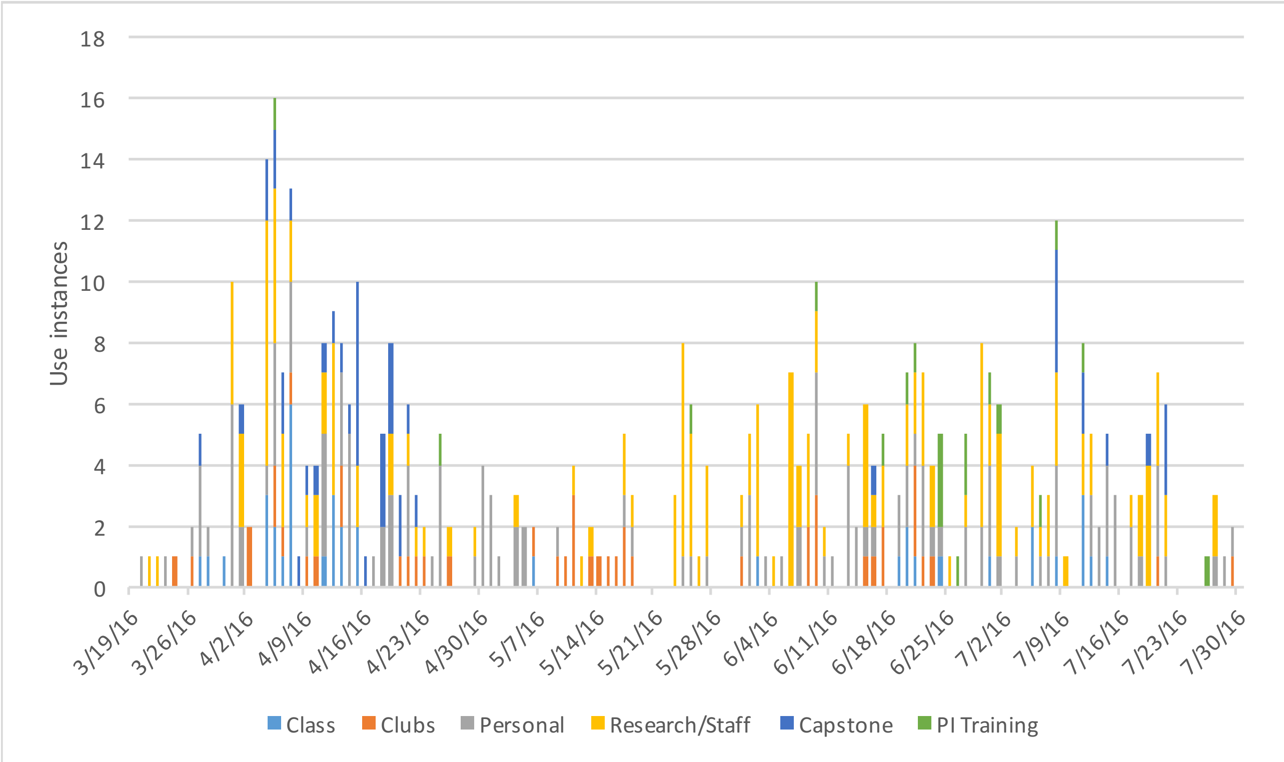
Majors	Year 2013	Year 2014	Year 2015	Year 2016	Total	%
ME	1229.55	2033.25	1358	601.3	5222.1	63.2153506
ID	158.33	260.83	429.9	277.4	1126.46	13.6361931
AE	81.19	52.13	53.66	46.9	233.88	2.83119936
BME	208.78	225.03	157.5	121.53	712.84	8.62917801
ECE	49.13	30.31	164.98	86.32	330.74	4.00372361
NRE	148.16	57.69	20.57		226.42	2.74089345
CS	25.17	18.66	57.59	25.23	126.65	1.53314263
Phy		1.91			1.91	0.02312122
MT			33.66		33.66	0.4074661
MSE/PTFE	0.56				0.56	0.006779
MSE			26.87		26.87	0.32527077
MGT/ME		4.28			4.28	0.0518109
MGT		19.42	14.91		34.33	0.41557668
ME/ID			38.14		38.14	0.46169807
ISYE		1.6			1.6	0.01936856
IEEE		0.18	2.05	0.53	2.76	0.03341077
EE	4.25	33.17	4.31		41.73	0.50515627
CMPE		0.57			0.57	0.00690005
Chem E	1.47				1.47	0.01779487
CHBE		3.05			3.05	0.03692132
CEE		3.02	42.48	0.62	46.12	0.55829876
CE	0.84			3.23	4.07	0.04926878
BIO		0.89			0.89	0.01077376
Arch	10.36			29.35	39.71	0.48070347
Grand Total	1917.79	2745.99	2404.62	1192.41	8260.81	100



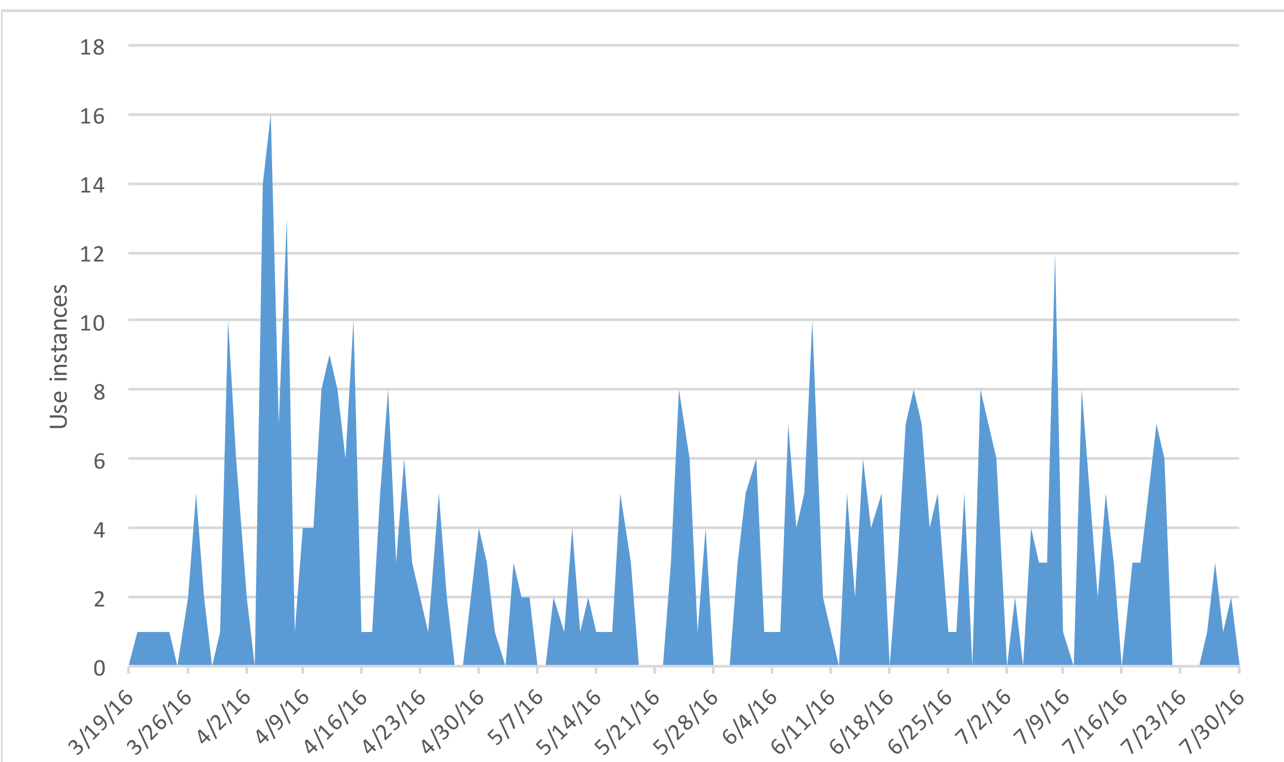
Appendix 6: Waterjet Daily Usage

Daily Waterjet Usage by Category

Category	Class	Clubs	Personal	Research/Staff	Capstone	PI Training
Total Hours	39	47	135	154	45	19



Total Use Instances by Day



Emerging Health and Safety Issues in Makerspaces

ISAM 2016 Paper No.: 22

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INTRODUCTION

Makerspaces have embraced a new generation of tools, such as 3-D printers and laser cutters, which greatly expand shop capabilities and increase interest and participation in fabrication. However, their small size, easy availability, and placement in many non-traditional locations such as libraries, meeting rooms, community centers, homes, and dormitories emphasize the need for evaluating and controlling their potential hazards.

One approach commonly used to control exposures is to follow a hierarchy of controls [1]. Implementation of controls in this order can help ensure inherently safer systems [2,3]:

- Elimination
- Substitution
- Engineering controls
- Administrative controls
- Personal protective equipment (PPE).

This paper reviews health and safety hazards posed by two common makerspace tools - 3D printers and compact laser cutters - and uses the hierarchy of controls framework to present recommendations to minimize effects of these hazards.

3D PRINTERS

Since emerging as a new technology in the 1980's, the term "3D printing" has grown to encompass many additive manufacturing technologies. Though the cost, availability, and user-friendliness of modern 3D printers makes them common in academic makerspaces, they can pose a number of unique hazards. For example, stereolithography (SLA) printers use liquid resin solutions whose health hazards and disposal issues have not been fully characterized, and any operation involving laser sintering not only has laser hazards but also inhalation hazards from the use of small particle size powders (plastic, metal, ceramic etc.) as well as handling concerns associated with combustible dusts. Potential generation of particulates or odors is relevant to many types of 3D printing, and the technology which has been evaluated most thoroughly for these emissions is the one most frequently in use in academic makerspaces: fused deposition modeling.

Fused Deposition Modeling (FDM) involves heating a thermoplastic polymer (often acrylonitrile-butadiene-styrene (ABS) or polylactic acid (PLA)) to at least its softening point and extruding that polymer through a fine-orifice nozzle which is moving in the xy plane. Such a process is inherently prone to potential aerosol generation, and indeed emission of particulates has been identified during FDM 3D printing [4,5]. The vast majority of these are ultrafine particulates (UFPs) [6], meaning their diameter is <100 nm. These particles are potentially hazardous if inhaled as they will deposit in all regions of the respiratory tract and, due to their small size, can pass directly through cell walls from the respiratory system to the circulatory system [7]. Considerable research into the potential health effects of UFPs is underway.

Humans have long been exposed to ultrafine particulates in the form of soot and other products of fuel combustion as well as such common activities as cooking or burning candles [8], and more recently from the use of computer laser printers [9]. It is unclear how much concern should be attributed to data showing emission rates from 3D printing that are comparable to these other commonly-accepted sources in the absence of toxicological studies or regulatory exposure limits.

Although work to-date on emissions of UFPs during 3D printing is limited and has not been uniform in terms of the part manufactured or placement of monitoring devices, the results suggest some general trends. ABS systems appear to emit more particulates than PLA, perhaps due to the higher temperature needed to soften ABS. Some data also suggest that enclosed printers emit lower levels of particulates, that multiple printers running simultaneously increase emissions, and that colored feedstock may emit more UFPs than uncolored feedstock. The heating of thermoplastics also emits volatile organic compounds (VOCs)[4], including the chemical styrene when ABS feedstock is used.

Given the available data, UFP generation is a potential hazard of 3D printing. One immediate way to control this hazard is to substitute PLA for ABS whenever possible to reduce overall emissions. Enclosure of 3D printers is a simple engineering control which can also limit exposure, either by purchase of an enclosed printer or by providing an enclosure post-purchase. It is also important to ensure adequate general ventilation, especially where multiple printers will be used. Monitoring can be performed to indicate if specialized local exhaust ventilation may be needed to further reduce exposure to UFPs. Exposures can also be limited by educating users to minimize the time spent directly in front of 3D printers.

FDM 3D printers can present ancillary hazards as well. 3D-printing processes that require use of a support resin require removal of this support material after printing. This is often accomplished using a caustic surfactant parts washer bath.

The caustic solution's high pH (often 12 or above) is hazardous to the skin and eyes, and the resulting mix of resin suspended in surfactant solution may not be lawful or safe to dispose down a regular drain. Caustic baths can be eliminated entirely if the part can be printed without such a support. If a less hazardous parts-washing material is available, substitution should be considered, but in many cases this is either not practical or introduces other hazards (e.g., d-limonene can be used to dissolve HIPS as a support material, but it is flammable, an inhalation hazard, and a sensitizer). Administrative controls such as user awareness of the hazard and training on a documented procedure for appropriate parts washer bath use are critical. This is of special interest if the location of the 3D printer and bath is not one where chemical use has been common or typical; users of the parts washer bath in such an area may not have needed chemical hygiene training previously. PPE such as safety glasses or goggles and appropriate gloves in the sizes and length to safely do this work must be available. A review of parts washer bath waste must be discussed in advance to ensure to appropriate management and disposal.

COMPACT LASER CUTTER SYSTEMS

Technological improvements and a rapidly growing marketplace over the past two decades have helped transform laser cutting from a largely industrial process to one well-suited for smaller venues such as makerspaces. These improvements have resulted in a proliferation of powerful and increasingly affordable compact laser cutter systems, many of which are small enough to fit on a desk or benchtop. These systems can process a wide variety of organic and soft metal substrates and excel in smooth cutting, engraving, and marking. With easy-to-use design and driver software, compact laser cutters operate much like a traditional printer, making them common tools in many makerspaces. As widespread as compact laser cutter systems have become, they are not without hazards.

Laser Hazards

The use of any laser can pose hazards to operators and others working nearby from beam and non-beam hazards. Beam hazards can result in thermal injuries to the eyes and skin from direct or reflected light; non-beam hazards include fires, electrical shocks, and laser-generated air contaminants.

Beam hazards are determined by wavelength, power, mode and speed (pulsed or continuous wave), and human contact. The American National Standards Institute [10] categorizes lasers into Classes. Class 1 are the least harmful and pose no potential hazard under normal operating conditions, while Class 4 are the highest hazard, capable of causing serious burns to eyes and skin. Most compact laser systems use gas tube CO_2 lasers in the 30 - 50 W range (larger units can exceed 100 W), making them Class 4 lasers. However, due to a combination of enclosures, shielded access covers, and beam interlocks, the overall system classification is generally Class 1.

Laser-Generated Air Contaminants

Highly concentrated beam energy transfer at the substrate interface results in localized melting, evaporation, volatilization, and spattering, which in turn generates primary and secondary aerosolized particulates, gases, and chemical vapors. These products are derived from a combination of the substrate itself (e.g., monomer release from PMMA), pyrolysis, and interactions with the cutting atmosphere. Laser-generated emissions are specific to the substrate material (composition and thickness), process performed (through-cutting, engraving, marking), processing / cutting speed, laser pulse rate, and laser wavelength and power. Information about laser-generated air contaminants comes largely from laboratory experiments with industrial lasers as well as (non-laser) substrate thermal degradation studies.

Several investigators have used enclosed chambers with controlled, monitored exhaust ventilation to evaluate emissions from laser cutting. For example, Pilot et al. [11] measured total particulate (aerosol), nitrogen oxides, and ozone emissions from plasma arc and laser (CO_2) cutting of mild and stainless steel in air. They found that laser cutting produces negligible levels of nitrogen oxides and ozone, and significantly less particulate aerosol, than plasma arc cutting. Subsequent work [12] demonstrated that laser cutting is also "cleaner" than grinding or circular metal saw cutting, that air-assist cutting produces lower emissions than non-air assist cutting, and reconfirmed that lasers generate fewer aerosols than plasma torches. Regardless of substrate, laser-generated aerosols tended to have multi-modal size distributions, centered around a particle diameter of about 0.45 µm, well within the respirable range of particulate matter. The authors further evaluated electrostatic precipitation as a means to reduce downstream particulate concentrations, documenting removal efficiencies > 85% for particulate matter only but not addressing methods to filter or adsorb gases and chemical vapors.

Haferkamp et al. [13] evaluated CO_2 laser cutting emissions from thermoplastics: polyamide (PA), polyethylene (PE), polycarbonate (PC), polymethylmethacrylate (PMMA), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). Aerosol particle size distributions generally had diameters between 0.03 and 0.50 µm, also well within the respirable range. With the exception of PMMA, each of the materials emitted in excess of the (German) occupational exposure limit for total aerosols, with PA, PC, PE, and PP emitting the highest levels. The relatively low aerosol emissions from PMMA and PS, however, were made up for by very high concentrations of gaseous and vapor emissions. Laser cutting of plastics also generated elevated levels of specific hazardous compounds, including hydrogen chloride, benzene, dioxins/furans, and PCBs from PVC; methylmethacrylate monomer from PMMA; styrene and 1,3-butadiene from PS; and polynuclear aromatic hydrocarbons (PAHs) from all materials.

In a non-controlled work environment, concerns about possible occupational over-exposures to emissions from CO_2 laser cutting operations at a manufacturing site led the US National Institute for Occupational Safety and Health to perform a health hazard assessment [14]. Personal and area air samples collected during laser cutting of several materials, including acrylic plastics, generated airborne levels of ethyl acrylate up to 6 times the permissible exposure limit.

A valuable tool for evaluating laser emissions was identified from the Laser Zentrum Hannover (LZH), a research institute in Hannover, Germany [15]. This resource consists of a searchable on-line database for emissions reference data generated from LZH applied research on different laser operations, laser types, and substrates.

In a different context, Pierce et al. [16] reviewed occupational hazards from medical laser procedures, including Nd:YAG and CO_2 systems. Laser- and electrosurgical-generated smoke plumes constitute a significant hazard to which 500,000 healthcare workers per year may be exposed [17]. In addition to hazardous chemicals, medically-generated smoke can also contain viable cellular matter as well as potentially infectious material such as viruses, viral DNA or RNA, and bacteria. While not relevant in most makerspaces, these findings have implications for laser use in biomechanical engineering, biopolymers and films, and related disciplines.

A brief summary of commonly-recognized laser cutting emissions by substrate material appears in Table 1. It is based upon references noted here, from substrate composition, and other (non-laser) thermal degradation studies [e.g., 18].

Table 1. Common laser cutter emissions, by substrate[1]

Metals	Potential heavy metals
Wood (incl. MDF and plywood)	Soot, benzene, formaldehyde, acrolein, PAHs
Polyamide (Nylon®)	Cyanide, nitrogen oxides
Polycarbonate	Benzene, toluene, xylene, cresol, PAHs
Polymethylmethacrylate	MMA and ethyl acrylate, acetone, formaldehyde, phenol, PAHs
Polyoxymethylene (Delrin®)	Formaldehyde
Polystyrene	Styrene monomer
Polytetrafluoroethylene (Teflon®)	Fluorocarbons, HF
Polyvinylchloride	HCl, possible phosgene, benzene, trace dioxins/furans and PCBs

[1] In addition to substrate particulate aerosols

Controlling Laser Cutter Hazards

User Training

The control of any hazard begins with good user training, onboarding, and the development of a culture of safety. Appropriate levels of supervision are critical until new users can demonstrate proficiency in the proper and safe use of any tool. Due to the CNC nature of modern compact laser cutting systems, the “barriers to use” are often low.

Factory-Supplied Safety Features

Compact laser cutters should be purchased as part of a factory-supplied system, including a complete enclosure, beam-interlocked access lid or door, shaded view panel, and a means to provide contaminant exhaust. The device should also carry an electrical safety listing from a recognized organization.

Although the laser hazards of most compact cutting systems are effectively controlled by a combination of features, some institutions still require internal registration for all high power lasers - purchasers should consult their environmental health and safety office. Users and supervisors should also regularly inspect the enclosure and lid, noting any cracking, crazing, or discoloration. If any component is found damaged or broken, the laser cutter should be removed from service, locked out, or otherwise disabled from use, and repaired or replaced.

Fire

Fires are serious and real hazards since small ones (usually self-extinguishing) occur frequently during cutting. Users must remain with the laser cutter during active cutting and shortly thereafter. The air assist feature significantly reduces the risk of larger fires by removing debris from the cut, and some new systems now come with integral high temperature alarms and / or automatic shutdowns.

In addition to a room that meets applicable building and life safety code requirements, every space with a laser cutter should also have at least one portable fire extinguisher close by. Multi-class ABC dry chemical fire extinguishers are common, inexpensive, and effective; however, their fine dry chemical powder will damage sensitive electronics and optics. Carbon dioxide or other clean media extinguishers are strongly recommended instead. Consult the institutional fire marshal or environmental health and safety office for assistance, including fire extinguisher use training as required. Integral fire suppression systems are now also available as an option for some laser cutter systems.

Laser-Generated Air Contaminants

Particulate aerosols, gases, and vapors emitted during laser cutting must be controlled through a blend of careful material selection, proper settings and feed rates, and the application of appropriate ventilation. Makerspace managers are encouraged to carefully review the materials permitted for use, and consider limiting or banning those with the “worst” emission profiles. Since many different materials actually look alike, some organizations have established procedures to ensure that only locally-sourced, approved materials are used.

The containment and removal of laser-generated air contaminants is critical, even for small compact laser cutters. True local exhaust ventilation that meets good engineering practices [19] and ultimately discharges outdoors is the most reliable, effective, and safe method for handling potentially hazardous airborne contaminants. These systems require a thimble-style connection to the laser cutter exhaust port (to avoid back-pressures or excessive suction), ductwork, a fan, and discharge from a high point on the building to ensure good mixing and avoid re-entrainment indoors. Unfortunately, new ventilation systems of this type are generally expensive, and even connecting to an existing system can be costly. In some cases, through-the-wall or -window discharge can be safely accommodated, with certain additional restrictions or pre-treatment controls. Consult the environmental health and safety or facilities engineering department for guidance.

Many suppliers offer recirculating filtration units for laser cutters, offering quick and self-contained solutions for managing exhaust emissions. Users are strongly urged to be aware of the capabilities - and limitations - of these devices, and to consult colleagues and environmental health and safety professionals for experiences with specific brands and models before purchase. These devices rely upon multiple filters to trap and remove particulates, generally followed by one or more canisters of activated charcoal and/or other specialty adsorbents for the removal of chemical vapors and some gases. While particulates can be readily captured by HEPA filters, gases and chemical vapors as well as ultrafine particles require adsorption, neutralization, scrubbing, or other means for removal. Filters improve in efficiency over time, but once the active sites on these other kinds of air cleaners reach saturation, a continuous steady-state release of contaminants will occur back into the room. Self-contained filtration units also require regular maintenance, including periodic replacement of costly filters and canisters; depending upon the adsorption media and contaminants, some of these components may require special handling and disposal as hazardous waste.

CONCLUSIONS

Laser cutters and 3D printers are used in many academic makerspaces to create sophisticated items quickly, easily, and affordably. However, these technologies present some under-appreciated hazards regarding the generation of air contaminants (particulates/aerosols, VOCs) and waste management. Makerspace managers are encouraged to become aware of these potential hazards and implement exposure minimization strategies by following the safety hierarchy of controls.

Although research into potential health hazards of 3D printers and laser cutters continues, there is a decided paucity of data at present. Collaboration between environmental health and safety professionals and academic makerspace managers to gather data on these and other new devices under standardized conditions is recommended. Azimi et al. [4] provide one example of a standardized "test artifact" as designed by NIST [20]. The authors are interested in hearing from others who have conducted studies on these tools or would be interested in collaborating in the future. 3D printers and laser cutters will only grow more ubiquitous with time, and a fuller understanding of appropriate controls for their unique hazards will serve to enhance the safe operation of academic makerspaces.

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Makerspaces and Machine Safety: A Machine Manufacturer's Perspective

ISAM 2016 Paper No.: 23

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I. ABSTRACT

New equipment usage models such as those brought forward in makerspaces and hackerspaces present unique safety challenges. Industry-accepted standards for safe machine design provide guidance in the general case but do not completely address the challenges encountered in group-use environments.

All stakeholders – designers, manufacturers, suppliers, and makerspace operations staff - must consider how equipment will be used by inexperienced operators with little or no training on safe operation. This paper discusses the roles and responsibilities of these stakeholders to provides machines and resources that emphasize safety for users of all experience levels and proposes a framework for both designing and evaluating machines for suitability in a makerspace setting.

II. INTRODUCTION

Machine safety is a responsibility shared by all stakeholders from machine designers to end users. Fig. 1 lists important responsibilities of each stakeholder.

STAKEHOLDER	RESPONSIBILITIES
Regulatory and Enforcement Agencies	• Create and maintain concise and unambiguous design guidelines for safety. Provide fair, firm, and consistent enforcement
Machine Designers	• Identify and mitigate safety hazards • Complete risk assessment
Manufacturing, Production, and Supply Chain	• Ensure product quality and component integrity
Sales and Marketing	• Accurately represent capabilities and performance
Purchasers and Purchases Influencers	• Evaluate appropriateness of machinery for specific usage case
Safety Officers and Makerspace Administrators	• Provide a safe and clean workspace with bright work lighting, First Aid Equipment, etc. • Create and cultivate a safety culture
Instructors, Trainers, and Mentors	• Demonstrate safe workflows to novice users • Critique and correct unsafe use. • Assess proficiency to justify tool access
End Users	• Understand the hazards and associated risks inherent when using the machine • Recognize limitations of skill or knowledge • Provide feedback to other stakeholders to improve safety

Fig. 1 Machine stakeholders and responsibility

It is the responsibility of machine manufacturers to not only interpret safety codes, design standards, etc. but design machines that are responsive to the needs of the end user's environment.

The majority of CNC machines and other digital fabrication tools designed today are intended to be used as production tools. In such scenarios, these tools are used by experienced operators and often in a limited and repetitive capacity (i.e., making the same part over and over again).

Makerspaces and hackerspaces, however, present an equipment usage model that is significantly different from this status quo. Machines will be placed in multi-user environments with novice operators and varied, non-repetitive applications (i.e., prototyping and small batch manufacturing).

Novice CNC machine operators present several safety-related challenges. These include:

- Increased likelihood of setup errors or usage errors
- Failure to recognize programming errors
- Possess limited experience and therefore are not prepared to react to unexpected results such as a machine crash

In addition, a primary goal of makerspaces is to reduce tool access barriers. To achieve this goal, many makerspaces employ an operational model with some or all of the following features: self-paced and on-demand training materials, after hours or 24-hour access to tools and machines, computerized safety training or proficiency assessments, safety officer not on premise to proactively identify/mitigate risk, and peer community mentorship.

While the fundamentals of safe machine design do not change, all stakeholders should recognize how the equipment usage-models of makerspaces should effect machine design, procurement, and support above and beyond industry accepted safety guidelines.

III. A FRAMEWORK FOR EVALUATING MACHINE SUITABILITY FOR MAKERSPACES

Fig. 2 presents a five-level hierarchy for hazard mitigation in machine guarding described by Titus [1]. In this hierarchy, the desirability of the hazard mitigation solution decreases as the level increases from Level 1 (most desirable) to Level 5 (least desirable).

	DESCRIPTION	EXAMPLES
LEVEL 1	Eliminate the hazard with product design	• Eliminate pinch points or crush points • Identify failure modes; design for graceful failure
LEVEL 2	Isolate the hazard with hard guarding	• Add Belt Guards • Use Safety Screws • Isolate Electrical Connections
LEVEL 3	Add additional safeguard layers	• Safety sensors • soft guarding
LEVEL 4	Implement Administrative Controls	• Training • Safety signage • Proficiency assessments
LEVEL 5	Require Personal Protective Equipment (PPE)	• Goggles • Gloves • Protective clothing • Face shields

Fig. 2 Five-level hazard mitigation hierarchy

The five-level hierarchy is a useful framework for machine designers to identify general safety concerns and design appropriate measures to address those concerns. However, this hierarchy does not fully emphasize the unique safety challenges of makerspaces presented by novice users and open access tools.

As an expansion of this five-level hierarchy, the following additional hierarchy is proposed for evaluating machines for makerspaces:

	DESCRIPTION	EXAMPLES
LEVEL MS1	Determine equipment suitability for makerspace environment	• Is the machine's power, size, and performance appropriate for novice operators? • Is the machine end-user serviceable? • Does the machine exhibit "graceful failure" in event of operator error?
LEVEL MS2	Assess usability of machine for novice operators	• Is the control intuitive? • Does the control assume prior knowledge or jargon? • Does the machine have access control?
LEVEL MS3	Provide training resources	• Are learning resources on-demand? • Do they lend themselves to self-paced study? • Are tutorials and instructional materials intrinsic or extrinsic?

Fig. 3 Proposed hierarchy for evaluating suitability of machines for makerspace

The proposed hierarchy can be a framework used by machine manufacturers to design more makerspace appropriate products. It is also useful as a tool for facility stakeholders to evaluate the suitability of a machine for use in a makerspace setting.

IV. APPLYING THE FRAMEWORK: TORMACH PCNC 440 CNC MILLING MACHINE

The Tormach PCNC 440 is a small CNC mill (Fig. 4). This design was an iteration on two previously successful small CNC designs but also addressed feedback from educators, makerspace stakeholders, and other customers who provided insights on the novice user CNC machine experience.

The following examples illustrate each level of the proposed MS design framework in practice.

Fig. 4 The Tormach PCNC 440 CNC mill is a small full-featured CNC milling machine capable of precision metal cutting with a table saw-sized footprint.

MS-1 EXAMPLE: DETERMINING APPROPRIATE MACHINE COMPLEXITY FOR THE MAKERSPACE SETTING

The process of selecting equipment for group-use facilities is often subject to feature creep instigated by stakeholders with competing interests. Admissions staff and talent recruiters want to impress prospective students and staff with state-of-the-art showpiece equipment (Fig. 6). Researchers or project teams may campaign for a specific high-end feature set to leverage the equipment in their own research goals.

Adding equipment complexity increases the training requirements for safe operation of the machine, and as an often unintended result, restricts tool access to novice users. Fig. 5 lists several common negative outcomes instigated by increasing machine complexity.

COMPLEX FEATURE	**NEGATIVE OUTCOME**
Advanced Control Feature (5-axis, etc.)	• Complexity is added to both programming and setup. • Increases likelihood of operator error.
Faster machine speeds	• Operators are not able to recognize or react to programming or setup errors in time to avoid machine crash or other bad outcomes.
High spindle HP	• Higher kinetic energy is destructive to machinery and safety guarding in the event of operator error.

Fig. 5 Examples of negative outcomes associated with increasing machine complexity

The increased risks associated with these negative outcomes must be mitigated by additional training, mentorship, and supervision (Fig. 5). These, in turn, create new barriers that restrict tool access for novice users.

Stakeholders should not ignore the negative outcomes of added complexity when evaluating if a machine is appropriate for the makerspace.

Fig. 6 These large 5-Axis machining centers at Autodesk's Pier 9 corporate makerspace facility are complex to operate. They are not appropriate for novice users to operate unsupervised. Image by Dwight Eshliman Photography, http://eschlimanphoto.tumblr.com/post/92094745681

Fig. 7 summarizes several design engineering decisions made during the development of the PCNC 440 to address safety considerations that are crucial in the novice user experience.

DESIGN FEATURE	**DISCUSSION**
Axis Speed limited to 120 IPM	Operators have time to react to unexpected motion. This is consistent with Mode 2 of CE directive.
Spindle Power < 1 HP	¾ HP spindle motor is comparable in power to 1 HP handheld trim router.
Plastic Tool-changer Bolts	Plastic bolts are designed failure points in the case of an operator instigated toolchanger crash.
"Right-sized" motion components	Axes and spindle motors will stall under excessive loads to protect machine from damage and limit operator safety risk.
Full Enclosure	Sheet metal and Lexan enclosure protects operators from projectiles (e.g., tool or fixture breakage).

Fig. 7 Design considerations of the PCNC 440

MS-2 EXAMPLE: INTUITVE HUMAN -MACHINE INTERFACE DESIGN

PathPilot® was developed by Tormach as an affordable CNC controller for use with Tormach's CNC mill and CNC lathe product lines. Unlike traditional machine controllers, PathPilot takes design inspiration from current Human-Machine Interface (HMI) design thinking to provide intuitive feedback to the operator. This is *discovery learning* and reinforces positive operator behavior [2].

One example of good HMI design is how PathPilot helps operators discover wrong inputs by highlighting incorrect entries in high contrast red color (Fig. 8). This helps novice operators to quickly recognize and understand the error.

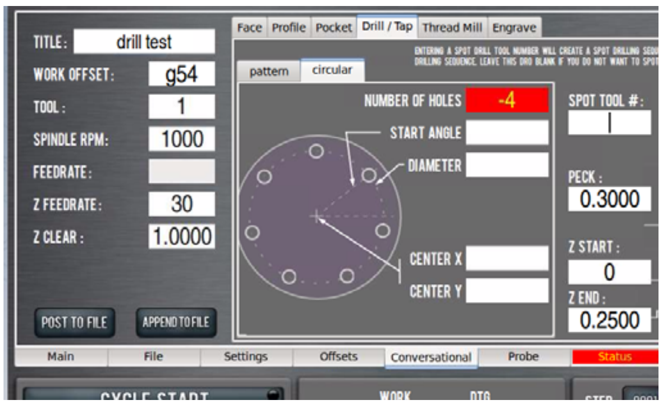

Fig. 8 PathPilot flags incorrect entries for easy recognition.

Another way that we have incorporated discovery learning is with tool tips. These tips appear when operators hover the cursor over one of PathPilot's buttons or inputs (Fig. 9).

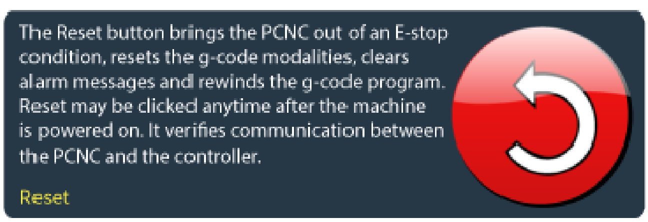

Fig. 9 PathPilot tooltips provide the operator with on-demand information at the point of application. Operators do not need rely on manuals or other secondary documentation to infer function.

MS-3 EXAMPLE: ON-DEMAND RESOURCES

On-demand learning resources reduce learning hurdles. Tormach has built a web-based PathPilot® simulator (Fig. 10). It can be accessed from any device with an internet connection. This tool can be used as an on-demand training tool to assist for novice users. Future plans include integrating the PathPilot simulator with Tormach's YouTube library to demonstrate product workflows.

Fig. 10 Web-based simulator of PathPilot® control system designed by Tormach, Inc.

CONCLUSION

Machine manufactures must work with makerspace stakeholders together to develop products for the unique needs of the makerspace usage model. Applying the proposed makerspace risk mitigation framework put forth in this paper in addition to a general purpose hazard mitigation hierarchy is a is an effective model to reduce barriers to machine usage by novice operators.

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Building a safety-based culture for a student-run makerspace

ISAM 2016 Paper No.: 24

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INTRODUCTION

MIT MakerWorkshop* is a new student-run machine shop on MIT's campus. It was founded with the goal of providing extra operating hours; making access more transparent; and sharing fabrication skills among students. Staffing the shop exclusively with students has enabled these goals, but the large staff of varied skill levels presented a unique need to build a safety-centered culture. Makerspaces run by a small staff ensure consistency in culture because they are present every day. When a shop has 30 or more volunteers, designing a safe culture is crucial for sustainability. A student-run shop with large staff and high turnover needs real mechanisms for normalizing safety.

MIT MAKERWORKSHOP

MIT MakerWorkshop is supervised and maintained by 40+ student volunteers known as 'Mentors.' The student Mentors are responsible for the maintenance and operation of, and the training of Users on all machines in the space. To facilitate these tasks, Mentors are divided into teams responsible for a specific area of the shop or group of machines (e.g. Mill Team is responsible for the upkeep of and training of Users on the mill). Each team has a Machine Master, a Mentor who coordinate the other team members to ensure tasks are accomplished. Furthermore, the Mentors elect students to serve on the executive committee, who in turn make major decisions about topics such as policy, purchasing, and membership, in conjunction with the space's faculty advisor, known as the 'Maker Czar.' Currently, the facility has over 800 trained Users comprised of undergraduate students, graduate students, faculty, and staff.

METHODS

To ensure the sustainability of the space, MIT MakerWorkshop was designed with a safety culture in mind from the beginning. Safety was instilled in the organization by making it central to trainings, transparent standards, and the students' sense of ownership.

Mentors, organized into Machine Teams, provide trainings to Users. Every week, each Machine Team is responsible for posting training hours on the website for easy, transparent training registration. The trainer points out the Emergency Stop (e-stop) location at the beginning of every training. Safe operation is the most important learning objective. Beyond safe operation, each training provides instruction on work piece fixturing; necessary Computer-Aided Design/Manufacturing (CAD/CAM) software and important techniques for proper machine operation. These sessions can take between 30 and 90 minutes depending on the User's level of experience and the machine.

Certification happens at the training if the trainer believes that he or she would be comfortable with the user operating the machine on his or her own during the trainer's shift. Almost all trainings end in certification. This high passing rate relies on MIT MakerWorkshop commitment to continuous learning. Users are encouraged to ask questions at the end of trainings. Every machine has a refresher guide designed to help any user who has completed a training double check their knowledge when they return to the machine.

Safety training is taken even more seriously for the Mentors, student volunteers who have supervisory and management roles to the community. Every prospective Mentor is vetted for their 'safety-mindset'. Fig. 1 shows our acceptance rate for new Mentors. The application process requires at least two existing Mentors to recommend an applicant. Beyond that, every member of the community has a chance to review the prospective Mentors and draw attention to safety concerns. The philosophy is that it is easier and less risky to teach advanced machine skills than it is to instill a safety mindset.

New Mentors complete basic trainings for each machine before receiving a separate 'supervision training'. Supervision training emphasizes the importance of safety, and makes sure that Mentors know what risks to look and listen for. After peer vetting and supervision training, the Maker Czar certifies that the new Mentor is ready to ensure the safety of Users in a supervision check-off. As shown in Fig. 2, anywhere between 5 and 30 new Mentors go through this training in a given semester.

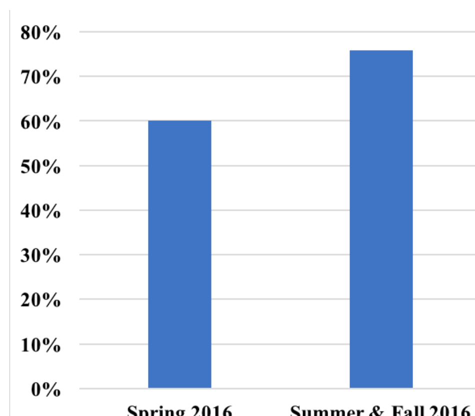


Fig. 1 Acceptance rate of new Mentors based on skill and safety mindset. Note that in Spring 2016, 10 students applied to become Mentors, while for the Summer & Fall semesters, 29 students applied. This Fig. shows that, even though the space was hard-pressed for student volunteers in Spring

* Formerly named MIT MakerWorks

2016, MIT MakerWorkshop did not compromise on our safety-based culture and settled for a lower acceptance rate.

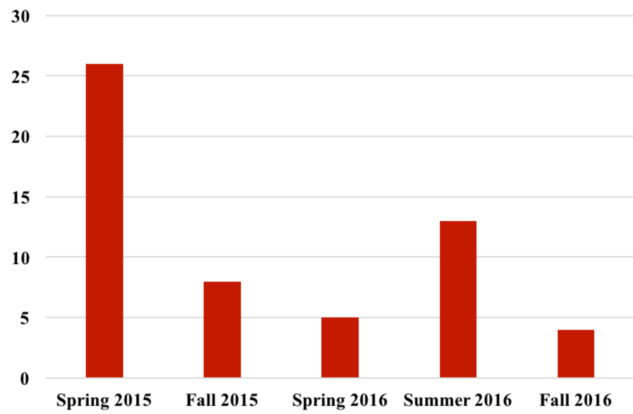


Fig. 2 New Mentors trained each semester. Note that a large number of Mentors (>25) were trained in Spring 2015 prior to the grand opening of MIT MakerWorkshop. After this semester, on average 8 Mentors are trained each semester. In the event of >5 Mentors, multiple supervision training sessions are offered to ensure the average number of Mentors per training does not exceed 5, allowing for a more in-depth and focused training.

Transparent rules and standards are essential to safety in a student-run shop. With a large part-time volunteer staff, miscommunication or confusion is much more possible. Thus, simple and clear rules, written in digestible formats, convey critical safety points like dressing-standards and do's/don'ts. Off-hours access is an important incentive for recruiting Mentors and allowing the space to adapt to User needs. Off-hours access is allowed with specific rules. This policy avoids the needs for exceptions, which can lead to a culture of not following rules. The Off-hours Access Policy is shown in Appendix I as an example of a simple policy guide. Additionally, all machines are classified below the policy as MW1 Class, MW2 Class, and MW3 Class where the classifications are based on the probability of injury when using the machine, and the severity of injury. The least dangerous machines are considered MW1 Class, whereas the most dangerous are MW3 Class. For instance, a User on the 3D printer has a high probability of injury when using the machine, however the injury is not likely to be severe. Fig. 3 shows that the community appreciates the lack of exceptions.

Even with clear policies, off-hours access still has a higher risk of misuse than standard operating hours. To address this risk, cameras are installed and transparent off-hours access rules are posted in the shop. Every Mentor opening the space on off-hours must have a buddy present. That buddy needs to be trained on each class 2 or 3 machine in use. Fig. 4 shows that the clear, public posting of this policy ensures that the majority of the mentors know the policy, know where it is posted, or feel comfortable asking about it.

A universal sense of ownership among the community is critical to safety. If students feel responsible for the sustainability of the space, they will apply the extra effort to operate machines safely. Orientation, or 'Maker Monday,' is the first part of building that sense of ownership. This training is followed by a session on hand tools and proper workpiece fixturing. Every user must go through a 'Maker Monday' to access the space because culture and expectations are the foundation of safety. After orientation, users must get training or certification for each machine in the shop.

At these 'Maker Monday' orientations, the Mentors emphasize an important point that is repeated often in the community: this space exists because students choose to respect the safety policies all the time. There is no tolerance for ignoring Mentors or making exceptions to rules in a safe shop. This mantra is explained to users who find the rule-following tedious. Because the shop is not necessary for any course, Mentors are able to kick out any user for improper or unsafe behavior. Fortunately, no Mentor has needed to exercise that responsibility. When explaining this cultural strength of MIT MakerWorkshop to new users, Mentors set the expectation that new users will not change this record.

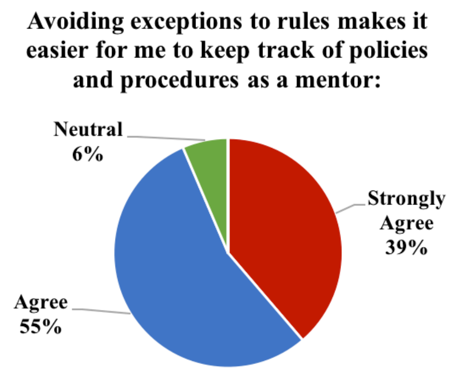


Fig. 3 Shown in this Fig. are the results from a survey sent to all the Mentors of the MIT MakerWorkshop in Fall 2016. Of the 31 respondents, the vast majority of them reported that that avoiding exceptions makes is easier to enforce safety policies. Note that no respondents chose "Disagree" or "Strongly Disagree" to this question.

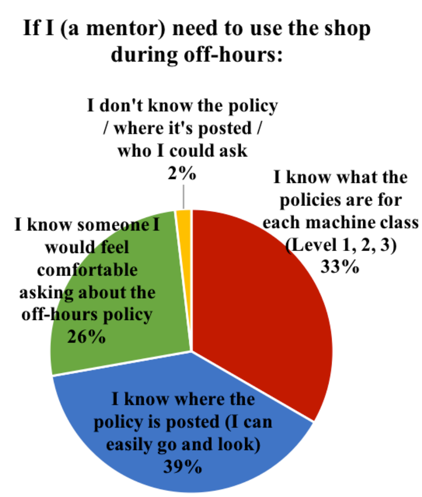


Fig. 4 This Fig. shows the results from a survey sent to all the Mentors of the MIT MakerWorkshop in Fall 2016. Of the 31 respondents, almost all of them either know the policies for operating the machines off-hours, know where the policy is posted, or feel comfortable asking someone about the policy.

RESULTS

In its 1.5 years of operation, there has only been one minor injury at MIT MakerWorkshop. A user sliced his thumb with a putty knife while removing a part from the 3D printer bed. This incident motivated a change in the User shop orientation, 'Maker Monday', to further emphasize the importance of proper fixturing and the hazards of hand-tools. This example of improper tool use was used as a lesson to learn from. At MIT MakerWorkshop, we continue to strive to create an environment where the rules are clear, exceptions are avoided, and Users feel comfortable and empowered to ask questions. By making the safety culture central to every aspect of training, policy, and operation, we hope to ensure MIT MakerWorkshop is a safe space.

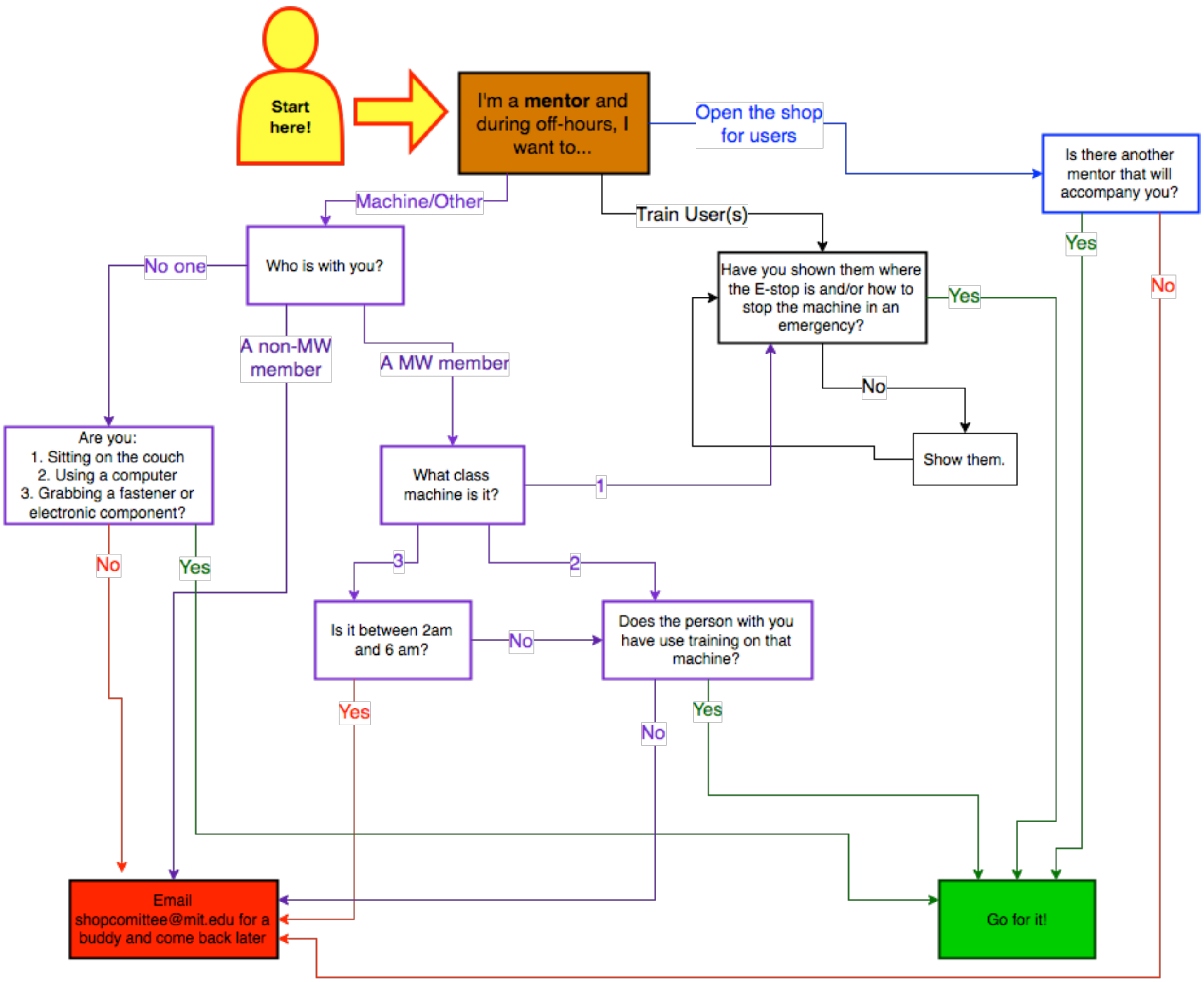
CONCLUSION

At MIT MakerWorkshop, safety is not only a number one priority, but it is emphasized through the community of Mentors who run the space and detailed in policies that are easy to understand and enforce. Additionally, clear, publically posted policy guides allow for the dissemination and retention of safety policies.

ACKNOWLEDGEMENTS

The authors would like to thank MIT's Provost Martin Schmidt, the MIT School of Engineering, the Martin Trust Center, the Richard H. Lufkin Memorial Fund, the MIT Department of Mechanical Engineering, Prof. Dennis Freeman and the MIT Project Manus initiative for providing support, encouragement and funding for the MIT MakerWorkshop. The authors would also like to thank Prof. Martin Culpepper for serving as an amazing faculty advisor (Maker Czar) for our space. Finally, the authors would like to thank all Mentors, past and present, for all their time and dedication into designing, building, and maintaining the MIT MakerWorkshop.

APPENDIX I: EXAMPLE OF SIMPLE POLICY GUIDES - MENTOR OFF-HOURS ACCESS POLICY.



MW1 Class		MW2 Class		MW3 Class	
Machine	*(Probability, Severity)*	*Machine*	*(Probability, Severity)*	*Machine*	*(Probability, Severity)*
Cordless drill	(2,1)	Laser Cutter	(1,2)	Angle grinder	(3,2)
Palm Sanders	(2,1)	Water Jet	(1,2)	Circular Saw	(3,2)
Dremel Tool	(3,1)	Band Saw	(2,2)	Lathe	(3,3)
Jigsaw	(2,1)	shopbot	(2,2)	Milling machine	(2,3)
Non-powered hand tools	(3,1)	cold saw	(2,2)	Drill Press	(3,3)
3D Printer	(3,1)	soldering iron	(2,2)	Belt/disc sander	(3,2)
gen. electronics	(1,1)			Miter Saw	(3,2)
				Bench grinder	(3,3)

EnVision Interns: The Power of Volunteer Student Teams for a Maker Space on a Large Campus

ISAM 2016 Paper No.: 26

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INTRODUCTION

Creating a positive student culture is critical to the success of a Maker Space. At UC San Diego, EnVision: the Arts and Engineering Maker Studio [1] was opened in January 2016 with a mission to support close to 7000 undergraduate engineering and visual art students. For such a large group of students encompassing 10 majors, we did not want to leave the culture formation to chance. A survey of students identified that many users of the space used only a small number of tools in the space, and did not feel comfortable with the rest of the tools in the space. We wanted to create a set of tutorials and example projects that would teach new students how to use the space. We also wanted to create a group of students that could become leaders and mentors to other students.

In its first summer of operation we created the EnVision Intern positions where we asked students to volunteer 10 hours a week during 2 consecutive 5-week periods. We received 205 applicants, and were able to place 99 students based upon their schedule. The Interns where organized into teams of 4-6 students, and a total of 17 teams were created. Each team was provided with a pre-defined topic area, and a student leader was selected for each team. Leadership training was provided to the leaders. Over the summer, tutorials and example projects were created for our 3D printers, laser cutter, vacuum former, and basic shop tools such as soldering, drilling, and sanding. In addition, a LED art display was created to show how many 3D printers would be in use to passersby. Specific class projects were created for a Chemical Engineering and Spatial Visualization class. A survey of the interns was administered to assess the internship experience. So far the students response and enthusiasm was overwhelmingly positive with many students asking to continue working on their projects even after their intern period has ended.

A. ENVISION FORMATION

The EnVision Arts & Engineering Maker Studio is a university maker space built by a collaboration between the Jacobs School of Engineering and the Visual Arts Department of the Division of Arts & Humanities. The space was created to fill a gap in hands-on instruction, and to provide an innovative and inclusive environment where students can build, create, and learn. The space opened in January 2016.

EnVision offers students almost 3000 square feet of reconfigurable open floor-space. Students have access to: 3D printers, Laser cutters, a PCB fabricator, thermo-formers, computers, electronics, and software. Users are also provided with an abundant supply of hand and craft tools from power drills to sewing needles.

An early emphasis of the space was supporting freshmen level hands on classes. New hands on classes had been created over the past 2 years, and the space currently supports 6 departments of Engineering and the Visual Arts department, and has housed up to five freshman classes (nearly 500 students) a quarter. In addition to the classes, EnVision holds “Open Access Hours” where students can use the space for continuing project work or personal projects.

The logistics challenge of supporting such a large group of students from different majors was apparent early on. We created online tutorials for the equipment with required test questions to ensure they were read. Custom software and hardware was created so that each major piece of equipment had a Student ID card swipe on it. A machine would become operational only if the student had completed the online training for that machine. To augment the online training, training sessions were held during lab sessions. Yet despite these initiatives, as discussed below more needed to be done to create the culture of inclusiveness and empowerment we sought.

B. DESIGN THINKING STUDY

The authors are the directors of the EnVision Studio, and we had specific objectives and priorities when we opened the space. However, unbeknownst to us, we had overlooked a key issue. These oversights came to light when we had the space evaluated by a team of students in a Cognitive Science class on human centered and design thinking, Cognitive Design Studio - COGS 102C taught by Dr. Nancy Renner. A team of 5 Cognitive Science students used the Design Thinking approach, which focused on observation, interviews with users of the maker space, and empathy with the user. The team interviewed a random set of 33 students, and asked questions about their usage and interactions in the EnVision Maker Studio. Of the 33 students, 15 indicated some level of unease with the tools and the layout of the EnVision Maker Studio. Some recorded keywords included:

Reluctant	Uncomfortable	Cautious
Not sure who to ask	Trouble locating	Confused
Not sure if allowed	Disoriented	Don’t want to touch
Intimidated	Not obvious	

The uncomfortably with the space was a common theme among students who were introduced to the space in a class. These students were familiar with the tools required in their class, but were unfamiliar and intimidated by the rest of tools and space. We had overlooked this issue, since some of our prior experience was in a smaller space where all students took the same introductory design class that familiarized the students with the tools of the space.

The cognitive science students started to improve the space by adding large signage to explain different areas. However, a more significant contribution of the study was identifying the problem. We felt that to truly feel part of a space students need to build projects. Our objective became to create a set of modules or "warm-up" projects that would introduce student to various aspects of the space. We wanted to inspire students to create and provide tangible examples of how students can become involved. The cognitive science students' insight became the motivating factor for use to create the intern program and make our new space more welcoming to students of all abilities.

C. INTERN RECRUITMENT

In a smaller maker space interested students typically find their way to the space and become involved. However, our space was large and new. So many potential student volunteers did not even know that the space existed. We also wanted to make sure that we had representations from all departments that used the space. Accordingly, we emailed all 6266 Engineering undergrads and 418 Visual Art undergrads, with an invitation them to volunteer to become EnVision Interns.

Many of the students were taking summer classes on campus, which are scheduled in 4-weeks sessions, Summer Session I (SSI) and II (SSII). We asked that each applicant commit to volunteering 10 hours a week during at least one of these sessions.

We received a total of 205 student applications. The application had a number of questions about areas of expertise and prior project experience. However, due to the large number of applicants, we did not have the time to review all of these details. It turns out that the most important applicant information became: schedule, project preferences, and interest in being a team lead. An algorithm was used to match up students based on project preference and mutual availability. We ended up admitting 59 students for SSI and 40 students for SSII for a total of 99 EnVision Interns. The primary reason for not admitting a student was schedule compatibility.

D. TEAM LEADERSHIP

For each project, a team leader was selected who self-selected on their application that they were interested in being a team leader (36% of the applicants indicated an interest in becoming tam lead). In the instances where multiple team leaders indicated interest, leaders were chosen based on project scope and the prior experience and skills. Leaders were responsible for coordinating the team effort and reporting progress in a weekly meeting of all team leaders. Leaders were also given access to the door code for the studio for after hours work with their team. Towards the end of the Summer Session I it became apparent that some of the team leaders found out that it was not that easy to be a leader. To address this issue, a leadership seminar has held for team leaders of both sessions run by Dr. Ebonee Williams, the Director of the Gordon Leadership Center on campus. During this seminar, SSI leaders expressed some of their experiences and struggles with each other and the leads for the upcoming SSII. Two of the prominent struggles were scheduling and personality differences. Dr. Williams led the students through exercises that highlighted the effects of expectations and differing communication styles. Students from both Summer Sessions reported benefitting from the seminar, with SSI students all indicating that they wished they had the seminar before their internship began.

E. PREDEFINED PROJECTS

To get projects quickly off the ground, project areas were predefined. Initially 15 project areas were listed in the intern application, and based upon responses 9 projects were selected for SSI and 7 projects were selected for SSII (with some projects having more than one group). The project areas were:

- On-line Tutorials: video and written tutorials for 3D printers, Laser cutter, and vacuum former, and drill press.
- Mini-projects: students develop some expertise on the same equipment as the online tutorials.
- Integrated project: students combine the use of all of the equipment to create a project
- Class projects proposed by 3 faculty members.
- Collaborative workspace design: students design a 700 sq. ft. extension of EnVision.
- An EnVision Wiki page to track all of the intern projects and progress as a showcase of student work
- Display case of 3D printed examples of 3D printer options.
- Parts vending machine to supply EnVision users with consumables.
- Weekend Access Alert system, to alert the supervisor of the EnVision Maker Studio that students are waiting outside of the locked doors to get into the building.
- LED Window Art Display: students design an interactive display to highlight activity in EnVision and incite curiosity.
- Laser Cutter Examples: students characterize various materials and laser strength for engraving and cutting, and build a display case of examples.
- Vacuum Former Enclosure: students build an enclosure to assist in the removal of noxious fumes emitted while thermoforming.

F. INTERN SURVEY RESULTS

An anonymous survey was administered to the EnVision Interns at the end of the summer. Of the 99 EnVision Interns 59% (n=58) completed the survey. The breakdown by major is shown in Table 1.

Table 1: Breakdown by Major

	EnVision Interns	Email Solicitation
Engineering	85%	94%
Visual Arts	11%	6%
Other	4%	0%

Of the engineering students the breakdown by gender and Under Represented Minority (URM) based upon Ethnicity is shown in Table 2.

Table 2: Engineering Student Breakdown

	EnVision Interns Engineering Majors	Engineering Student Body
Gender	41% Female	29% Female
URM by Ethnicity	13%	15 %
Non-Native English Speakers	31%	Unknown

Motivation for applying for the internship and what was ultimately found to be most rewarding is shown in Table 3.

Table 3: Motivation

Question	Most Common	2nd Most Common	3rd Most Common
What was the 1st reason for applying to the Intern program?	Learn new technical skills (31%)	Work on interesting projects (24%)	Develop better hands-on experience (19%)
What was your 2nd reason for applying to the Intern program?	Build resume (33%)	Learn new technical skills (29%)	Work on interesting projects (17%)
What was the most rewarding part of the program?	Work on interesting projects (26%)	Meet other students / network (17%)	Develop better hands-on experience (19%)

Each team of interns had a student leader. In between summer session 1 and 2, a leadership training session was held for the student leaders. The following question relating to teamwork were rated on scale of: Very Poor=1, Poor=2, Average=3, Good=4, Very Good=5. The average ratings are shown in Table 4.

Table 4: Teamwork and Leadership

	Summer Session 1 (pre leadership training)	Summer Session 2 (post leadership training)
Rate the teamwork in your group	3.94	4.28
Rate the student leader in your group	3.82	4.48

Students were asked to rate their making ability compared to an average student before and after the internship. The rating levels were: Significantly Below Average=1, Below Average=2, Average=3, Above Average=4, Significantly Above Average=5. The data was categorized in 3 groups based upon the pre-internship ranking: Low (Significantly Below Average and Below Average, Medium (Average), and High (Above Average and Significantly Above Average). The results are shown in Table 5.

Table 5: Self-Assessed Making Skills

Pre-internship making skill	Before the Internship experience	After the Internship experience	Change
Low (n=13)	1.77	3.77	2.00
Medium (n=31)	3	3.94	0.94
High (n=14)	4.14	4.21	0.07

Additional questions included plans after the internship, and overall recommendation. These are shown in Table 6.

Table 6: Post Internship Plans and Overall Recommendation

	Yes	No or Unsure
Do plans include future involvement with the Envision Space?	90%	10%
Would you recommend the EnVision Intern Program?	97%	3 %

Selected quotes about the Best Part of the Program:

- “Gaining hands-on project experience while working with a team of motivated individuals”
- “Feeling part of a team outside of our project group and connecting with the instructors, also knowing that this was a program enabling me to grow without intimidation.”
- “The teamwork and how diverse each team was.”
- “I loved working with other students who were as passionate as I was to contribute to UCSD's makers studio. “
- “Being able to actually work on a project that would bring real benefits for others was an enriching and exciting opportunity.”

Selected quotes about the Areas for Improvement:

- “more information from the instructor about the project in the early stages”
- “More teammates, more time, and bigger budgets.”
- “More time to work on a project and more complex projects.”
- “Needs to be more interaction and help from the maker space staff with each group.”
- “Have more time to complete the projects”
- “More faculty and team mentorship and organization”

G. INTERN SURVEY DISCUSSION

Tables 1 and 2 describe the student population in the internship program. We were successful in attracting visual arts students to the maker space with almost twice as much representation as in the targeted student body; an increase from 6% to 11%. We were very successful in increasing the number of female engineering students raising the number from 29% in the engineering student body to 41% among EnVision Interns from engineering majors. However, we did have a 2% drop in the percentage of URMs. We did not specifically target URM students and organizations in our solicitations, but plan to do so for the next iteration.

Development of hands-on skills was an important motivating factor for joining the internship program and significant success was made in achieving these goals. As seen in Table 3, a combined 50% of the students listed as their 1st reason for applying to the internship program as learning new technical skills and hands-on experience. In Table 5 we see a significant increase in students' self-assessed making skills. Students who entered the program with below average skills increased their average skill level to above average. As expected students coming in with a higher skill level did not have as much room to grow, so their increase was lower.

Teamwork is always an important factor in group projects. While students did not initially list the team experience as a top reason for applying for the internship program, it did rise to a 2nd Most Common rewarding aspect of the program as shown in Table 3. As described in Section D, it became apparent during SS1 that students leaders were having a difficult time, and leadership training was implemented before summer session 2 for both new and old student leaders. Table 4 illustrates the effectiveness of this training with meaningful increases of rating for both leadership and teamwork in summer session 2. The overall high rating for teamwork is significant especially due to the 31% of engineering students being non-native English speakers. Prior work [2] showed that non-native English speakers rated team experiences as especially high even when it was difficult for them to communicate. In this study too the non-native English students related the teamwork in their group as higher than for native English speakers (4.22/5 vs. 4.03/5)

An area with room for improvement related to faculty and staff mentorship, which is shown in some of the student comments. We quickly realized that the number of EnVision Interns overwhelmed the ability of the faculty and staff director to closely mentor. For next summer we plan to have a graduate student and experienced undergraduate students workers help student teams with their projects.

Overall the internship program was highly successful with a 97% approval rate by the students, and with 90% of the students planning to stay involved wit the maker studio.

H. TUTORIALS

Reading a tutorial is not enough to fully gain competence with a device. We have found that warm-up projects are an effective way for students to learn how to use machines and gain confidence in a space. Many students come to college with very little hands-on experience, and can become quickly intimidated if thrown into a team project with more experienced students. Indeed in a prior introductory design class [2] we found that building a model pendulum clock was one of the more popular aspects of the class and key to getting students working effectively on a more complex team project.

We wanted EnVision to be a space where students felt empowered to use tools and to remove barriers to creating. To facilitate this, EnVision uses an online tutorial system that certifies students on specific machines. Students are required to watch a brief tutorial on machine safety, and take a corresponding quiz. After passing the quiz, students can use their student ID to access any machine that they've been certified for. The first tutorials we created used existing YouTube videos that weren't specifically catered to the EnVision machines. Students found the videos difficult and the quiz hard.

The Online Tutorial group was charged with creating original video and quizzes [1] that prepped students for safe machine use, rather than simply challenging them to pass a test.

I. LED WINDOW ART DISPLAY

We wanted our space to highlight abilities to use technology in a wide range of uses. We also wanted to create a buzz on campus about the space. EnVision is housed in a building with windows facing a walkway, so we repurposed the upper portion of the windows to build a LED display that would not impede light entering the room, but still be visible to people walking by the building. As with many maker spaces, the availability of 3D printers can become an issue. Accordingly, our display will provide information about the current percent usage of 3D printers. While we could have conveyed this information as simple text or a webpage with usage status, we challenged our students to integrate art with engineering.

Fig. 1. LED Window Display of 3D Printer Animation

This project was inspired by the Live Wire display created by Natalie Jeremijenko [3] which was a spinning wire that would rotate based on the speed of the internet connection providing a visual and audible background signal indicating the bandwidth of the internet connection (in 1995 this was often an important factor). We also were inspired the UCSD Stewart Collection [4] of art projects that used moving text including Bruce Nauman's Vices and Virtues and Barbara Kruger's moving text display. The EnVision Interns and a prior student volunteer created an animation of a 3D printer.

The students are continuing the project and adding current sensors to each 3D printer in the space, so that the speed of animation will increase as more 3D printers are in use, as shown in Figs 1 and 2.

Fig. 2. Outside View of 3D Printer Animation

J. MINI PROJECTS

On-line tutorial are used to certify that students can use a 3D printers, laser cutters, and electronic tools safely. But true engagement requires actual use. Accordingly, teams were tasked with creating mini projects, which are 1-5 day projects that would guide students through the use of the equipment. These mini-projects are described in more depth [5].

One mini-project involved laser cutting the UCSD mascot of a Triton, 3D printing a base, and creating a simple LED circuit as shown in Fig. 3.

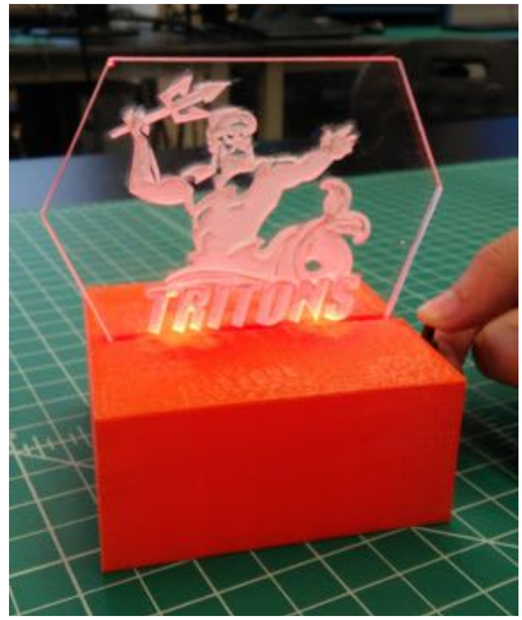

Fig. 3 UCSD Triton Mini- Project

Another project was to create a tutorial on how to use parametric CAD to use a laser cutter foamcore to create 3D folded shapes. The team used a thickness parameter so that a flat patterns could be automatically adjusted for varying thickness of the foamcore. Some of the final folded shapes are shown in Fig. 4.

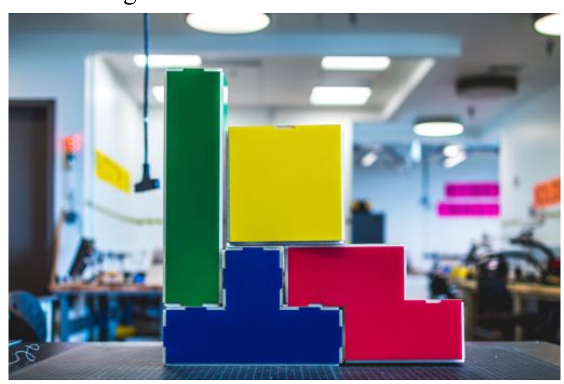

Fig. 4. Folded Tetrimino Shapes Laser Cut from a Parametric CAD files.

A third project integrated a range of skills to build a drawing robot. Fig. 5 shows a vacuum formed top of the robot and Fig. 6 shows the mechanism of the drawing robot.

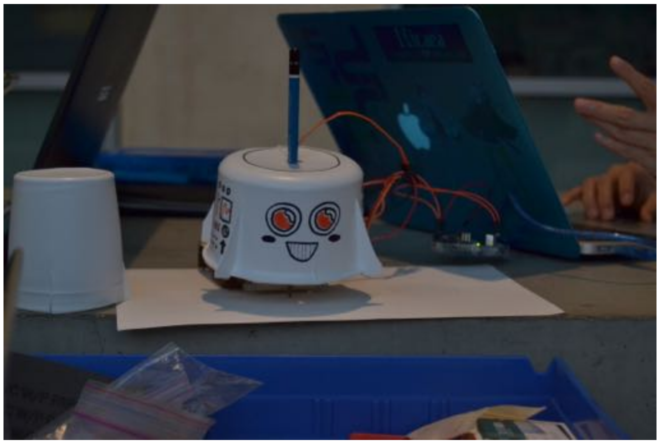

Fig. 5. Vacuum Formed Top for Drawing Robot.

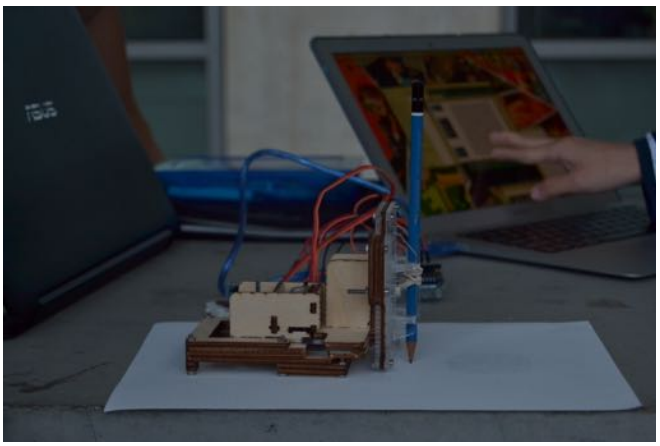

Fig. 6. Drawing Robot Mechanism.

K. LESSONS LEARNED

One of the key lessons learned was that the workload to supervise a large number of teams was significantly more effort than anticipated. We did try to hire 2 recent graduates to help oversee the teams, but one received a job offer early in the summer and the other was off campus for the first Summer Session. The assignment of team leaders was a good way to quickly get started, but next time we will provide leadership training early on. In future years, we will be better prepared for the workload and hopefully have more experienced students to guide new teams.

But overall the biggest lesson learned is that there was a deep well of student initiative and passion for building and creating a student centered maker space. Student volunteers are leading our efforts in terms of creating on inviting and empowering culture for our maker space.

L. SUMMARY

We had a challenge of kick starting a culture in our maker space and forming a group of motivated students to be stewards of the space and create tutorials and resources for other students. In a smaller campus this may have occurred organically. However, in a large university there was the need to consciously create student leaders who would form the positive culture of inclusiveness we desired. When we sent out the solicitation for student intern volunteers we did not expect over 200 applications for this unpaid position. This is an indication of an unmet need among our students for participating in hands-on projects. Ultimately we accepted 99 students who were placed in teams and worked in 17 teams. The number of female engineering students was significantly higher than the engineering student body (41% vs. 29%), but the percentage of URMs dropped from 15% to 13%. The program also attracted visual art students to work side by side engineering students at a rate of almost twice their representation on campus relative to engineering majors (11% vs. 6%). The faculty and staff were initially overwhelmed by the load of supporting so many projects. However, we did adapt and effectively utilized student leaders in each group. Leadership training was shown to improve effectiveness. The students were highly motivated and a survey of the interns indicated a high level of increase in making ability. Of the intern group, 90% indicated an interest in continuing involvement for the space, and some have continued as volunteers during the school year. Overall 97% recommended the intern experience. We plan to repeat the intern program in the coming summer, and utilize lessons learned.

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AKNOWLEGEMENTS

There are so many we would like to thank for supporting getting EnVision off the ground, including: Dr. Ebonee Williams, Director of Gordon Leadership Center for her leadership training; Dr. Nancy Renner and her Cognitive Science 102Vstudents for evaluating use of the space; Joshua Jain a recent UCSD graduate who mentored student teams; Sebastian Bommer an early student volunteer who laid the foundation for the LED Window Art Display, and all 99 EnVision Interns.

Coaches and Their Impact: One Model for Empowering Teaching Assistants in an Academic Makerspace

ISAM 2016 Paper No.: 27

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ABSTRACT

This paper presents one possible staffing model for academic makerspaces, and hopes to spark ideas about how to empower student workers elsewhere. The Product Realization Lab, or PRL, is Stanford University's most heavily used makerspace and teaching lab. In the previous year, more than 1,000 students of all backgrounds used the PRL. At the heart of this academic makerspace is the team of 18-20 Teaching Assistants who help to operate and oversee open work sessions in the lab. In this paper, the unique role of Teaching Assistants as design "coaches" will be discussed. Benefits of the staffing model for both Teaching Assistants and their students will be presented. The paper includes a qualitative examination of reflections essays from students in an introductory design and manufacturing course, in order to determine the impact of the Product Realization Lab and Teaching Assistant "coaches" on the students' work. Ideas for improvement of this academic makerspace will be presented.

INTRODUCTION

The Product Realization Lab is an academic makerspace open to all students at Stanford University. The Lab facilities cover 9,000 square feet, and include 5 areas of focus – a woodworking lab, machining lab, foundry, welding/sheet metal room, and rapid prototyping lab. Of the more than 1,000 students who used the space in the previous year, about 30% came from departments other than Mechanical Engineering or Product Design. Each year, the PRL employs 18-20 graduate students as Teaching Assistants (TAs) to help manage the lab. A team of 5 dedicated academic and administrative staff teach courses, train Teaching Assistants, and direct outreach. In addition, a dedicated faculty member teaches several classes in the PRL, the most heavily subscribed of which is the ME 203: Design and Manufacturing course. Fig 1. shows a Venn Diagram which has been adapted from a recent review of academic makerspaces, and shows how the Product Realization Lab model compares to other universities [1].

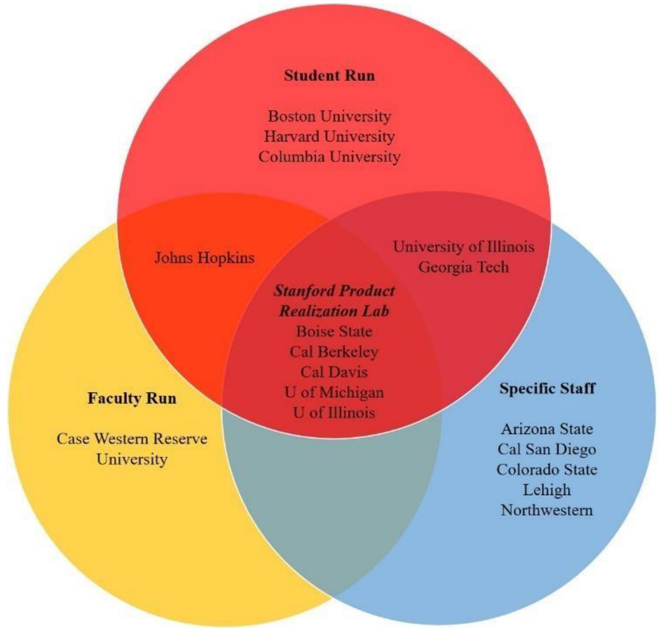

Fig. 1 Venn Diagram comparing different operational models for makerspaces, adapted from [1].

TEACHING ASSISTANT MODEL

One unique aspect of the Product Realization Lab model is the high level of responsibility and reward given to the Teaching Assistants. Each Teaching Assistant is provided a full tuition allowance from the university, as well as a stipend for living expenses. This effectively covers the cost of each Teaching Assistant's Master's Degree.

All PRL Teaching Assistants are graduate-level students; most – but not all – also received their undergraduate education at Stanford. Most TAs come from an undergraduate background in Mechanical Engineering or Product Design, but several other backgrounds are represented, including Business and Civil Engineering. One factor is common to the Teaching Assistants: they have all spent extensive time in the Product Realization Lab working on their own engineering and design projects.

As academic makerspaces at universities across the United States move toward various student staffing models, the graduate-level Teaching Assistant model at the Product Realization Lab warrants further exploration. Other models include the use of student volunteers and undergraduate hourly staff. At Stanford, undergraduate course loads and restrictions on hourly work limit an undergraduate's ability to staff the Lab, and it has long been the belief of the Lab's Director that all student workers doing the same work should be compensated at the same level.

The most significant "product" of the Product Realization Lab are the alumni Teaching Assistants, and there is significant energy and effort that goes into their training and cultivation of skills. Given their critical role as design coaches and mentors, it remains the position of the PRL Leadership Team that graduate student Teaching Assistants are the most appropriate staff for this makerspace.

A. RESPONSIBILITIES

Teaching Assistants in the Product Realization Lab are entrusted with a high level of responsibility. They sign a one-year contract to work with the PRL, and more than 90% return to the TA position for a second year. Their duties begin with two weeks of full-time training, before the academic year begins.

During this training period, the Teaching Assistants learn about safe operation of machines and machine maintenance. They practice teaching 4-hour "structured laboratories" which introduce students to the processes of milling, turning, welding, sandcasting, and finishing. They are trained in First Aid and CPR by the American Red Cross. During these two weeks, the Teaching Assistants form a community that will serve them throughout the school year, by learning how to work together and how to complement each other's diverse skills.

Once the academic year begins, PRL Teaching Assistants are expected to work 20 hours per week in the lab. As a team, they keep the lab open in 4-hour blocks from 8:30am – 11pm, 6 days each week. The Teaching Assistants' official priorities are to 1) supervise student safety, 2) protect the safety of lab equipment, and 3) help all students successfully complete their design projects. In addition, TAs are responsible for grading students' work, and are expected to spend 2 hours each week coaching a small group of novice design students.

There is a range of programming offered in the Product Realization Lab, and TAs are an integral element in each offering: demonstrations, workshops, structured labs, and courses. For example, in Spring 2015, Will Tucker (MSME '15), a Teaching Assistant in the Product Realization Lab, created a course entitled "Scan, Model, Print! Designing with 3D Technology" through the Stanford Student Initiated Courses program. Creating this course afforded Tucker the experience of teaching a group of students the new material that he created. Learning to work with a diverse student body is a skill that all of the Teaching Assistants in the PRL earn through their many hours of engaging with students.

With these responsibilities, the position of a Teaching Assistant in the Product Realization Lab is both physically and mentally demanding. The graduate students who hold Teaching Assistant positions in the PRL also take courses, but they generally do not participate in research lab work. The TAs are encouraged to consider their work with students in the PRL not as just a job, but rather as much a part of their education as a research thesis would be.

B. COACHING

There are twenty courses that are taught in, or supported by, the Product Realization Lab [2]. The most heavily subscribed of these courses is ME 203: Design and Manufacturing, in which more than 200 students are enrolled each year. For many of these students, the PRL is their first exposure to making.

As such, a primary goal of the Product Realization Lab is to teach students to learn resilience in the face of failure. The National Research Council has argued that in the 21st Century, a 'fluency' approach instead of a 'skills-based' approach is necessary in education. Teachers must "empower people to manipulate the medium to their advantage and to handle unintended and unexpected problems when they arise." [3] How does the Product Realization Lab accomplish this goal?

It starts on the first day of class. In ME 203: Design and Manufacturing, Professor David Beach asks all 80 students to stand up, raise their arms, and yell, "I failed!" After several repetitions, some students laugh and others cast nervous glances at their classmates. This exercise helps set the tone that failure is not only commonplace, but that learning from the challenges is something that is celebrated in ME 203.

Teaching Assistants model this behavior while they coach the students on design projects. Once per week during the 10-week course, each TA meets with a consistent group of 4-5 student coachees. Teaching Assistants instruct and grade a series of these students' assignments, beginning with brainstorming. Students are challenged to brainstorm 60 ideas, and to select a project based on a high level of the idea's 1) meaningfulness to them, 2) feasibility to create in the PRL, and 3) uniqueness of product after benchmarking.

Fig 2. Teaching Assistant Jamaal Montasser guides ME 203 students through a structured laboratory on the lathe.

Teaching Assistants coach students through each step of the design process, including:

- Project selection (using a decision matrix)
- Low-resolution prototyping (using materials like cardboard, clay)
- High-resolution prototyping (machining or otherwise transforming metal and plastic)
- CAD Design
- Creating a detailed Bill of Materials
- Product testing and assembly
- Product photography and documentation

Teaching Assistants are trained to "leave students with as much or more momentum as they had previously" after every interaction. TAs consistently use phrases like *what if, could be, maybe, perhaps, let's try it out,* when working with students; these are phrases whose frequent use have been found to encourage exploratory and playful learning in other makerspaces [4]. These interactions contribute to a highly-refined, student-designed project at the completion of the course. An example progression of student work is shown in Fig. 3.

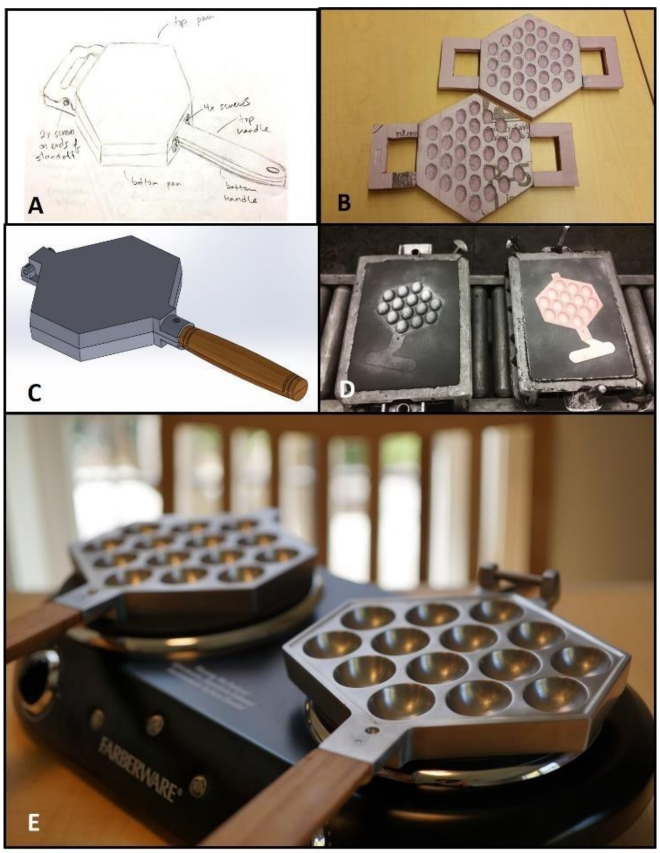

Fig. 3 Process photos of a student's work in ME 203. This "egg-puff iron" went through stages of (A) sketching, (B) prototyping, (C), CAD modeling, (D) sand casting, and (E) final presentation.

C. REWARDS

In addition to financial benefits, the Teaching Assistants receive ample rewards under this makerspace staffing model. TAs can use the lab after hours and during holidays, if accompanied by another person. They also have access to several professional development opportunities throughout the year, such as workshops to learn new skills (for example, a three-day blacksmithing workshop with a local professional smith), and "Meet the Makers" dinners with manufacturing professionals.

The Learning Factory at Penn State, an early experimentation with the campus makerspace, found that makerspaces can provide a kind of "home and social identity" for their students [5]. The Teaching Assistants at the PRL strongly benefit from this social community. They participate in weekly staff lunches, run a winter ski trip, and attend an annual TA Alumni networking event.

Finally, Teaching Assistants are empowered with additional responsibilities in their 2nd year. Veteran TAs chose an area of the lab in which they will become a "Specialist". They spend a majority of their time there, and have the freedom to build improvements for the space, suggest new equipment, and share their knowledge with other Teaching Assistants. Specialist TAs lead specific process workshops in areas such as sandcasting pattern making and silicone molding.

D. IMPACT & INSIGHTS FROM REFLECTIONS ESSAYS

What effect are the Teaching Assistants and the Product Realization Lab having on students? Students of the ME 203 class were asked to write an essay reflecting on their experience. The authors of this paper examined the essays to determine the qualitative impact of the Product Realization Lab. The authors adopted a similar research method which has been used previously by Burke to study makerspaces in libraries [6].

Students were given the following open-end prompt during the last week of the class:

"Write an essay describing what you have learned through the ME 203 adventure."

No other instructions were given. 70 students responded to the prompt in March of 2016. Their responses ranged in length from a short paragraph up to several pages in writing. Each essay was read, and the responses were coded into a set of categories which best matched the thoughts expressed. Then, the responses were tallied to determine the 11 most commonly shared thoughts. Results are shown Table 1 below.

Table 1: The 11 Most Common Reflections of Students in the ME 203: Design & Manufacturing Class.

Response ("I...")	# of Respondents	% of All Respondents
Learned a new manufacturing skill	35	50%
Am proud of my final product	28	40%
Learned resilience in the face of failure	22	31%
Am grateful for the TAs	21	30%
Gained creative confidence	18	26%
Learned the importance of creating a plan *before* coming to work in the PRL	18	26%
Learned time management skills	17	24%
Found prototyping to be valuable	14	20%
Had little prior experience	14	20%
Was challenged by selecting an appropriate project	11	16%
Gained a new appreciation for how things are made	10	14%

The students' responses to the open-ended prompt are informative. They suggest which lessons learned were more memorable – and which were potentially most important.

Students most frequently responded that they learned a new practical or technical skill, such as sheet metal forming, sandcasting, or machining. However, many of the top lessons learned were "soft" skills rather than technical skills.

A significant number of students reported being surprised by how long it takes to "make", and how important it is to learn time management skills. And, while many students felt it important to mention they had no prior experience, an even greater number gained creative confidence and learned resilience in the face of failure.

E. RECOGNITION OF TEACHING ASSISTANTS

A significant portion (30%) of students directly mentioned their gratitude for help received from Teaching Assistants in the PRL. The university has also recognized the effective work of the Teaching Assistants.

In 2015, Stanford awarded the Centennial Teaching Assistant Award to the entire team of PRL TAs, calling them "The Product Realization Lab Nineteen". This award 'recognizes outstanding teaching assistants for their tremendous service and dedication in providing excellent classroom instruction for Stanford students' [7]. It was the first time in Stanford's history that the award was given to an entire group of TAs.

F. IDEAS FOR FUTURE IMPROVEMENT IN THE PRL

In order to better understand the impact of the academic makerspace on students' learning, more directed survey questions are necessary. Current research is under way by Dr. Sheri Sheppard at Stanford University. Dr. Sheppard and colleagues shadowed coaching sessions throughout ME 203, and administered surveys which will help to measure students' motivation levels and to understand the importance of prototyping in students' learning.

How might makerspaces equip their staff to be effective design coaches? One idea is that while universities have makerspaces, they also have athletic programs. The Product Realization Lab Leadership team could offer a workshop for the Teaching Assistants led by one of Stanford's 140 athletic coaches. Coaches might share new ideas with the TAs regarding how to motivate, encourage, or provide timely feedback.

Additionally, many students (26%) responded that they learned an important lesson to create a plan *before* working in the Product Realization Lab. It is important to teach this lesson as early as possible in students' coursework. "Expert" Teaching Assistants might hold 'office hours' in their lab area of expertise. This could be a dedicated time when students receive coaching about topics like tooling, work-holding, and geometry changes to make parts more readily manufactured with the toolset of the lab.

Finally, there has not yet been a longitudinal study about the lasting impact of the makerspace on students after they have left the university. The authors propose a follow up survey with the students studied in this paper, one year after their completion of the ME 203 course. Currently, the Product Realization Lab is building an alumni email list which will include any student who has used the PRL for class or independent work. We hope that this list will spark ideas, create job connections, and cultivate a sense of Product Realization community after graduation.

G. CONCLUSION

A qualitative examination of student's essays demonstrates the impact of the academic makerspace. While students report learning new technical skills, they also frequently learned important "soft skills" such as resilience in the face of failure and time management. Perhaps most important are the newfound pride and creative confidence which students report.

A recent review of academic makerspaces found that the impact of makerspace correlates with the staff support which is provided [2]. The PRL staffing model gives both high responsibility and high reward to its Teaching Assistants. This is one possible staffing model which hopes to spark ideas in other academic makerspaces about how to empower student workers.

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ISAM
2016
Paper No.:
28

Invited

Maintaining the Ethos of MIT's Original Makers Space - The MIT Hobby Shop and One-on-One Mentorship

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MIT's Hobby Shop traces it's origin back to 1938 when ***sixteen bold MIT students were granted permission to use a room in the basement of Building 2 to create a space for a student club. With equipment they found around the Institute, they set up a wood and metal shop. The club members chose the name "Hobby Shop" based on the philosophy that the well-rounded individual pursued interests outside of their profession—hobbies.*** Thanks to their imaginations, talents and resourcefulness a well-equipped shop creating limitless possibilities opened. The original Hobby Shop constitution stated that the shop was only to be used by students for non-academic work. The shop operated as a club with a student foreman and members who started as apprentices and progressed to journeymen, and finally, master craftsmen.

In the 1950's, the school hired a Shop Master to help instruct students and maintain the shop machinery and facility. The Hobby Shop Club eventually disbanded, but the ethos for having a space for the MIT community to make, build and hack remained. Membership and access was expanded to MIT's entire community including faculty, staff, alumni (and their spouses), and was eventually funded by MIT's division of Student Life.

Today, the Shop has two full-time professional instructors to teach making skills, run the daily operations and foster a making community. While no students supervise the Shop, it is encouraged that everyone supports and watches out for each other; this helps to establish trust and fosters the Shop's great sense of community.

There is a modest term membership fee, and a one-hour safety orientation for each member. One of the Shop's strengths is that the staff instruct and guide both beginning and advanced members on machinery and tool use in order to help them transform their ideas into reality. Projects can be academic or personal, serious or just for fun. While staff occasionally support academic classes, the Shop remains separate from any of the Institute's academic departments.

The Hobby Shops pedagogical approach is unique; the instructors use a one-on-one making skills instructional method. Instead of providing members with overall instruction on each machine and tool, instructors work with members to deconstruct and assess their projects and develop specific completion plans using tools and machines that will yield the best results for their project. Instructors teach machining tasks incrementally and based on each member's needs, making it easier for members to eventually understand larger mechanical operations.

The Librarian's Role in Academic Makerspaces

ISAM 2016 Paper No.: 29

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INTRODUCTION

Academic makerspaces form and are launched in many different ways on college campuses. Some are situated within disciplinary bounds (e.g., University of Victoria's Maker Lab in the Humanities, Georgia Tech's Invention Studio, and any number of design school labs that predate the "makerspace" term). Others are new, independent entities on campus, such as Case Western Reserve's think[box], while still others are grounded within the library, like the University of Michigan's UM3D Lab.

For academic libraries that develop makerspaces, the most common value proposition is their provision of access to the whole campus—all disciplines. For this and other reasons, many libraries are building such spaces: a survey of the Association of Research Libraries in June of 2015 found 27% of respondents offering maker spaces or services and another 37% investigating or planning them [1].

The library may not be the only or obvious place on campus for an open-to-all, general use academic makerspace to be housed, but libraries—and more importantly, librarians—are uniquely situated to support an academic makerspace program. The core values of librarianship, the professional training of librarians, the institutional resources of libraries, and the trends in changing approaches to academic librarianship all align to support makerspaces and learning by making in higher education.

CORE VALUES OF LIBRARIANSHIP

Librarianship attracts many values-minded professionals, who are committed to public service, social justice, and democracy. Like many professional and academic disciplines, librarians have enshrined their core values in statements by professional organizations, ours being the American Library Association. The ALA's Core Values of Librarianship [2] list the "essential set of core values that define, inform, and guide our professional practice" as: Access, Confidentiality/Privacy, Democracy, Diversity, Education and Lifelong Learning, Intellectual Freedom, Preservation, The Public Good, Professionalism, Service, and Social Responsibility.

While nearly all of the above values will enrich an academic makerspace, perhaps the most important in this context are: Access, Democracy, Diversity, Education and Lifelong Learning, and Service.

A. ACCESS

When an academic library opens a makerspace, it commits to giving access to the space and its tools to an entire campus community. This can make for a high-impact campus makerspace, that nurtures interdisciplinary collaboration and helps builds a community of makers.

B. DEMOCRACY

The modern American library is founded on the concept of free and equal access to information, and a library makerspace program extends that goal to the realm of tools and skills, seeking to democratize access to these.

C. DIVERSITY

Libraries have a mandate to serve all, and to reflect the diversity of their communities. This compels them to reach out to underrepresented groups in promoting a makerspace, and to provide a variety of resources (e.g., not just 3D printing). My colleagues at the NCSU Libraries have run an exemplary diversity and inclusion program, "Making Space" [3].

D. EDUCATION AND LIFELONG LEARNING

Librarians' commitment to lifelong learning, and their unique standing as both in- and out-of-classroom educators, suit them well to the makerspace setting, a new one on campus that can span both formal and informal education. Academic makerspaces support students in learning skills they can take with them beyond graduation, and often connect with off-campus groups that can support continued learning.

E. SERVICE

The service ethic that librarians bring to an open-use makerspace can enrich it as a welcoming place of learning. Another important text in librarianship, S.R. Ranganathan's "Five Laws of Library Science" [4], states the following:

1. Books are for use.
2. Every reader his or her book.
3. Every book its reader.
4. Save the time of the reader.
5. The library is a growing organism.

Extending this approach to a makerspace, librarians understand, for example, that tools are for use, and that makerspace staff should save the time of their users.

Additionally, many libraries value and strive for superior *customer* service, an orientation that can ground a makerspace with a clear way to engage new and potential users.

PROFESSIONAL TRAINING AND SKILLS OF LIBRARIANS

Librarianship is a rapidly changing profession, being heavily altered by the overwhelming growth of information technology and the digitalization of information resources.

However, our traditional skill set remains relevant even as the content, systems, and communities we work with shift. In addition, librarians are increasingly adding new skills, often through benefit of the colocation of Library Science and Information Science graduate programs, as they are repeatedly called to adapt to "changing roles" [5].

The core training for librarians typically includes: learning the spectrum of information resources and how to evaluate them, the practice of developing collections to meet a particular community's needs, organizing and cataloging information, and reference and research methods [6]. Many of these skills are directly relatable to makerspace work.

A. INFORMATION RESOURCES

A makerspace contains a variety of resources—tools, materials, supplies—that need to be researched, selected, and made accessible. A librarian's text-centered training is still relevant here. Additionally, many of the core tools of an academic makerspace involve digital fabrication, which is itself an information process. There is a direct tie here to a major of librarianship's past few decades: information literacy. Some librarians, myself included, cast the processes and tools learned in an academic makerspace as a literacy continuum, whether they define it within information literacy, digital literacy, or (new) media literacy.

B. COLLECTION DEVELOPMENT

Just as selecting individual resources takes skill and effort, a curatorial eye greatly benefits the totality of resources made available in a makerspace. By training and grounded in serving a particular community, librarians are well suited to make or inform a makerspace that fits its own academic community, with tools that will get used and resources and programs that align with that community's needs and strengths.

C. CATALOGING

Anyone who has managed a makerspace knows it is a process of constant (re-)organization of materials and supplies, which begs for a system and an organizational mind. Librarianship is steeped in classification systems which can not only bring order to the chaos, but also make individual items more easily accessible. Cataloging non-textual items is new territory to most librarians, but they have skills to offer here.

D. REFERENCE & RESEARCH

The unique ability of the reference librarian, which is sharpened over many hours of practice, is to assess a user's inquiry and help them along a path of discovering reliable information resources and answers. Librarians are trained in the "reference interview," which involves listening and interviewing the user to confirm their true information need. The goal is to leave users (in our setting, college students) better able to search and find resources, rather than simply walking away with an answer. The utility of this skillset in a makerspace, where a diverse group of users with very different skill levels seek to learn and use a variety of tools, is hopefully self-evident.

A higher-level opportunity for librarians in doing academic makerspace work is to connect the research process with a making or prototyping process, and thereby help students make much more informed design decisions, better address the markets they pursue, and overall produce better work.

research methods.

E. INSTRUCTION

Very few academic librarians have a deep training in pedagogy, but many have some training in teaching and over time become thoughtful classroom instructors. In an academic library, both disciplinary librarians and dedicated instruction librarians regularly teach in the classroom, and additionally offer drop-in workshops in the library on everything from research skills to audio/video production. For makerspaces to have an impact on college campuses, this dual approach to learning experiences is a good strategy as it reaches students both in and out of the formal curriculum.

F. EMERGING SKILLS

Perhaps what best suits librarians to makerspace work is their grounding in a culture of lifelong learning. The profession is very aware of the changing information landscape, and many academic libraries are proactively expanding their portfolio of services and developing new expertise. For example:

- Many libraries now have a dedicated librarian position for assessment of library services and usage.
- There is a growing focus on user experience design, with librarians learning that field's tools and approaches to improving services, usability, and more.
- Research data management, data visualization support, and other data services are now offered at many libraries.

While each of the above examples represents an area of expertise that would be useful in a makerspace project, they are more offered to show librarians' adaptability.

Makerspaces themselves require a wealth of new skill development, especially for staff that hope to serve as guides to their use. Training in the software, hardware, and maintenance of what are often makerspaces' most in-demand tools—3D printers and other digital fabricators—is crucial.

Librarians have shown they can take on these new skills, but not without some difficulty—"these are not standard skills for librarians" [7]. Some see less of a case for translating skills than for transformation:

> Libraries can both reinvent traditional library positions and create new roles that require technical skills as well as flexibility and ambiguity. This will require continuous learning on the job and support for this retooling or retraining by administration, possibly a shift in the library culture… [7, p. 5]

INSTITUTIONAL RESOURCES OF LIBRARIES

In early 2011, still early in the incredible current wave of interest in makerspaces, Phillip Torrone (now at Adafruit Industries) wrote an article in *Make* magazine [8], "Is it Time to Rebuild & Retool Public Libraries and Make

'TechShops'?" The article and its question reveal a Maker movement insider's view of libraries: they represent a huge amount of public infrastructure that could be leveraged to provide space, tools, and programs for makers. Many of the article's presumptions and conclusions were misguided—principally among them, the notion that a for-profit company should be tapped to "convert" treasured public institutions. However, five years later many libraries are looking to the Maker world to rejuvenate their spaces and engage their communities in new ways.

While Torrone addressed the world of public libraries, academic libraries have all of the infrastructure he called out: existing locations, paid staff, budgets and funding sources. More often than not, libraries occupy prominent central locations on campus, and offer more open (and staffed) hours than any other campus service. Beyond the skill set I have described above, libraries also have experience providing large communities with access to space and resources and doing so safely, with providing technology and IT infrastructure at scale (e.g., computers, WiFi, software, assistive technology). All of this is a lot to lean on when creating a new program such as a makerspace. New hardware, and especially higher-end makerspace tools, bring new issues (e.g., ventilation), but there is a lot to build upon.

Unlike a campus department or college (e.g., an engineering school), academic libraries are almost always funded centrally with a mandate to serve the full campus population. They are more often seen and described as "neutral ground" for scholars. Libraries often have large amounts of space and staff to support their mission and provision of service to all. That said, many libraries are already providing a level of service and serving a population that challenges their resources.

While there are a lot of the right ingredients for a makerspace on an academic library's balance sheet, that's not enough for a library to get involved. Another necessary resource that is less tangible is leadership—on some campuses, libraries serve a role of technology leadership, while elsewhere they serve more of a support role. Some libraries develop an innovative culture that supports boundary-crossing work on their campuses.

I expect that the more clearly librarians can connect makerspaces with the core values of librarianship and the goals of their organizations, the more support they will find for developing makerspaces.

TRENDS IN ACADEMIC LIBRARIANSHIP

Academic libraries find themselves in a long period of transition, perhaps most profoundly shaped by the shift from print to digital consumption of information (databases, journal articles, books). The profession has responded with some clear trends in practice, many of them relevant to and compatible with the growth of open-use academic makerspaces.

A. THE THIRD PLACE

Libraries have long been moving away from the "storehouse of books" model, with the digital shift accelerating that move. The concept of the "third place," articulated by sociologist Ray Oldenburg, has crystallized as part of a new model. The third place is defined by its contrast to the first (home) and second (work) places. Oldenburg states:

> Though a radically different kind of setting from a home, the third place is remarkably similar to a good home in the psychological comfort and support that it extends [9].

Libraries have come to embody the third place model by openly embracing social activity, from the noise of conversation to the buzz of coffeeshops and regular programs and events.

B. LEARNING COMMONS

Another relatively recent trend in libraries has been the focus on "learning spaces"—the conceptualizing of the library itself as learning space, as well as the development of new models of physical spaces in libraries. Most influential among these new learning space models is the "learning commons" (also: information commons, research commons, digital commons), seen as the antidote to the confining computer labs that came before it. Now a fixture of many flagship academic libraries, a learning commons typically offers an appealing locale for students to collaborate in groups, with flexible furniture, ready access to technology, and dedicated library staff and services [10].

C. CONSUMPTION TO CREATION

In response to changing user needs, especially around technology, and at least partly influenced by the explosion of creativity and user-generated content/media that came to be described as "Web 2.0," there is a trend of libraries offering increased support for content creation, including in multimedia formats like audio, video, photography, and web publishing. Some librarians have even called for a "Library 2.0," a solidifying of this trend into a new approach to librarianship [11].

This shift is perhaps most fully realized in a makerspace, with its wide array of tools, materials, and making experiences. However, the chaos and mess-making (and iteration and failure) of these spaces can be seen as threatening to the traditional library culture of order and organization.

APPROACHES TO LIBRARY MAKERSPACES

With the trend in academic librarianship moving toward creation and learning spaces, then, it seems natural that makerspaces would be embraced, and they have been [12]. Many libraries are purchasing equipment, developing services and even renovating to develop dedicated spaces for making. Some clear models or approaches are beginning to take shape.

A. ACCESS TO TOOLS

Much as they give access to information resources, computing, and software, some libraries are now giving hands-on access to tools in dedicated makerspaces, almost always including 3D printers. An easier model to implement, though it has limitations, is to simply lend tools (e.g., electronics kits, 3D scanners, even robots and drones), leveraging libraries' existing mechanisms and policies for lending materials.

B. SERVICES

Some academic libraries have opted to develop maker-related services—again, the most popular being the 3D printing service. Libraries bring to this their service ethic and technology infrastructure, offering services to all of campus that might otherwise only be available to a few.

C. EVENTS AND WORKSHOPS

With their prominent, central locations on campuses, libraries are great locations for maker-related events, such as workshops, public lectures, and hackathons. Libraries and librarians can support and offer these types of activities, which can support makers and community building, even if they don't offer related services or access to tools.

The "pop-up makerspace" which only exists during events is another model, which can be less staff-intensive and so more sustainable.

D. EMBEDDED LIBRARIANS

Another recent trend in the library world is "embedded librarianship," which has librarians integrating themselves and their services into courses, research labs and teams, even dorms [13]. This presents yet another model for librarians to embrace makerspaces, in more of a support role. On campuses where makerspaces form without library involvement, or with library support but in a different physical location, an embedded librarian will no doubt enrich the makerspace with his or her skills and values.

CONCLUSION

Libraries and librarians undoubtedly must adapt if they are to lead successful academic makerspace programs that effectively serve their communities. These spaces necessarily comprise new technologies, new types of service models, and new modes of engaging and interacting with students and faculty.

Librarians, however, have much to offer the academic makerspace movement. Their deeply-held values can help can help make makerspaces the diverse, inclusive, and accessible they must be to realize their transformative potential. Librarians' translatable skills can make makerspaces more usable, organized, and responsive spaces of learning. Furthermore, makerspaces are at a confluence of trends in librarianship because they surface at a confluence of library strengths: community, technology, and creative learning spaces.

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MITERS: Lessons from 40 years of Student-run Shop Space and Community

ISAM 2016
Paper No.:
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INTRODUCTION

In this paper, we explore the history and running of the MIT Electronic Research Society (MITERS), MIT's oldest hackerspace and one of the oldest academic makerspaces in the country. MITERS is unique in that it is student-run, self-funded, and decentralized, traits which we believe are important in building a distinctive community. We will discuss how the space is funded and procures resources, why we believe it is unique in a positive way among makerspaces at MIT and in the country, and the pitfalls and difficulties of running a decentralized shop and how we avoid them.

HISTORY

MITERS was founded in 1974, during the infancy of minicomputers and transistor electronics as a way to provide students with easier access to computers they could play with[1]. Over the years, the space has been constantly evolving, with projects ranging from artsy hobbies to cutting edge research. The atmosphere of the space, and the emphasis of the equipment and supplies, is strongly driven by the interests of the most active members; in the past half a decade, MITERS has had a largely electromechanical focus, with a strong emphasis on metalworking, vehicles, and robotics. Its membership consists of primarily students, with a substantial number of alumni and affiliates who contribute to the space.

A UNIQUE SPACE

As a workspace with no centralized management, tools, supplies, and space use are dictated by the people who use the space. The space is 986 square feet, split evenly between electrical and mechanical work areas, with ample storage space for projects. However, **MITERS is more than a shop, it is a community.** This offers some very practical benefits. We will go on to analyze those benefits, and consider the reasons what makes MITERS more effective in these respects.

A. FISCAL EFFICIENCY

MITERS runs on a lean budget of less than $6000 a year - a fraction of what most shops run on. This is due to a combination of smart purchasing and cost-efficient procurement. Without the ability to spend “someone else's money”, our members actively contribute their own time and expertise into maintaining our existing tools and refurbishing used equipment.

B. POOLED KNOWLEDGE

As a community consisting of talented engineers and

Fig 1: The interior of MITERS. Go-karts and scooter skeletons hang from the ceiling near a bandsaw in the center, with a lathe to the right and stock shelves to the left.

engineering students, MITERS possesses an enormous pool of specialized knowledge. This enables our members to take on ambitious projects. Some of our more ambitious projects in recent years have included robotic legs, interferometric stabilization systems, and custom car-scale motor controllers, to name a few (see Appendix for projects). This also gives our younger members an opportunity to learn from experts one-on-one in a comfortable, informal setting

C. FLEXIBILITY

Traditional shops need hard-and-fast rules to avoid shop misuse or abuse. By having a strong sense of community, our shop can work with laxer rules that are enforced more by culture and peer pressure over punitive measures. This allows MITERS to be the *only* space on campus where students can work on large, multi-semester projects stored in the shop with no deadlines or fees, and let the community decide when projects are inappropriate for MITERS.

CREATING STRONG COMMUNITY

The largest factor that separates us from many other shops on our campus is our strong sense of community. MITERS is a tight-knit community of productive people. Any student or MIT affiliate is welcome to join by showing up and building a project at MITERS. There are a number of factors that go into making a strong community from this, but there are a few key themes: mentorship, conspicuous project inspiration, and storage.

MITERS has a strong culture of mentoring its members. We have no official mentorship program, but nevertheless, members go out of their way to help others on their projects. This not only encourages people to do projects and advance technically, but it also creates strong interpersonal connections between mentors and mentees, which eventually expands to the community.

MITERS is also famous for its amazing extracurricular projects that come out of it. Over the years, MITERS students have built motorized shopping carts, kiteboards and kites, go-karts, acoustic instruments, electric instruments, tesla coils, art, and so on (see Appendix). Not only do people build these projects at MITERS, but they are also displayed all over it, as seen in figure 1. This functions as conspicuous sources of inspiration to new members, and also shows that people at MITERS have the knowledge to build these projects. MITERS members also tend to document their projects. At least 80% of members have a personal website where they show off their projects, such as the website *BuildIts* in figure 2. Projects from these sites have been featured on Hackaday, Make Magazine, Popular Science, and Adafruit. The number of projects from current and past MITERS members on Instructables alone is over 200, with over 20 million combined views [2]. This information serves as an excellent base for building new projects and gives members lots of ideas and knowledge.

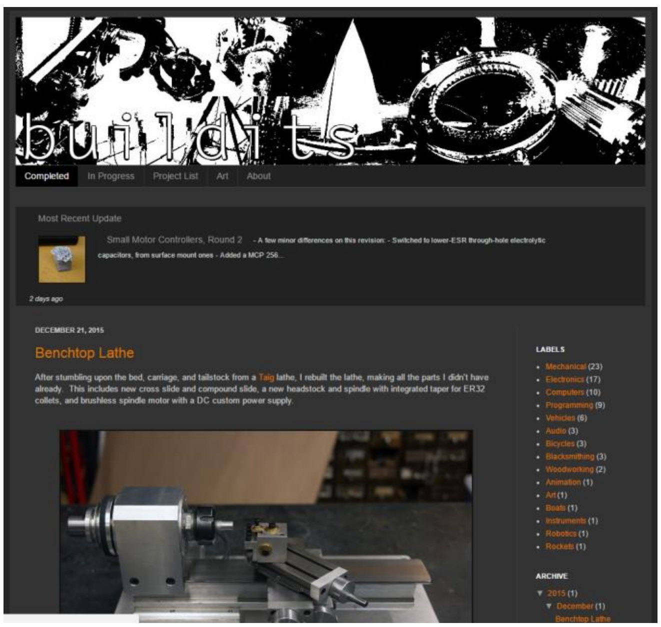

Fig 2: A keyholder's website, build-its.blogspot.com[3]. It hosts project documentation from bikes to a tiny lathe, which features pictures as well as technical descriptions. It is used a resource by other members as well as design inspiration.

Building of projects is enabled by project and materials storage space. At MITERS, we have a large variety of stock materials and "cruft" (machines or materials recycled from trash, flea markets, or old projects) to build things out of. Many projects at MITERS are made entirely out of cruft. Having stock materials lowers the activation energy needed to carry out a project to completion. Using cruft is cheaper than buying goods new and has an additional benefit of showing off previous engineering as a point of possible inspiration. While it is harder to design around what you have rather than what you can buy, having parts on hand encourages clever design and enables projects that would otherwise be far beyond the budget of students.

With mentorship, information, and space available, members have everything they need to build a complete project without ever leaving MITERS. This makes a strong incentive to connect with MITERS and participate in its culture and community.

STRUCTURE

MITERS has a decentralized structure with no fulltime shop managers. Instead, we simply have members and we have keyholders. Members are students or MIT affiliates who use the MITERS workspace. Keyholders are the people who are trusted to open and close the shop, to ensure people are safely using machines and tools and responsible in the case of injury, and are responsible for machine maintenance and stocking consumables. Keyholders are students, recent alumni, or staff. We currently have 34 active keyholders and, in addition, 20 active members who have not yet been granted keyholder status.

Keyholders embody many aspects desired in a shop manager. They are knowledgeable about their tools, responsible with regards safety, friendly, helpful, and have a strong feeling of ownership over the space. Like with any leadership role, good keyholders do not simply happen by giving students or members a label. There are 3 factors which influence how our members become good keyholders:

A. MENTORSHIP

Along with building community ties, mentorship allows smooth transfer of shop management. Older keyholders pass down not only technical information, but tips on the ins and outs of effectively running a workspace. This ensures a gradual transition from generation to generation of shop manager, preventing misinformed, sweeping changes to the structure and function of the space.

B. PEER FEEDBACK

Keyholders of any status give feedback to each other, including how to treat new members and how to be better keyholder. This reinforces the culture of the space, and prevents any one person or clique from gaining excessive authority over the space.

C. BUILD THINGS IN MITERS

Unlike other student run shops, where students are mandated to have open hours, or professional shop managers where their shop is their job, keyholders are free to open MITERS whenever the please. This means they open MITERS *when they are using it*. This results in keyholders who are active users themselves, and care a lot about the space far beyond the scope of a job.

TRAINING AND SAFETY

MITERS has an excellent safety record. We have had very few injuries over the years, with only one injury (a cut finger) requiring stiches and zero injuries among novice users. In fact, our safety record is better than that of several other professionally managed, student-accessible shops on campus. The way MITERS is able to accomplish this is by encouraging people to be safe, watch over each other, and ask questions. The freedom to ask questions is the key to safety as it ensures people are predisposed to learn safely when they do not know something.

The people who train others on machines are keyholders. This has many advantages over professional shop managers. We know that traditional group shop training is not always effective - an hour of lecture is certainly not enough to become familiar with a new tool. MITERS effectively has multiple shop managers when it comes to training through its many keyholders. Most equipment training happens one-on-one when people need to learn for a real project. The motivation of a real project, in addition to the individualized training, greatly improves knowledge retention rates, reduces equipment damage, and improves safety awareness. We are able eliminate training waitlists while improving the quality of our training.

But safety goes beyond training. Having multiple student keyholders means many people feel jointly responsible in watching over each other and ensuring that their peers are machining in the safest manner possible. That pressure creates an attitude of vigilance among your peers, instead of relying on a shop manger to catch people's mistakes. Additionally, since we have student keyholders, students feel less intimidated by peers over a shop manager and actually ask questions about techniques and tools as opposed to "figuring it out as they go". As a result of this and one-on-one trainings, we have an excellent safety record.

FUNDING

MITERS consumes far fewer resources than a traditional shop. MITERS runs on a low budget - our operating income is about $6000 a year, funded almost entirely by collecting admissions from an on-campus electronics flea market that runs monthly from April to October of each year. Regular purchases are limited to consumables such as wire, solder, and 3D printer filament. Most equipment, parts, and stock are donated or salvaged from labs on campus or companies in the area.

It seems impossible to get all of the things we do for free. Being part of to an institution like MIT allows us to take all of the high end refuse from labs - be it old CNC mills, scrap aluminum, or even wire. We also have access to three phase power, water, and all the other resources such as machining and expertise associated with an academic space. In addition, our good relationships with other facilities allows us to access other shops nearby, enabling us to tools that would not fit into our shop, such as a waterjet or welder.

Our members are also dedicated to maintaining and refurbishing machines themselves. For example, our CNC mill was free. It was found in a hallway, and one of our members asked that it to be donated to MITERS. It was an old mill that ran on floppy disks. Several Ph.D. students spent hours to bring it up to modern standards, and made it function reliably. New, a machine like that would cost upward of $20,000.

Despite our frugality, MITERS is outfitted with the following major tools (an incomplete list), with the layout shown in figure 3:

- Two manual mills
- Manual Lathe
- CNC Mill
- Three FDM 3D printers
- Vertical and horizontal Band saw
- Grinders and sanders
- Power tools – angle grinders, sanders, dremel tools, power drills
- Hand tools – screwdrivers, wrenches, pliers
- Soldering stations – through hole and surface mount
- Power supplies
- Oscilloscopes – up to 1GHz sampling
- Function generators
- Sewing machine

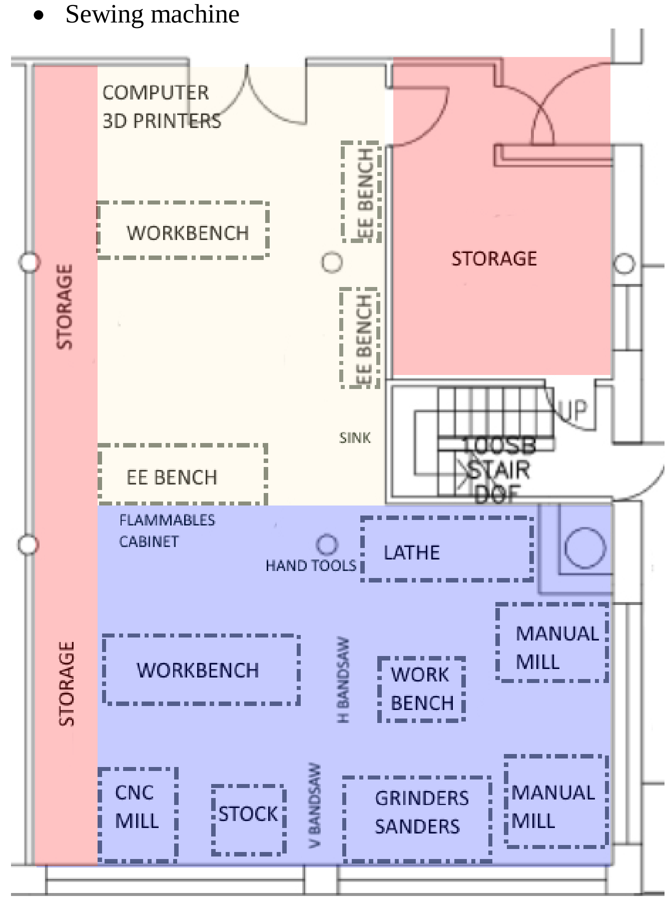

Fig 3: The floor plan of MITERS. Red, blue and yellow correspond to the storage, mechanical workspace and electrical workspace respectively.

This base set of tools changes by the kinds of projects people work on, and they will often procure the tool they need for a particular project. This means MITERS' resources grow over time to cover almost anything people want to build within reasonable limits. People also find funding for their own projects, through companies or through grants. The discarded project parts often contribute to MITERS stock, which continues a cycle of project growth.

CONCLUSION

MITERS is an effective space because of deep community investment, decentralized and numerous shop managers, as well effectively inspiring new members through its display of projects Despite the potential pitfalls of a student-managed shop, MITERS manages to maintain a superb safety record, run efficiently on a small budget, and have a wealth of projects come from it. . Its members and projects have attended Makerfaires and have been featured on places like Hackaay, Instructables, and several TV shows including ABC's BattleBots and Discovery Channel Canada. More importantly, MITERS provides an excellent peer-supported learning environment, teaching not only practical fabrication and design, but the ins and outs of managing a shared workspace and community.

APPENDIX

A selection of projects built at MITERS by MITERS members.

Fig 4: Gigatron, an autonomous go-kart built out of MITERS for New York Makerfaire Powerwheels Racing Series. The frame was built for under $500, and the electronics were partially funded by NVIDIA.

Fig 5: MITERS crossing the Harvard Bridge for MIT Moving Day 2016. From right to left: "Chitty bike" - a custom electric bicycle with speakers , "Doofwagon"- a motorized garden wagon, "LOLrio Kart" – a motorized shopping cart capable of 40 mph. Source: http://news.mit.edu/2016/crossing-charles-moving-day-parade-competition-0509 [4]

Fig 6: A jumping leg made out of hobby motors. A separate dynamometer that characterized the motors was also built at MITERS. Source: build-its.blogspot.com[3]

Fig 7: A collapsible kayak built out of aluminum tubing and PVC fabric. Source: http://www.avamakesthings.com/[5]

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Increasing Staff Effectiveness in Volunteer-Run Student Makerspaces

ISAM 2016
Paper No.:
31

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INTRODUCTION

A number of universities have recently opened "maker spaces," providing students with increased access to tools, equipment, training, and other learning resources. The MIT MakerWorkshop (MW) - situated on the Massachusetts Institute of Technology (MIT) campus - is one such space, and is notable in that it is operated entirely by students on a volunteer basis. This introduces numerous challenges for successfully operating the space, as responsibilities must be efficiently divided, communicated, and executed among a large body of unpaid individuals with varying experience and time commitments. Over the past 1.5 years, the members of the MIT MakerWorkshop have developed a number of strategies and tools for more effectively managing organizations of this kind. This document summarizes many key recommendations in four areas: (a) governance structure and distribution of labor, (b) physical boundaries and posted information, (c) streamlining communication and reducing information overload, and (d) philosophy of rules and policies.

Fig. 1: The MIT MakerWorkshop, which houses numerous prototyping, fabrication, testing, and measurement tools.

CHALLENGES IN VOLUNTEER-RUN MAKERSPACES

At any one time, the MIT MW is comprised of 30-40 active "mentors" (staff members) who manage and run the organization. Mentors execute all operational and administrative duties associated with the shop, including:

- Staffing the shop during open hours
- Hosting shop orientations for new members
- Offering structured machine-specific trainings
- Management & coordination of staff shop (assigning shifts, hosting meetings, etc.)
- Developing training for new machines
- Developing policies and rules
- Creation and maintenance of documentation
- Purchasing, budgeting, and fundraising
- Recruitment and training of new mentors
- Shop cleaning and machine repairs/maintenance
- Interfacing with other entities within and beyond MIT

All mentors are volunteers; most join the MW for the purpose of working shifts and helping their fellow students to sharpen their fabrication and design skills. The difficulty of fulfilling all of these responsibilities is further compounded by having a large, all-student staff; this introduces the following challenges:

- **High turnover rate –** Staff turnover is inevitable every few years; students continue to graduate, and many can only participate for 1-2 years before leaving. Minimizing the familiarization period for new mentors is therefore a key problem, especially if some are expected to fill leadership positions.

- **High variability in skills & experience –** Staff members are trained on each machine, but expertise still varies widely among individuals and each is always learning new skills. Additionally, mentors who know the most about the shop are typically older students, and therefore the most at-risk for graduating and carrying their knowledge with them.

- **Competing responsibilities –** Mentors are graduate and undergraduate students; coursework, research, and other extracurricular activities compete for their time and attention. Most MW mentors contribute just 3-5 hours of volunteer time per week, with mentors in leadership positions contributing additional time.

- **Institutional wisdom –** Each mentor knows their own tips and tricks for machine use, shop management, navigation of MIT systems, etc. Documenting - and equally importantly, finding - this knowledge is labor-intensive and difficult to coordinate.

- **Unpaid volunteers –** The MW staff works for free, and therefore is not incentivized in the same manner as paid employees.

Without addressing these issues, student-operated shops such as the MW would fail after a short time. MW leadership has developed and implemented many strategies to combat these challenges.

GOVERNING THEMES

Recommendations are offered in four areas, connected by two overarching themes:

1. **There should always be an easy and clear means**

for staff to find the information they need

2. **Eliminate unnecessary information**

It is not realistic to expect all knowledge to be documented in its ideal location, nor for each staff member to perfectly recall every policy, procedure, and technique. Mentors will often be consulting documentation or other mentors for help. Therefore, the following recommendations focus on improving staff communication and streamlining the process of discovering and disseminating important information.

SHOP MANAGEMENT RECOMMENDATIONS

A. GOVERNANCE STRUCTURE & DISTRIBUTION OF LABOR

Create an Executive Committee (ExCom) to manage administrative duties of the shop, such as setting its vision, managing finances, creating shop policies, interfacing with other entities, and managing the staff. A small, dedicated leadership group allows behind-the-scenes tasks to be efficiently addressed while ensuring swift decision-making and implementation of changes and improvements. In the MW, major policy changes are not decided on solely by ExCom, but are deferred to a democratic vote by all shop staff members.

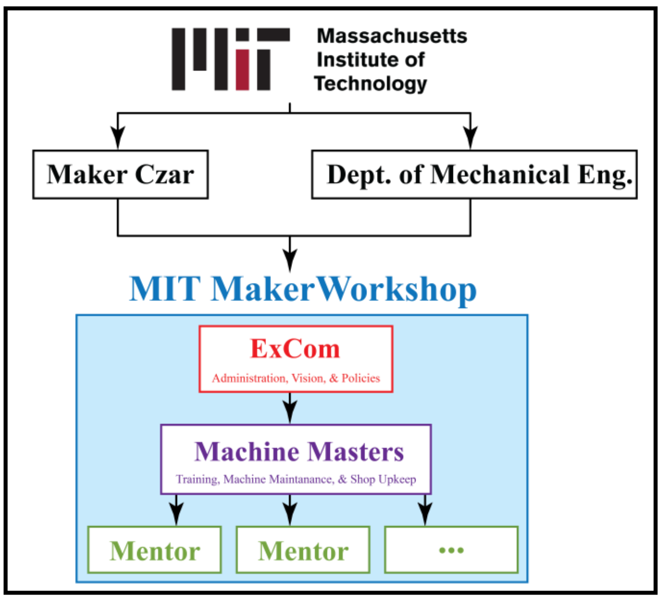

Fig. 2: Governance chart for the MIT MakerWorkshop

Divide staff members into "Machine Teams" and assign related tasks to each team. The pairing of tasks with appropriate teams reduces confusion about who is accountable for which shop tasks, while also matching mentors with others from whom they can learn tips and tricks. Each Machine Team is led by one "Machine Master." This arrangement distributes leadership responsibilities among more mentors, reducing the likelihood that the graduation of a single individual will cripple shop operations. The MW Mill Team is one example team – its members coordinate training, inventory management, upkeep, and maintenance of the milling machine, as well as consult with users on advanced operations. However, their responsibilities extend beyond their machine alone; they are also responsible for maintaining and cleaning the areas and storage features in close proximity to the mill.

Ensure that younger mentors participate in leadership roles to promote the natural transfer of institutional knowledge and sustainability of shop culture.

B. PHYSICAL BOUNDARIES & POSTED INFORMATION

Coordinate the shop layout and the shop policies. Location-dependent policies (for example, zones requiring specific PPE) should match the shop layout. Boundaries should be clearly marked (with signage) so zones with specific rules are easily identifiable. A visual boundary helps both staff and users to remember the applicable policies, and also eliminates confusion regarding where policies do and don't apply.

Fig. 3: Safety glasses line, beyond which PPE requirements and other safety rules go into effect. This makes it easy for everyone to know where rules do and don't apply.

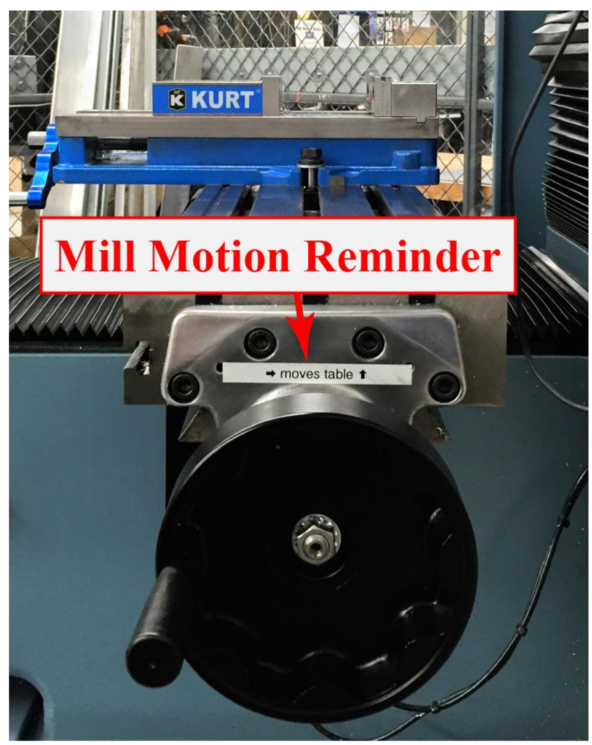

Fig. 4: Mill handle label, reminding users which direction the table moves

Post important information close to the location where it will be used so that it can naturally be stumbled upon when needed. For example, prices for sale of stock materials are laminated and taped to the desk near the MW computer where transactions are made. Even if mentors do not remember stock prices when charging students (or do not remember where prices are posted), they will encounter the information simply by going to the appropriate computer. Useful signage is not limited to posters; labels and indicators can be very helpful, as is seen in Figure 4, where stickers are used to help users remember the manual mill motions.

Don't post unnecessary information. Too much extraneous information results in all of it going unnoticed and ignored. Less important information, such as policy documents, can be stored digitally, with a hard copy kept in a binder.

C. STREAMLINING COMMUNICATION & REDUCING INFORMATION OVERLOAD

Establish a single platform for staff communication in order to reduce email overload and provide a clear and consistent means by which messages will reliably reach the right people. Platforms such as "Slack" serve this purpose well, as they are designed for collaboration among large teams. Each staff member may join and leave individual "Channels," as well as set unique notification preferences for each channel. This makes it easy for mentors to communicate in many channels, but only receive notifications for messages which are most relevant to them (thereby avoiding much of the tedium and overload associated with email).

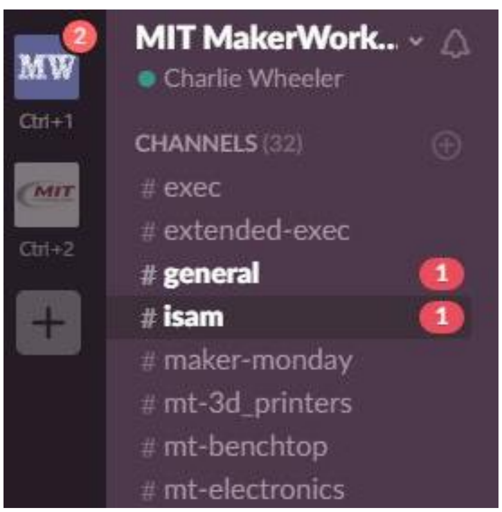

Fig 5: Slack allows the MW to separate conversations by topic. Pictured here are a number of example channels, including channels for ExCom, the ISAM 2016 conference, and a few machine teams. Mentors may enter and leave channels as they please.

Critical announcements should be brief, highly visible, and clearly-worded. Any included explanation should be no longer than necessary, for risk of the message being ignored or misinterpretted.

When collecting data from staff (for example, shift time preferences), use online tools such as Google Forms rather than email. There are many benefits to this: form fields reduce the likelihood for user error; the information is automatically centralized in one document (useful when printing it for discussion at a meeting); the information is automatically archived in a location accessible to all staff members; and, future workload can be reduced by reusing forms for periodic events.

Create a single "Staff Tools" webpage, which includes links to the shop's most-used webpages & tools so that they can all be found in one location.

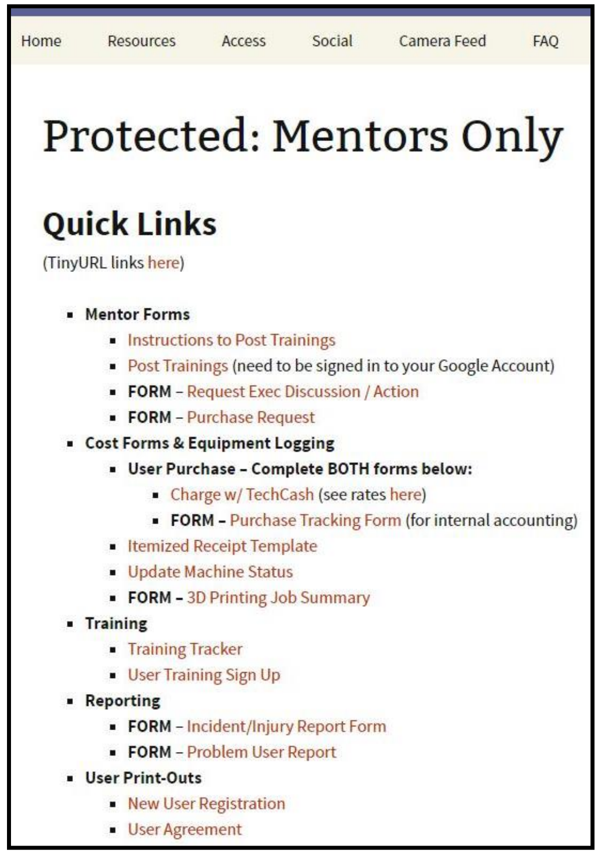

Fig 6: The MW "Mentors Only" page, with links to the most-used e-resources, such as purchase request forms, training signups, and the training credentials database.

Create agendas for all meetings. Carefully define discussion points and ensure that the meeting leader understands the goal of each point beforehand so that he or she can keep the discussion on-topic and always moving towards a resolution and action items.

Before concluding meetings, ensure each action item has a defined deliverable, a person accountable for it, and a deadline. Effective meeting planning reduces time waste, encourages participation of all members present (when appropriate), and helps maintain attendance at future meetings (volunteers quickly learn not to attend unnecessarily long and boring meetings).

When polled about the effectiveness of communication among mentors in the MIT MW, mentors responded very positively. Just one respondent out of 31 polled disagreed with the use of Slack as a communication platform, while over 80%

of mentors “Agree” or “Strongly Agree” that it fulfills its task as an effective and easy-to-use communication tool (especially when compared with email).

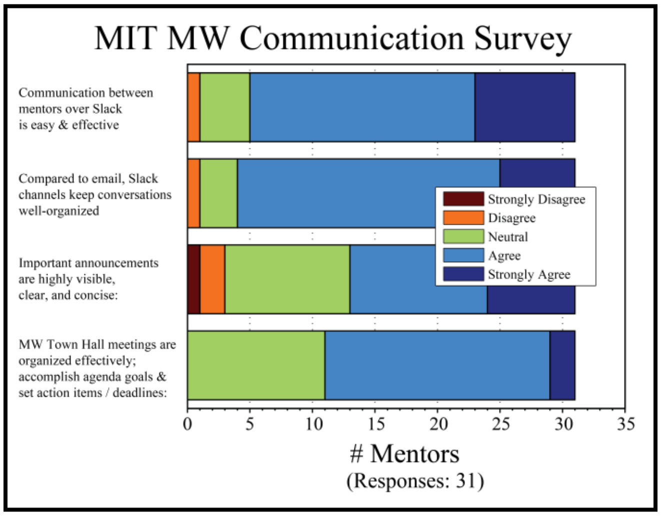

Fig 7: Results from 2016 MIT MakerWorkshop Mentor Survey on the topic of communication. Mentor answers demonstrate strong support for the current communication methods.

Similar results are observed with regards to announcement visibility and the effectiveness of “Town Hall” (all-staff) meetings. Over half of mentors “Agree” or “Strongly Agree” that these objectives are achieved, while most or all of the rest hold a “Neutral” opinion. Just three mentors “Disagree” or “Strongly Disagree” with the visibility of important announcements, while none disagreed with the effectiveness of Town Hall meetings. This suggests that there is still room for improvements to the MW policy announcement process, but the current system is still effective for the great majority of the staff.

D. PHILOSOPHY OF RULES AND POLICIES

Do not create exceptions to policies and rules. Instead, revisit problematic policies and rework them such that they do not need exceptions. MW mentors have observed two major problems with exceptions: (a) exceptions are unnecessarily confusing, difficult to memorize, and easy to forget; and (b) exceptions place additional burden on staff to evaluate the situation and determine whether an exception applies or not (especially when students are supervising other students). When exceptions are eliminated, it is much easier for both users and staff to remember, understand, and follow the policies.

All policies and rules should have a simple, clear motivation. If a shop user asks why a rule exists, a mentor should be able to explain it. There are many benefits to this: knowing why a rule exists (a) makes the rule easier to remember; (b) promotes a deeper understanding of any relevant machinery/equipment; (c) reinforces a shop culture where decisions are made based on rational reasoning; and (d) promotes respect between staff and users (rules are always enforced for a good reason, rather than as a show of power).

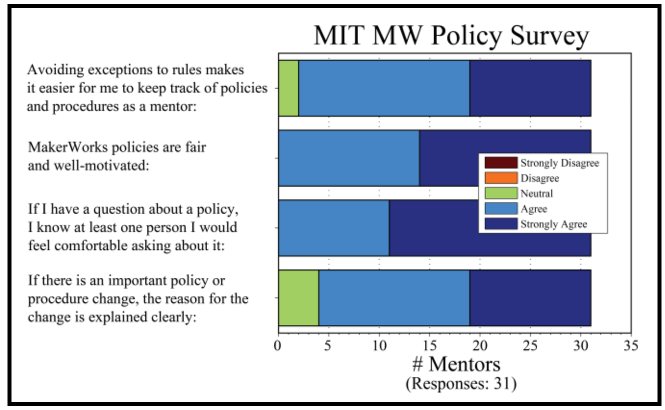

Fig 8: Results from 2016 MIT MakerWorkshop Mentor Survey on the topic of policies. Mentor answers demonstrate strong support for MakerWorkshop policies and their motivations..

When MIT MW mentors were polled about policies, the response was overwhelmingly positive, with approximately 87% of mentors choosing “Agree” or “Strongly Agree” for every policy-related question. Of the remaining ~13%, all were “Neutral” and there were no “Disagree” or “Strongly Disagree” responses. This suggests that, at least for shop staff, MW policies are considered transparent, well-motivated, and easy-to-remember.

OVERALL MENTOR OUTCOMES

Targeted questions about shop specifics provide insight as to the effectiveness of its management, but other knowledge can be gained by looking at general data related to the mentors. Perhaps the strongest indicator of mentor satisfaction is retention rate – when a mentor continues in his/her position each semester, this indicates satisfaction with the role. This is especially true for an organization whose staff works on a volunteer basis and must contribute a reasonable amount of time each week.

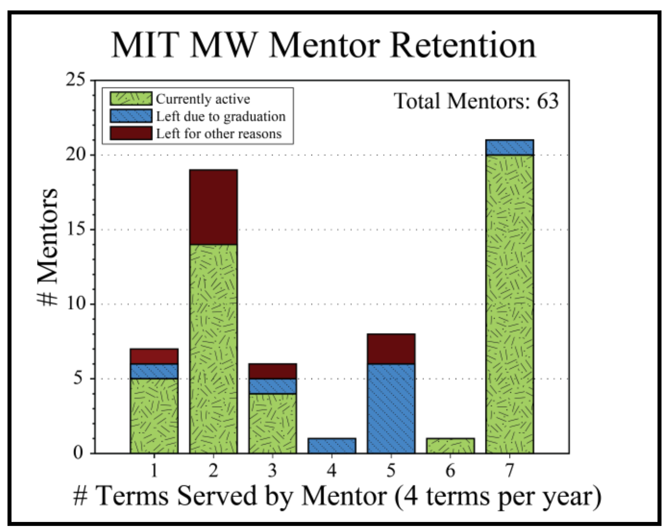

Fig 9: MIT MakerWorkshop Mentor Retention since opening in May 2015

Figure 9 shows the mentor retention data for the MIT MW since its inception in the spring of 2015. As of Fall 2016, 44 of

63 total mentors recruited (70%) are still active mentors, with nearly half of those (20) having served since the opening term. Of mentors who have left their mentor positions, 10 mentors (53%) only left due to graduation, while 9 (47%) left for other reasons (coursework and other competing time commitments).

As seen in Figure 10, when polled about the general outcomes of MIT MW mentorship, the staff again gave very positive responses. No question received more than one “Disagree” response and there were no “Strongly Disagree” responses. On average, of the nine areas polled, 24% of mentors responded “Neutral,” 48% responded “Agree,” and 26% responded “Strongly Agree,” indicating strong and consistently-positive outcomes from participation in the MIT MW as a mentor.

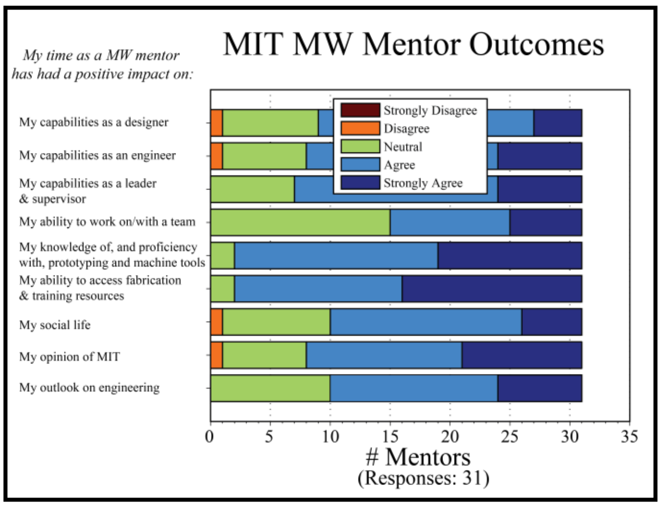

Fig 10: Results from 2016 MIT MakerWorkshop Mentor Survey on the topic of general mentor outcomes. Mentor answers demonstrate very positive outcomes and high satisfaction from spending time as a MW mentor.

CONCLUSIONS

Despite the challenges operating a maker space run by a large team of volunteers, high staff satisfaction and retention rate may be achieved through thoughtful shop management, layout/allocation of resources, communication, and rules/policies. The lessons learned while operating the MIT MakerWorkshop and laid out in this paper can be translated to other spaces of a similar nature to produce positive results, reduce overhead workload and improving staff satisfaction.

ACKNOWLEDGMENTS

The author would like to thank MIT’s Provost Martin Schmidt, the MIT School of Engineering, the Martin Trust Center, the Richard H. Lufkin Memorial Fund, the MIT Department of Mechanical Engineering, Prof. Dennis Freeman, and the MIT Project Manus initiative for providing support, encouragement and funding for the MIT MakerWorkshop. The author would also like to thank Prof. Martin Culpepper for serving as an amazing faculty advisor (Maker Czar) for our space. Finally, the author would like to thank all of our mentors, past and present, for all their time and dedication to designing, building, and maintaining the MIT MakerWorkshop.

Safety in a Student-Run Makerspace via Peer-to-Peer Adaptive Training

ISAM 2016
Paper No.:
33

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INTRODUCTION

The Invention Studio at Georgia Tech is a free-to-use, student-run makerspace that serves the entire body of students and employees of the Georgia Institute of Technology. Campus makerspaces, such as the Invention Studio, provide a low barrier of entry to hands-on prototyping and fabrication experience relative to the classic machine shop model [1]. The student supervision of the space creates a unique environment that fosters campus community involvement in "maker culture", which is shown to have a positive impact in the professional development of students in S.T.E.M majors [2, 3]. Despite the numerous proven benefits offered by student-leadership in campus makerspaces, student-run makerspaces are uncommon, due in part to skepticism over the ability of student oversight to maintain a reliably safe workshop environment.

Founded in 2009, the Invention Studio has grown consistently in terms of staffing, space, and impact on campus culture. Without existing procedures to accommodate rapid growth, the Invention Studio developed a series of policies to mitigate administrative concerns over safety and quality of service. After the implementation of the checklist training program in 2014, the Invention Studio saw a decrease in the occurrence of recordable work-related injuries, as defined by OSHA [4]. These policies, which are described below and packaged in the appendices, may serve as inspiration to readers who are facing similar challenges with the growth of their own student-led makerspaces.

HISTORICAL BACKGROUND

Reacting to growing industry demand for engineering students with hands-on experience, the George W. Woodruff School of Mechanical Engineering at Georgia Tech created the Invention Studio in 2009. Initially recruited to oversee a small prototyping facility for the Capstone Design course, faculty champions selected ten volunteer student instructors for their prior experience in a machine shop environment. This tightly-knit group facilitated student access to tooling through peer-to-peer instruction while offering opportunities for non-academic tool usage to a limited number of people [3].

At this initial time, safety policies were mostly divulged by word-of-mouth through instructor/user interactions. Due to the limited number of available instructors and minimal advertising, a small, yet highly engaged user base emerged. To continuously provide course support over time, this group acquired new members primarily through targeted recruitment of skilled and trustworthy members of the regular user base. The process was informal, guaranteeing safety only through the accountability of the limited number of highly invested volunteers. As the Invention Studio began to attract increased traffic, capital investment, and campus attention, the volunteer staff prioritized an increase in the availability of open hours. The rapid rise in staffing requirements led to a mass recruitment effort, where the previously utilized method of accountability through recommendation was no longer an option.

Following a brief period where tooling and procedural information was lost through graduation of key early members and an increased concern regarding the safety of operations, the student leaders of the Invention Studio recognized the need for more sustainable, methodological training solutions to accommodate the diverse user groups. The first attempt at student-generated policy to address this operational gap was introduced in 2014, and can be seen in Appendix 1. These policies and procedures, which are the primary focus of this paper, established and reinforced the current distribution pathways for knowledge, shown below in Fig. 1. Prototyping Instructors (or PIs) are student volunteers who maintain the space. Support staff includes professional staff hired by the Woodruff School. As can be seen in the Appendix 2, safety track record has been excellent. There have been zero OSHA defined reportable injuries since the implementation of the policies and First Aid Kit Usage shows that the worst injuries were small cuts requiring a bandage.

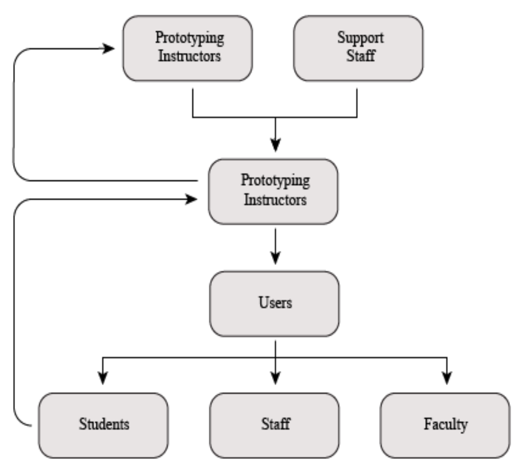

Fig. 1 Knowledge Transfer Pathways in the Invention Studio

A. *VARIOUS USERS, VARIOUS NEEDS, VARIOUS EQUIPMENT*

Because the Invention Studio serves the entire population of the Georgia Tech campus, the user base is composed of individuals with various levels of hands-on experience, technical education, and project aspirations. Because of the need to minimize the barrier to entry for equipment access in the Invention Studio, users are not typically required to record demographic information, such as major, gender, or project type. The diversity of majors that participate in the space may be inferred by an analysis of the PIs. The Invention Studio's student leadership began keeping records of involvement since the Fall semester of 2012, despite operations since Fall 2009. In that time, over 230 students had served in an instructional or leadership role in the Invention Studio. Fig. 2 shows the majors of all recorded student volunteers in the Invention Studio over the past four years.

To date, student volunteers from 16 majors/disciplines have served as PIs. Note that abbreviations ending in "E" represent an engineering major, with mechanical engineering representing the most significant contribution of PIs. This can be attributed to the Invention Studio's location within a Mechanical Engineering building in conjunction with hands-on ME course requirements. Other strong sources of PIs include Aerospace Engineering, Biomedical Engineering, and Electrical Engineering. Members of other majors that do not teach CAD and traditional manufacturing methods - such as Chemical Engineering, Computer Sciences, and Human-Computer Interaction are also represented in the figure.

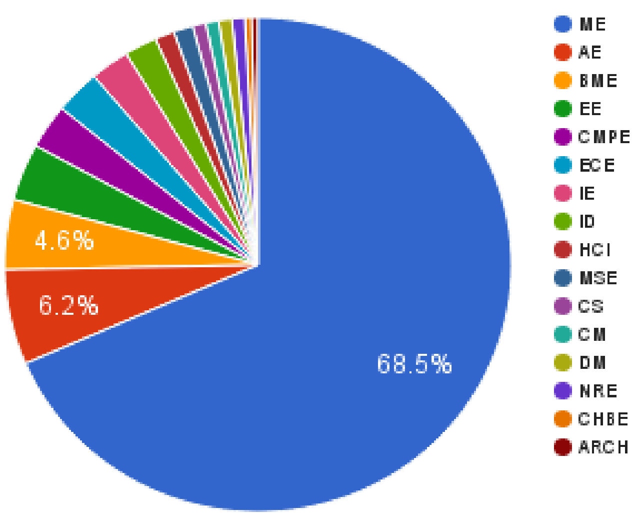

Fig. 2 Breakdown of Majors of All Recorded PIs

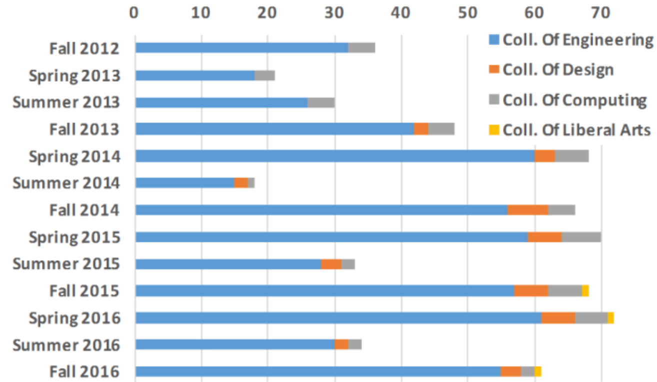

Fig. 3 Colleges of Active Prototyping Instructors per Semester

Fig. 3 illustrates the student involvement per semester by Georgia Tech. The number of active Prototyping Instructors fluctuates between semesters, with high turnout in the spring and fall, followed by a low participation in the summer, reflecting a campus-wide decrease in student presence. Four of Georgia Tech's six colleges have been represented in the Invention Studio's student volunteer base since Fall 2012, and participation of the College of Design and College of Liberal Arts is attributed to increased advertising and a campus-wide initiative for multi-disciplinary collaboration.

A wide variety of users require assistance with a broad range of projects - from holiday gifts to custom linear actuators. To successfully accommodate these project requests, the makerspace offers tools and equipment for processing many different methods and materials. As of the time of writing, the Invention Studio currently has six distinct categories of equipment, each with tools or features that require escalating levels of expertise and finesse. Examples of these categories and the tool offerings are shown in Table 1. Users are introduced to the appropriate tools and techniques for their projects as needed, but PIs generally train users on low-risk tools first. PIs who feel confident about the students' grasp of low-difficulty and low-risk tools provide additional training on higher difficulty tools, as listed below. Please note, the equipment list is not meant as an all-inclusive list of the available tools in the Invention Studio. Rather, it serves as an example of different training paths available.

Table 1 Equipment Available to Students by Difficulty Level

Tool type	Lowest Difficulty	Intermediate Difficulty	Highest Difficulty
Electronics	Soldering and Bread boards	Arduinos, Raspberry Pi programming	PCB milling machine
3D Printers	Afinia UP and UP mini	Makerbot Z18, UP box	Formlab, Hyrel
Waterjet	3 axis control	5 axis A-Jet technology	Advanced materials
Laser Cutter	Standard operating mode	Rotary attachment	Higher focal length lens
Wood-working	Handheld power tools	Planer, Table saw	Jointer, Wood lathe
Metal-working	Hand Tools	Metal Mill/Lathe	6 axis CNC

B. VARIED USER TRAINING OPPORTUNITIES

While access to equipment incentivizes participation of select users, the method of instruction delivery is key to creating a socially comfortable environment. Peer-to-peer learning has been shown to be beneficial in a classroom setting [5]. The Invention Studio takes advantage of the student-run aspect by creating a comfortable environment due to being taught by peers rather than traditional machine shop personnel. The comfort level is also increased by allowing the students to come and learn the equipment on their schedule. Rather than having structured and inflexible training times for students, the Invention Studio offers walk-in training on most of the equipment. To accommodate users who are not comfortable with the informal teaching methods, the volunteers in the Invention Studio offer structured training sessions on the equipment after normal studio hours.

Many times there are students who would like to learn the equipment but do not have a specific project in mind that they could use it for. For those students, the studio offers after-hours workshop events. These events serve to teach the students targeted equipment, ultimately working towards the same final goal of creating something they can take home such as a steel rose for Valentine's day. There are also events held for specific groups on campus, such as the "Ladies Night in the Invention Studio" for female engineering students. [6]

SAFETY AND TOOL TRAINING

C. PROTOTYPE INSTRUCTOR BASIC TRAINING

The perks granted to PIs, particularly 24/7 access to the equipment, prove attractive to many regular users in the space. Many students are inspired to become Prototyping Instructors, and therefore contribute to the culture of safety. To become a PI, the checklist program must be completed by recruits. A full copy of the Invention Studio current checklist at the time of writing can be seen in Appendix 3. The goal of the checklist program is to ensure a baseline competency for new PIs on all major equipment in the makerspace. The checklist does not indicate mastery or advanced knowledge of the equipment, but it does guarantee an understanding of safety protocols among Invention Studio PIs. The process was designed as a hands-on training tool, where the students learn through practice as has been shown to work in other instructional labs [7]. For each of the sections of the checklist, the potential PI must follow guidelines to create a specific object using key equipment in that category. For example, the woodworking task is to build the GT emblem shown in Fig. 4 by utilizing the relatively low-risk wood shop equipment.

Ideally, potential PIs have already spent time using the Invention Studio's equipment before attempting the checklist. However, if there is a tool they are unfamiliar with, they must get the appropriate training at least 24 hours before the start of that checklist item. This ensures that candidates do not simply copy what they have just been shown. In times of high machine traffic, students may seek supplemental information from the training videos created for the majority of low-risk tools in the Invention Studio. This "flipped classroom" technique exposes the students to an overview of safety guidelines and procedures, which allows for time in the studio to be focused on the details of practical machine use [8]. Because these videos feature the specific equipment available in the Invention Studio, students can draw directly from the lessons in the instructional videos when machine time becomes available. However, as Ian Charmas points out in his 2014 MakerCon presentation, videos can quickly become outdated [9]. Therefore, rather than solely relying on videos which require significant time, planning, and coordination to produce; an equipment and rules wiki-style site is monitored and populated by the Prototyping Instructors to serve as an up to date reference.

Fig.4 Woodroom Checklist Item

Once a potential PI feels confident enough in his or her knowledge, work on the checklist piece may begin. If they require help from the PI overseeing their room, the work done on the checklist task is discounted, and the recruit must retry that task another day. Following the completion of the task, the PI will compare the student's object with the sample object, and, if satisfied, he or she will sign off on that checklist item. The signature confirms that task was completed correctly, safely, and independently. Following completion of all checklist items and a brief culture-fit interview, the student assumes the role of PI, and begins overseeing the space, maintaining safety for the users and other volunteers.

D. *ADDITIONAL PROTOTYPE INSTRUCTOR TRAINING*

The training does not end once a person completes the checklist and is accepted as a Prototype Instructor. Because students are responsible for the upkeep and making equipment purchase recommendations, it is necessary to ensure specialized knowledge is transferred from one year's class to the next and is not lost when an expert member graduates. Each student has the option to specialize in any of the equipment in the studio to become a "master" of that tool. To do so, the student must complete the guided curriculum outlined by the current masters of their tool of choice (see Appendix 4 for example). The curriculum goes over how to repair the equipment as well as some of the nuances of the tools. Keeping with the theme of hands-on learning and makerspace culture, the apprentice student must complete a complex project using their newly mastered tool to prove their competency and finish their mastership training.

Another form of training offered to accepted Prototype Instructors is in an independent learning format called the "Maker Grant" program. Maker Grants are monetary grants given to any PI who wants to learn how to make a particular item using Invention Studio tools. The applicant PI must write a proposal outlining the budget, idea, and what he/she will learn from the experience. The premise behind funding personal projects is that if a student learns how to build a specific project, then they will be able to pass that knowledge on to the rest of the volunteer group and expand the library of knowledge that can be passed on to the users of the space.

RESULTS OF TRAINING

Efforts to appeal to as many different types of Georgia Tech students as possible have had outstanding success in attracting users and keeping them safe. As discussed previously, tools available in the Invention Studio are used by students and faculty from various engineering and non-engineering disciplines. As mentioned earlier, to keep the barriers to entry as low as possible, students are not required to sign in to use most equipment in the space, and this limits the ability to record demographic usage data. However, the professional printers and waterjet both require user input and therefore can be used to represent the usage of the studio as a whole. Fig. 5 shows the breakdown of unique users of the Professional 3D printers during last four years.

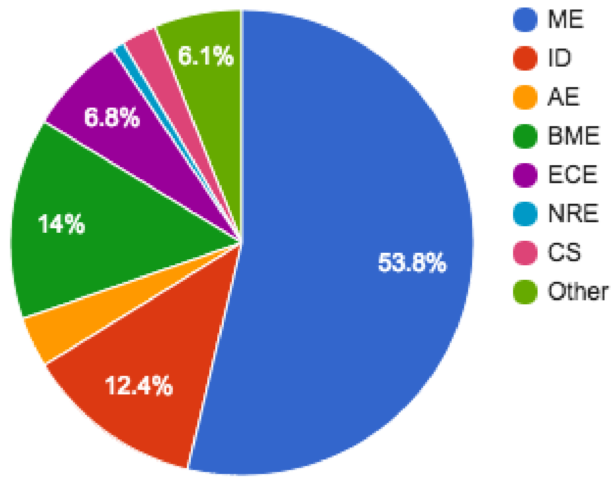

Fig. 5 Professional 3D Printers unique users by Student Major

As shown, approximately half of the total printer use comes from users outside the School of Mechanical Engineering even though the Invention Studio is housed in the mechanical engineering building. See Appendix 5 for a complete list of all majors and the amount of material used.

Besides accommodations for the user of any major, the Invention Studio prides itself on accessibility for a wide range of project possibilities. For diagnostic operations, one of the major tools, the waterjet cutter, requires logging of usage reasons in addition to standard equipment. Usage over the most recent semester, Summer 2016, indicates the diversity of usage in the Invention Studio. This data is shown in Fig. 6, and it provides a quantitative breakdown of the different uses of the Invention Studio. It is important to note that only 2% of the actual Waterjet use is for basic PI training. This exemplifies the impact the aforementioned training videos and other resources have to streamline the training process. Even during a semester with a low academic presence from decreased student population, equipment is still used regularly. Refer Appendix 6 for information on the daily usage of the waterjet from March 2016 to July 2016.

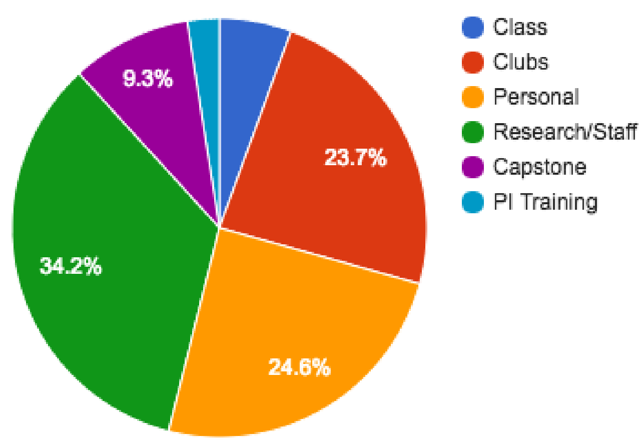

Fig. 6 Waterjet Usage by User Category

The instruction methodology of the Invention Studio seeks to enforce the diversity of projects and users that it naturally inspires. Through outreach events, space combats the pervasive issue of poor representation of females in STEM fields. Among the documented reasons for low female participation in STEM are a lack of opportunity, lack of role models, and a highly unbalanced male-to-female ratio [10]. Ultimately, those factors serve as barriers to hands-on familiarity by intimidation. Through the peer-to-peer training approach of the Invention Studio, some of that intimidation is mitigated. The Invention Studio has many strong female leaders who are Masters and PIs to serve as a role model. A biannual ladies' night hosted by the Invention Studio is specifically targeted towards women. The number of active PIs has doubled since 2013 due to these efforts.

Conclusion

The largest cause for concern in a student-run makerspace has always been safety. However, the case study of the Invention Studio shows that with the right training practices in place, a student-run environment can provide a genuinely safe and accessible learning environment. The student involvement and efforts of the Invention Studio have produced an open and welcoming culture for all Georgia Tech students ever since its conception. The specialized training for student volunteers keeps the equipment functional and mitigates the loss of knowledge from student graduation. The Invention Studio has been shown to be a safe environment through peer-to-peer adaptive training practices.

Acknowledgements

The authors of this paper would like to thank the following supporters of the Invention Studio and its mission:

The George W. Woodruff School of Mechanical Engineering - particularly School Chair, Dr. Bill Wepfer - for the continuous commitment to hands-on education, and for the belief in and support of the student-run makerspace model.

Dr. Craig Forest, for inspiring the founding members of the Invention Studio, reminding the space of its history and roots, and for the constructive advice and encouragement on this paper. The Invention Studio would not be what it is today without his invaluable input and creative vision.

Dr. Julie Linsey, for the advisement, resources, and time devoted to the Invention Studio and its student volunteers.

Mr. Clint Rinehart, for his expert guidance and mentorship on tool operation, repair as well as for generating the data from the Professional 3D printers reported in this paper.

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Appendix 1: Invention Studio Checklist V1.0

Georgia Tech Invention Studio
ULI Basic Skills Test
Version 1.0 (April 2014)

Name: ___________________________
Date:____________________________
GT Email: ________________________

Before you start the test:
1. Read this wiki article: http://inventionstudio.gatech.edu/wiki/ULI_Recruitment_and_Training
2. Find a ULI to check you off.
3. Perform the test tasks!

Hints:
-You can take each test separately.
-If you fail a section you will have to wait 24 hours to retake it.

3D Printer Test *Required: Standard .stl file.*	ULI Name: __________________________ ULI Signature: _______________________

1. Obtain the standard .STL file from the ULI training wiki article.
2. Use the slicing software that corresponds to the printer you want to use to slice the file and put it on an SD card. Use a raft and support material.
3. Print out the part.

Wood Room Test *Required: 2x4 board scrap.*	ULI Name: __________________________ ULI Signature: _______________________

1. Go into the wood shop.
2. Take a 2x4 board or another similar piece of scrap board and use the miter saw to cut off a 6” section.
3. Use the band saw to cut it in half.
4. Drill two holes in each piece. Use the drill press for one piece. Use the hand drill for the other.

Georgia Tech Invention Studio
ULI Basic Skills Test
Version 1.0 (April 2014)

Name: ____________________________
Date:_____________________________
GT Email: _________________________

Waterjet Test *Required: Standard .dxf file.*	ULI Name: ___________________________ ULI Signature: ________________________

1. Take the standard .DXF file from the wiki.
2. Import it into OMAX Layout.
3. Prepare the file for cutting. Use tabs and nesting to make two copies of the default part.
4. Export to OMAX Make. Set proper material settings.
5. Cut out the part.

Laser Cutter Test *Required: Standard .dxf file.*	ULI Name: ___________________________ ULI Signature: ________________________

1. Use the standard .DXF file from the wiki.
2. Open the file using Inkscape, EngraveLab, or AutoCAD.
3. Edit the file for laser cutting.
4. Send the file to JobControl.
4. Cut out the part using proper settings for the material you’re using.

Appendix 2: First Aid Kit Usage from Nov 1, 2015 - Oct 31st, 2016

Room	# Minor Injuries
Waterjet/Laser Cutters	29
Woodroom	29
Electonics and Metal	36
3D printers	45

Waterjet Room	
Date	Item
11/11/2015	Gauze
11/12/2015	Bandage
11/19/2015	Bandage
1/16/2016	Bandage
2/18/2016	Bandage
3/4/2016	Bandage
3/9/2016	Bandage
3/12/2016	Bandage
3/14/2016	Bandage
3/15/2016	Bandage/Antiseptic wipe
3/20/2016	Bandage
3/23/2016	Bandage
3/25/2016	Bandage
3/31/2016	Bandage
4/7/2016	Bandage
4/7/2016	Bandage/Antiseptic wipe
4/7/2016	Bandage
4/12/2016	Bandage/Antiseptic wipe
4/17/2016	Bandage
4/21/2016	Bandage
4/21/2016	Bandage
4/21/2016	Bandage
4/23/2016	Bandage
5/6/2016	Bandage
6/9/2016	Bandage
7/26/2016	Bandage
7/27/2016	Bandage/Antiseptic wipe
9/16/2016	Bandage/Antiseptic wipe
9/22/2016	Bandage

Woodroom	
Date	Item
11/4/2015	Bandage
11/7/2015	Bandage
11/9/2015	Bandage
11/17/2015	Bandage
2/4/2016	Bandage
2/12/2016	Bandage/Antiseptic wipe
2/16/2016	Bandage/Antiseptic wipe
2/16/2016	Bandage
3/18/2016	Bandage
3/26/2016	Bandage/Antiseptic wipe
3/26/2016	Bandage/Gauze
3/28/2016	Bandage/Antiseptic wipe
3/30/2016	Bandage
3/30/2016	Bandage/Antiseptic wipe
3/31/2016	Bandage/Antiseptic wipe
4/2/2016	Bandage/Antiseptic wipe
4/3/2016	Antiseptic wipe
4/21/2016	Bandage
4/27/2016	Antiseptic wipe
6/9/2016	Bandage
8/31/2016	Bandage
9/25/2016	Bandage
9/28/2016	Bandage
10/19/2016	Bandage
10/19/2016	Bandage
10/20/2016	Bandage
10/24/2016	Bandage
10/25/2016	Bandage
10/28/2016	Bandage/Tape

Electrolounge/Metal Room	
Date	**Item**
11/1/2015	Bandage
11/1/2015	Bandage
11/3/2015	Bandage/Antiseptic wipe
11/12/2015	Bandage
11/17/2015	Bandage
11/17/2015	Bandage/Antiseptic wipe
11/23/2015	Bandage
11/23/2015	Antiseptic wipe
11/27/2015	Bandage/Antiseptic wipe
12/5/2015	Bandage
1/20/2016	Bandage
1/28/2016	Bandage/Antiseptic wipe
2/10/2016	Bandage
2/11/2016	Bandage
2/15/2016	Bandage/Antiseptic wipe
2/25/2016	Bandage
3/1/2016	Bandage
3/8/2016	Bandage/Gauze
3/19/2016	Bandage/Antiseptic wipe
3/29/2016	Bandage
4/7/2016	Bandage
4/10/2016	Bandage
4/13/2016	Bandage
4/21/2016	Bandage
4/22/2016	Bandage
4/23/2016	Bandage
8/31/2016	Bandage
9/7/2016	Bandage
9/8/2016	Bandage
9/9/2016	Bandage/Antiseptic wipe
9/9/2016	Bandage/Antiseptic wipe
9/20/2016	Bandage
9/23/2016	Bandage
10/4/2016	Bandage/Antiseptic wipe
10/6/2016	Bandage
10/10/2016	Bandage

3D Print Room	
Date	**Item**
11/7/2015	Bandage
11/24/2015	Bandage/Antiseptic wipe
1/29/2016	Bandage
1/29/2016	Bandage
1/29/2016	Bandage
2/8/2016	Bandage
2/17/2016	Bandage
2/18/2016	Bandage
2/25/2016	Bandage
2/26/2016	Bandage/Gauze
2/26/2016	Bandage/Antiseptic wipe
2/29/2016	Bandage
3/5/2016	Bandage
3/7/2016	Bandage
3/9/2016	Bandage
3/12/2016	Bandage
3/17/2016	Bandage
3/20/2016	Gauze/Antiseptic wipe
3/29/2016	Bandage
3/30/2016	Bandage
4/6/2016	Bandage
4/16/2016	Gauze/Tape
4/18/2016	Bandage
4/18/2016	Bandage
4/30/2016	Bandage
5/1/2016	Bandage
6/13/2016	Bandage
8/4/2016	Bandage
8/31/2016	Gauze/Antiseptic wipe
9/13/2016	Bandage
9/16/2016	Bandage
9/20/2016	Bandage
9/20/2016	Bandage
9/21/2016	Bandage
9/29/2016	Bandage
9/30/2016	Bandage
10/17/2016	Bandage
10/19/2016	Bandage
10/26/2016	Bandage
10/26/2016	Bandage
11/19/2016	Bandage
11/25/2016	Bandage
11/28/2016	Bandage
11/28/2016	Bandage/Antiseptic wipe
11/29/2016	Bandage

Appendix 3: Invention Studio Checklist V3.1

Georgia Tech Invention Studio
ISPI Basic Skills Checklist
Version 3.1 (November 2015)

Name:________________________
Date:________________________
GT Email:________________________
GTID #:________________________
(If Applicable) SCC Team :________________________

Please note: If you are accepted as an ISPI or SCC team access holder, your information may be disclosed to other parties for the purpose of requesting access.

Before you start the test:
1. Read this wiki article: http://inventionstudio.gatech.edu/wiki/Recruitment_and_Training
2. Find an ISPI to check you off.
3. Perform the test tasks!
4. Do the 3D printer test last and drop off the checklist with the completed 3D printer part.

Hints:
-You can take each test separately.
-You have to wait 24 hours after getting trained to get checked off.
-If you fail a section you will have to wait 24 hours to retake it.
-You can keep your parts after you get signed off.

Wood Room Test *Required:* *Plywood Sheet* *2"x 4" Stock*	ISPI Name ____________________ ISPI Signature ______________________	Date:

Refer to the examples provided for how the completed product should look. Using only the tools in the wood room, complete the following tasks:

1. Cut out a 3" by 5" plywood rectangle on the Bandsaw. This is to be used for the base.
2. Cut a 7" piece of 2x4 stock using the Miter Saw.
    a. Use the template to draw GT logo on remaining piece of plywood. Then cut out the logo using the scroll saw.
    b. Using the Spindle Sander, smooth the inside curves of the GT.
3. Use the disc sander to round edges on the plywood base.
4. Use drill press to drill holes two holes in the plywood base. (These holes will be use in the next step to attach the plywood base to the 2x4 piece, so choose the location of the holes carefully.)
    a. Select an appropriate drill bit for the wood screws.
5. Use the hand drill to attach the plywood base to the 2x4 using two wood screws
    a. CLAMP!
    b. Create two pilot drill holes in the 2'' by 4'' to prevent wood from splitting.
6. Use whatever tools necessary to attach the GT logo to the 2x4 using two wood screws.
    a. CLAMP!
    b. Create pilot drill holes to prevent wood from splitting.
7. Clean up after yourself.
8. Have a PI compare your copy to the example copies.

Laser Test *Required:* *Plywood Sheet (in a box over banana)* *IS Logo in Vector Format*	ISPI Name __________________ ISPI Signature ____________________	Date:

The goal is to engrave the IS logo using two different depths and cut out the design.

1. Demonstrate the laser shutdown and startup procedure.
2. Download and bring the IS logo from the recruitment page on a flash drive
    a. It is already in a vector format.
3. Change the Fill & Stroke of the existing lines to:
    a. Deep etch the gear
    b. "Invention Studio" and all shapes in the center are shallow etched
    c. "Design - Build - Play" is not etched
    d. Add a shape of your choice to cut out the design
4. Show the finished product to a PI to be signed off

Soldering Test *Required:* *Perforated board* *LED* *1k ohm resistor* *Wire and Solder*	ISPI Name __________________ ISPI Signature ____________________	Date:

1. Find and set aside an LED, 1K ohm resistor, a spool of wire, and a spool of solder
2. Turn the soldering iron on and wait for it to reach its optimal temperature
3. Tin the iron using a dab of solder and either a wet sponge or the steel wool
4. Strip a small amount of wire and solder it to the perforated board.
    a. Strip it on both sides so one exposed end goes into the board and the other can be clipped to by an alligator clip
    b. Mark wire either with the color of the insulation or tape as the positive end of the circuit
5. Place the resistor on the board and solder the resistor.
    a. Make sure to place the resistor close enough to the wire soldered in step 4.
    b. Make a solder joint between the wire soldered in step 4 and one of the resistor leads
6. Paying attention to polarity, solder the LED to the board
    a. Create a solder joint between the resistor and the positive end of the LED (negative end will have a shorter lead or flat side)
7. Create another wire like in step 4 and solder it to the negative end of the LED
8. Tin and turn off the iron
9. Wash your hands!
10. Hook up the circuit to a 3.0V power supply on the bench and demonstrate the lit LED to a PI.
11. Desolder all parts from your board and clean up.

Waterjet Test *Required:* *Small sheet of aluminum*	ISPI Name ___________________ ISPI Signature ____________________	Date:

1. Demonstrate waterjet shutdown and startup procedure.
2. Take the test .DXF file from the wiki and put it on a flash drive.
3. Bring the file to the waterjet computer and import it into OMAX Layout. The .DXF file is in inches.
4. Prepare the file for cutting. Use tabs for both parts.
5. Export to OMAX Make and set proper material settings. Be efficient with space on the test material.
6. Note: The material you are cutting is fairly thin, so be careful on how you clamp it so it doesn't bow or shift during cutting. If this happens, your cut was not successful.
7. Test the placement of your cut by going to various spots on the path. Make sure it doesn't go off the edges or collide with any weights or clamps. Also, reduce the amount of material wasted by locating your piece near previous cuts.
8. Cut out the part. When finished, record your information and the pump hours in the logbook.
9. Keep both parts. They will be used to complete the metal room checklist.
10. Show the finished parts to a PI to get checked off.

Metal Shop Test *Required:* *Components from the Waterjet Test*	ISPI Name ___________________ ISPI Signature ____________________	Date:

1. Complete the waterjet test and keep both parts.
2. Use the shear to remove the extra flange on one side of the large plate. After you do this, all four sides will be the same height.
3. Remove tabs and deburr the edges using the belt sander.
4. Place the smaller GT plate on the center of the larger plate. Use a center punch to mark the locations of the two holes in the GT plate on the larger plate. (These holes will be used to attach the GT plate to the big plate later on.)
5. Use the drill press and an appropriately-sized drill bit to create holes for a ⅛" diameter rivet (provided). Drill these holes where you marked them. (Hint: Take the rivet to the drill bit box, and use it to find the right size bit, it should be larger than the rivet.)
6. Countersink the holes.
7. Using the sheet metal brake, bend the large plate into a box. Make sure you bend the box so that the countersinks are on the outside of the box.
8. Use two rivets to fasten the GT plate to the inside of the box. Use the countersunk ⅛" rivets that are provided. If there are none available, regular ⅛" rivets are acceptable.
9. Show the finished box to a PI to be checked off.
10. Have a PI compare your copy to the example copies.

3D Printing Test *Required:* *Example File from Thingiverse*	ISPI Name ___________________ ISPI Signature ____________________	Date:

1. Unload filament from UP! Mini/Afinia.
2. Reload filament from UP! Mini/Afinia.
3. Complete and assemble propeller launcher build. Feel free to scale your parts, but all parts must be scaled by the same factor. http://www.thingiverse.com/thing:312971/#instructions The following steps must be displayed to a current ISPI for at least 1 part in the build:
   a. Print setup:
      i. Load a part
      ii. Orient a part (rotate the part so it fits on the platform)
      iii. Scale the part by .8
      iv. Print a part (including a walk-through of the print settings)
   b. Print cleanup:
      i. Remove part from printer
      ii. Clean up workspace
4. Show a PI that your completed and assembled part can fly

Appendix 4: 3D Printer Apprentice Checklist

3D Printer Apprentice Checklist (as of 08/20/2016)
You must complete all mandatory requirements for each printer

Apprentice Name:________________________________

Masterpiece requirement

Each apprentice must complete a “masterpiece” to be fully considered for a master's position. The “masterpiece” must be of sufficient complexity as to showcase the benefits of 3D printing technology. For any composition to be seriously considered an adequate “masterpiece” the work is required to exemplify, at bare minimum, a singular advanced additive manufacturing characteristic from the subsequent index:

1. Made of more than one material
2. Kinetic or interactive
3. Obvious focus on practicality, usability, or personalization
4. Integrated electro-mechanical design
5. A downright stupendous work of art that makes our jaws drop due to the impossibility of how it actually printed

Mandatory checklists

UP! Mini/ Afinia Printer

- ❏ Unload and reload filament
- ❏ Full understanding of print settings & print procedure
- ❏ Calibrate the build platform
- ❏ Diagnose common print errors
    - ❏ “Clacking” print head
    - ❏ Not extruding filament
    - ❏ Jittering axis
    - ❏ Printer emits long, unending beep
    - ❏ Filament looks “squished” on the build platform
    - ❏ Filament peeling from platform
    - ❏ Filament printing in “thin-air”
- ❏ Disassemble printer head
- ❏ De-clog nozzle
- ❏ Clean gearhead

<u>UP! Box Printer</u>

- ❏ List major differences between UP! Box and UP! Mini

<u>Makerbot Replicator Z18 Printer</u>

- ❏ Unload and reload filament
- ❏ Full understanding of print settings & print procedure
- ❏ Calibrate the build platform
- ❏ Diagnose common print errors
    - ❏ Smart extruder errors
    - ❏ Not extruding filament
    - ❏ Filament peeling from platform
- ❏ Disassemble printer head
- ❏ De-clog nozzle
- ❏ Know rules for printing large parts

<u>Hyrel Printer</u>

- ❏ Unload and reload filament
- ❏ Swap printheads
- ❏ Level print bed
- ❏ Calibrate Z Height
- ❏ Create your own slic3r settings for ninjaflex
- ❏ Prepare bed for printing
- ❏ Diagnose common print errors and live repair if applicable
    - ❏ Not Extruding
    - ❏ Over Extrusion
    - ❏ Peeling from the layer or the bed
    - ❏ Starts building off the plate
    - ❏ Extruding in air

<u>Formlab 1+ Printer</u>

- ❏ Prepare Formlab for printing
- ❏ Print something to exclusive to SLA
    - ❏ Full understanding of optimal part positioning and support structures
- ❏ Post Print Clean-Up

Faro Arm Scanner

- ❏ Startup the Faro arm
  - ❏ Attach Laser Probe to the arm
  - ❏ Connect required cords
  - ❏ Startup the correct software
  - ❏ Ready the program to take a scan
- ❏ Calibrate the faro arm
  - ❏ Calibrate the touch probe
  - ❏ Calibrate the laser probe
- ❏ Demonstrate knowledge of the settings
  - ❏ What is scan rate
  - ❏ What is scan density
  - ❏ What are the proper setting to not fill holes
- ❏ Scan a “complex” object
  - ❏ Scan requires at least two separate scans to get all of the sides of the object
- ❏ Cleanup the file
  - ❏ Combine your multiple scans to create on part
  - ❏ Fill all the holes in the part so that it is a printable file
- ❏ Export your file in an appropriate format
- ❏ Shutdown the Faro arm
  - ❏ Properly pack up components
  - ❏ Turn off everything that needs to be turned off

MCOR Iris Printer

- ❏ Know how to load an .stl file
  - ❏ Know orientation tricks for optimal color reproduction vs model durability
- ❏ Full understanding of print settings & print procedure
  - ❏ Knife/Cutter calibration
  - ❏ Glue Wheel checks & cleaning
  - ❏ How to properly attach the base paper layer to the print bed
- ❏ Diagnose common print errors
  - ❏ Error 28
  - ❏ Error 29
  - ❏ Inkjet problems
  - ❏ How to get Mcor Support to respond promptly (Jeff trick)
- ❏ Know how to reload paper
- ❏ Know how to refill glue
- ❏ Know when the glue line is clogged
- ❏ Know how to purge the glue system

BIBO Printer

- ❏ Explain CURA software options/navigation
  - ❏ How you do move the head/platform using CURA?
  - ❏ How do you save material settings in CURA?
- ❏ How do you move the head/platform using the touch screen?
- ❏ How would you fix a melty goopy mess on top of a print?
- ❏ Unload/reload 2 different types of filament
- ❏ 3D print a vase (single layer wall thickness, spiral formation)
  - ❏ Prepare the platform for proper adhesion

3D Printer Basic Knowledge

- ❏ What are the 6 types of 3D printing techniques?
- ❏ When should stereolithography be used?
- ❏ What are limiting factors for 3D printing?
- ❏ What is the difference between ABS and PLA plastics?
- ❏ When should you direct someone to use the professional 3D printers? (i.e. Stratasys, Objet Eden etc.)
- ❏ What is bridging?

Optional Checklist

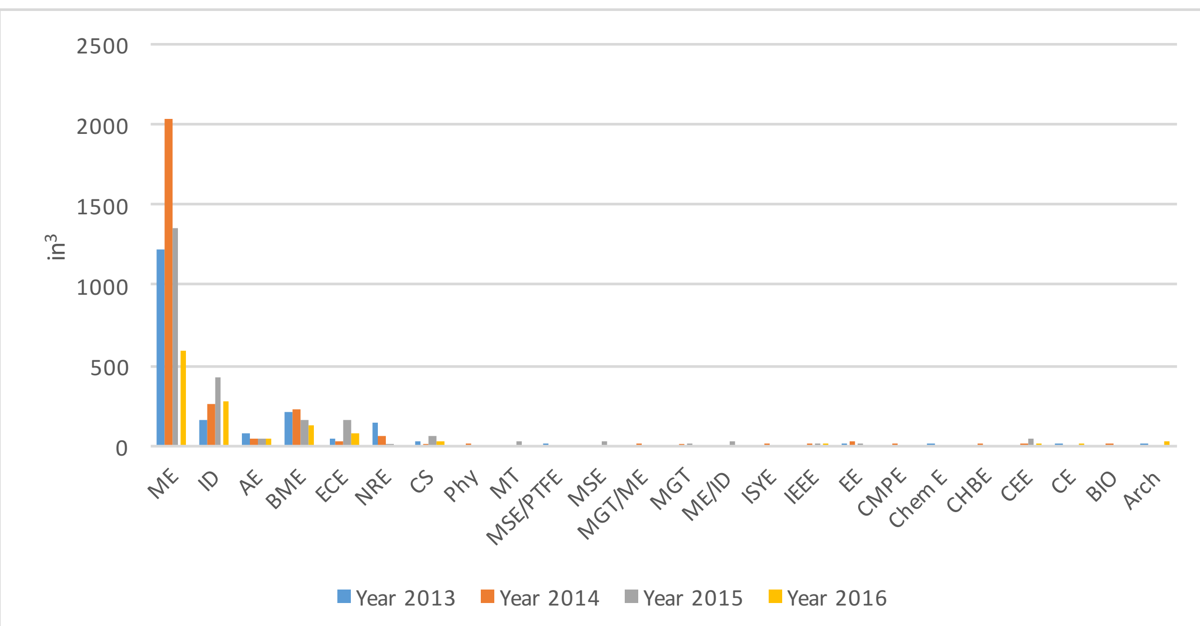
David scanner/ Next engine scanner

- ❏ Using the wiki/guide, scan an object
- ❏ Optional: Print your model in color on the MCOR

Appendix 5: Professional 3D printer material usage

Professional 3D Printers material usage in cubic inches by majors (as of 06/30/2016)

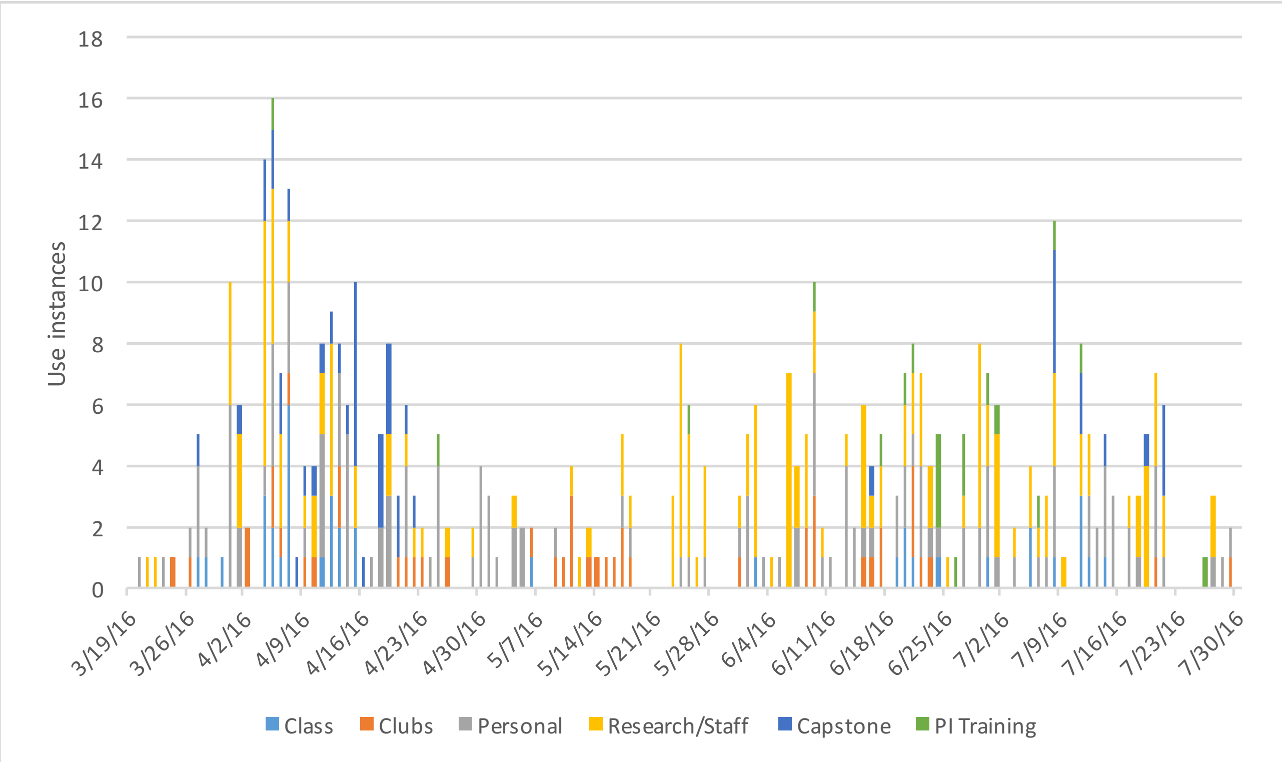
Majors	Year 2013	Year 2014	Year 2015	Year 2016	Total	%
ME	1229.55	2033.25	1358	601.3	5222.1	63.2153506
ID	158.33	260.83	429.9	277.4	1126.46	13.6361931
AE	81.19	52.13	53.66	46.9	233.88	2.83119936
BME	208.78	225.03	157.5	121.53	712.84	8.62917801
ECE	49.13	30.31	164.98	86.32	330.74	4.00372361
NRE	148.16	57.69	20.57		226.42	2.74089345
CS	25.17	18.66	57.59	25.23	126.65	1.53314263
Phy		1.91			1.91	0.02312122
MT			33.66		33.66	0.4074661
MSE/PTFE	0.56				0.56	0.006779
MSE			26.87		26.87	0.32527077
MGT/ME		4.28			4.28	0.0518109
MGT		19.42	14.91		34.33	0.41557668
ME/ID			38.14		38.14	0.46169807
ISYE		1.6			1.6	0.01936856
IEEE		0.18	2.05	0.53	2.76	0.03341077
EE	4.25	33.17	4.31		41.73	0.50515627
CMPE		0.57			0.57	0.00690005
Chem E	1.47				1.47	0.01779487
CHBE		3.05			3.05	0.03692132
CEE		3.02	42.48	0.62	46.12	0.55829876
CE	0.84			3.23	4.07	0.04926878
BIO		0.89			0.89	0.01077376
Arch	10.36			29.35	39.71	0.48070347
Grand Total	1917.79	2745.99	2404.62	1192.41	8260.81	100



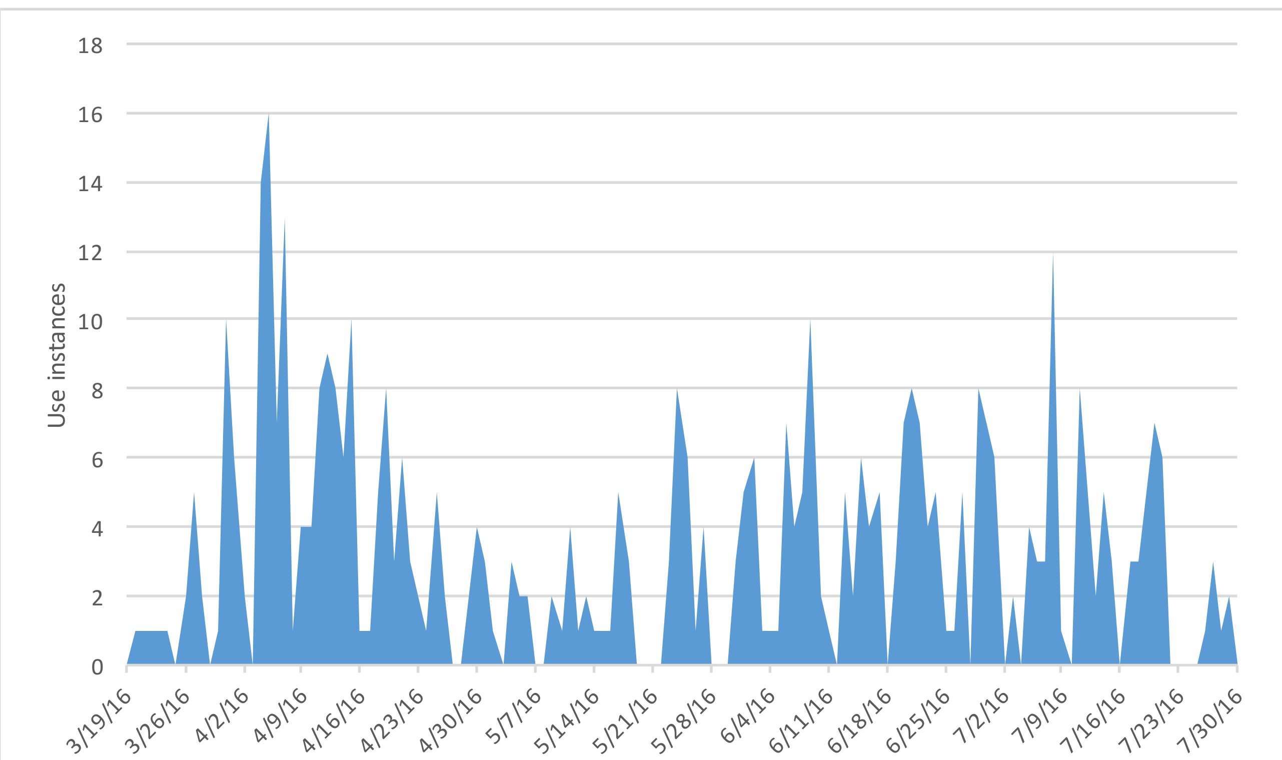
Appendix 6: Waterjet Daily Usage

Daily Waterjet Usage by Category

Category	Class	Clubs	Personal	Research/Staff	Capstone	PI Training
Total Hours	39	47	135	154	45	19



Total Use Instances by Day



ISAM 2016 Paper No.: 34

Invited

Digi-net: Creating, Assessing, and Improving a State-Wide 3D Printing Network

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I. Introduction

Hands-on learning plays a vital role in Engineering Education at Penn State University. For over two decades, the Bernard M. Gordon Award-winning Learning Factory has been the home for many of these efforts within the College of Engineering [1]. While undergraduate students from the Mechanical Engineering Department were the primary users for its first decade [2], much of last ten years has been spent expanding into the rest of the College and partnering across University Park campus [3]. The model has also been replicated at several of Penn State's 24 campuses, which are scattered across the Commonwealth (Fig. 1).

Figure 1 - There are 24 Penn State campuses across the Commonwealth.

Increased demand and limited availability at the geographically dispersed campus locations inspired the creation of a network of capabilities referred to as "Digi-net," short for Digital Fabrication Network (Fig. 2). Through Digi-net, all ~100,000 Penn State students have free access to 3D printing capabilities.

Digi-net was born out of the desire to better accommodate student needs—and to foster collaboration between design-minded faculty and students across the university. This required three things: 1) buy-in from the various stakeholders; 2) an inventory of the campus facilities and assets; and 3) a mechanism for allowing shared use.

These activities positioned Penn State well for a number of recent opportunities. We were a founding member of America Makes (National Additive Manufacturing Innovation Institute), and Penn State and the associated Applied Research Lab (ARL, a U.S. Navy University Affiliated Research Center) were among the first DMDII projects. It also helped secure significant funding from DARPA to lead several advanced manufacturing effotts (e.g., DARPA's iFAB Program their Open Manufacturing Demonstration Facility).

II. Philosophy

Making is a neutral discipline in which we are able to collaborate with individuals whose training and experience are distinct and diverse. It also provides an opportunity for our students to experience hands-on learning in new ways. For example, in addition to the traditional courses that require students to build or create a physical artifact (e.g., Capstone in Engineering or Pottery in Art), Digi-net has enabled new teaching opportunities. In Spring 2016, making was a critical component of a Technical Writing course in English, an Entrepreneurship course in Information Sciences and Technology, and a bioprinting course in Engineering Science.

The making capacity of Digi-net has also created a "technology push" environment in which faculty are finding new opportunities to put it to use. One example is a new Making for the Masses (M4M) general education course that will be offered in Spring 2017. Six faculty from Engineering, Architecture, Art, and Education have collaborated to create a course that allows students to experience different making philosophies, from problem-solving to self-expression. With an enrollment limit of 150 students and no restrictions on major, students from all disciplines will interact and discover both the historical and personal characteristics of the maker movement.

III. Resources

PSU has invested heavily in making, including additive manufacturing. When Digi-Net was first established in 2011, there were less than a dozen 3D printers on campus. Now there are more than 100. While the majority of these are associated with the College of Engineering (e.g., Mechanical Engineering, Industrial Engineering, Learning Factory), departments in the College of Arts & Architecture and Eberly College of Science have also become involved with 3D printing. There are, however, a number of other digital fabrication resources available to Penn State students, including laser cutters, water jet cutters, CNC machines, etc. Examples of the University's most visible making facilities follow.

Mechanical Engineering

The Mechanical Engineering Department has a strong legacy of supporting making, including initial support of the Learning Factory. They also host a wood shop, a metal shop, and a check-out room that provides materials and testing equipment to students.

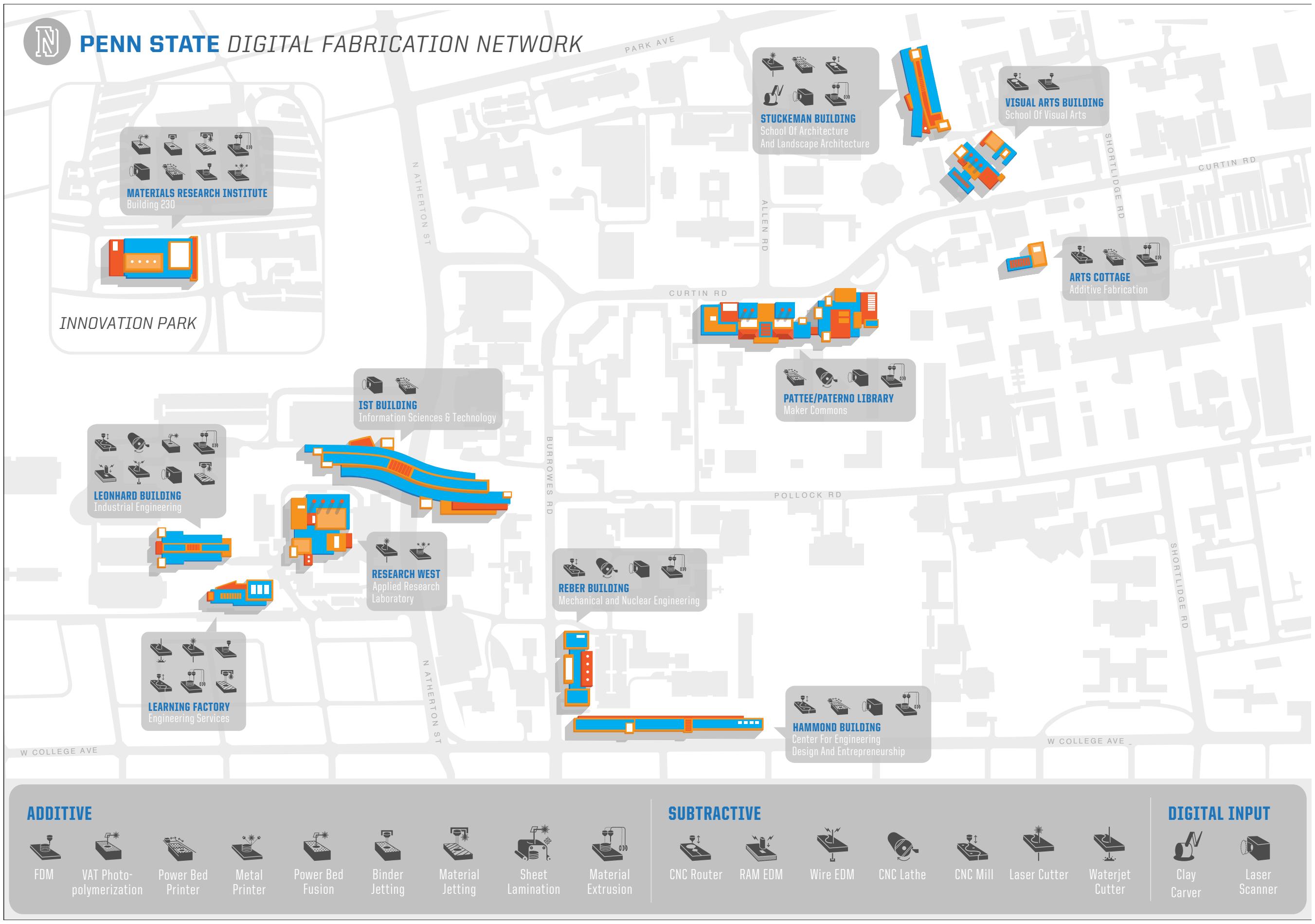

Figure 2 - The Penn State Digi-Net digital fabrication network. The map shows available resources and their location, including a breakout for the CiMP3D facility at Innovation Park.

Beginning in October 2014, the Mechanical Engineering Department made two MakerBot 5th Generation Replicators available to students. Printing was provided at no cost. In the initial printer deployment, students were allowed to specify a number of low-level print parameters such as layer height and infill percentage. Due to confusion and low initial yields, these values were standardized within a short time. A change in the MakerBot warranty procedure, which allowed us to repair our own printers on-site, also proved beneficial in improving up-time availability. In Spring 2016 an additional three printers were added and all five were moved to a dedicated facility.

The Learning Factory

In its original incarnation, the Learning Factory was a maker space disguised as a metal shop [4]. It had a number of machines for working metal and the resident expertise to support those activities. It also had a large space for assembling projects and using hand-held and small power tools. It was primarily used to support the senior ("capstone") design projects. After winning the NAE Gordon Prize for "innovation in engineering education" in 2006, the facility was expanded from ~3500 sq. ft. to ~6500 sq. ft. to include additional fabrication, prototyping, assembly, teaching, and computer spaces. At nearly the same time, the College of Engineering developed and embraced a multi-disciplinary capstone design model, and the space was immediately outgrown. Student engagement doubled, industry sponsorship tripled, and college participation quadrupled, making Learning Factory the largest college-wide, industry-sponsored capstone design program in the United States.

The Learning Factory is now home to over 200 senior capstone projects each year. These are client-sponsored projects, the vast majority of which originate in industry. The project teams are primarily multi-disciplinary (within engineering) with over 70% of the teams featuring students from at least two majors [3]. Each project requires the creation of a physical prototype, except for computer science and some industrial engineering projects (e.g., supply chain optimization, simulation, facility layout, which are required to use real-world data for demonstration and validation). Students learn the value of iteration and prototyping early in their design process. Other student teams, including Formula SAE and the Ecomarathon car also housed there. Students working on these projects are often employed as hourly staff to help with safety training, machine instruction, and general oversight and maintenance, helping keep costs low. Two full-time staff supervise and manage the facility.

The Maker Commons

When searching for a space to house a new making facility, discipline neutrality and location were important criteria. The main library at the center of campus was a natural fit and the Maker Commons was born. It is a "university-wide initiative to enrich the teaching and learning experience through 3D printing, rapid prototyping, design thinking and direct support for students, faculty and staff." [5]

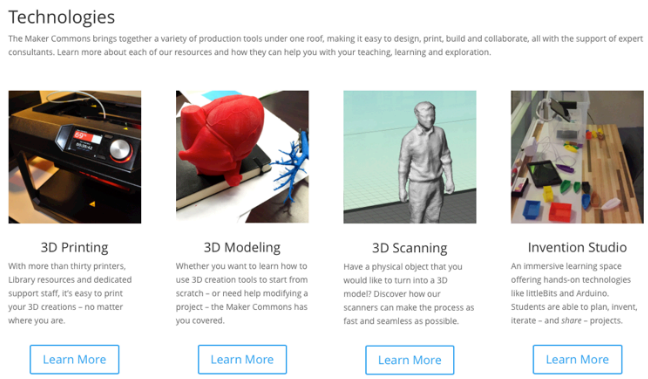

Figure 3 - The Maker Commons website provides tutorials and access to making resources. http://makercommons.psu.edu/technologies/

The facility includes everything students need for this kind of making (Fig. 3). Among the resources available are 32 5th Generation MakerBot Replicators housed in a special ventilation enclosure (Fig. 4). The machines use cornstarch-based PLA filament as their printing material. Other tools that support the 3D workflow are also available to users. These include 3D scanners, TinkerCAD, SolidWorks, and integration with thingiverse.com. In addition to additive manufacturing tools, students have access to LEGO and LittleBits for rapid-prototyping structures and electrical systems.

Figure 4 - The bank of 32 MakerBot 5th Generation Replicators in the Maker Commons.

The Maker Commons is staffed by 4 full-time employees. They also support the Media Commons in the adjacent space. They are paid for by the University's Education Technology Services, specifically Teaching and Learning with Technology.

The Maker Commons uses the MakerBot Innovation Center to manage the print submission process. Only .makerbot files are accepted for submission, so students are responsible for making the conversion from their CAD or .stl files. To facilitate this process, a number of bespoke tutorials are provided. These include "Creating a .makerbot file", "Using Thingiverse to Find a 3D Model", and "Submission Guidelines and Best Practices" (Fig. 5). Students are also able to check the status of their print jobs online.

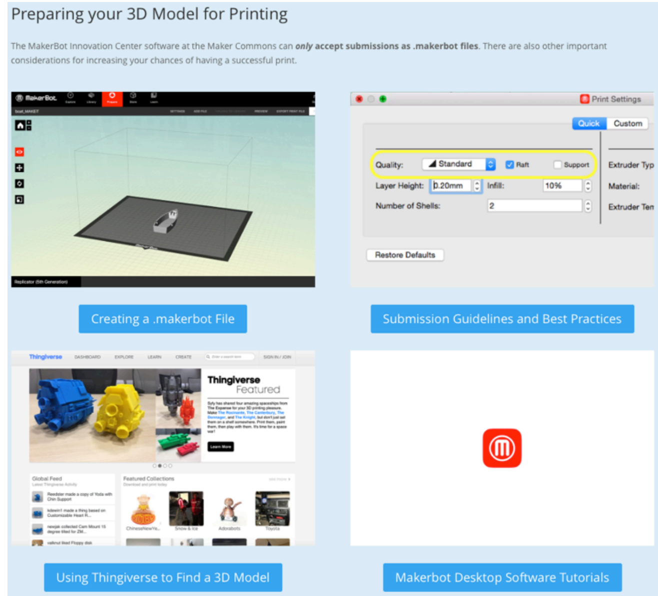

Figure 5 - A number of homemade tutorials guide students through the submission process. http://makercommons.psu.edu/submitting-your-3d-print/

Since the print submission and support process is primarily online, access is open to all 100,000 students at the 24 Penn State campus locations. However, the printers are all co-located at a single campus (University Park). Since the facility is located in the library, a distribution network was already in place: the InterLibrary Loan (ILL). This is the same "supply chain" used to ship library books and media between campuses. Using the ILL service, students are able to pick up their prints at any of the other 23 Penn State campus locations.

CiMP-3D

The Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D) is a collaborative effort between Penn State's Applied Research Laboratory, Penn State, Battelle Memorial Institute, and 3D Systems. It is housed in the Innovation Park facility adjacent to the Penn State University Park campus. The 8,000 sq. ft. facility provides more advanced additive manufacturing capabilities than those broadly available on campus. These include polymeric, ceramic, and metal 3D printing; it will soon be home to a hybrid manufacturing system as well, allowing for additive + subtractive capability within a single machine. CIMP-3D serves as the Manufacturing Demonstration Facility in Additive Manufacturing for DARPA's Open Manufacturing Program and provides tours to more than 1000 people per year. Other resources supporting design and material characterization activities, including computed tomography (CT) scanning, are also available in the center. CIMP-3D has a dozen full-time staff and conducts $8-10M of externally-funded and industry-sponsored research per year.

IV. USE

The increased availability of making facilities has enabled new courses and teaching strategies. This includes a revamped junior-level design course in Mechanical Engineering (ME 340), the upcoming general education Making for the Masses course, and an Engineering Design course dedicated to Design for Additive Manufacturing. A new graduate program in Additive Manufacturing & Design is also in development, engaging faculty in 5 departments and 2 colleges at Penn State. The freshman-level introduction to engineering design course, which services over 2,000 students each year, also makes extensive use of making facilities.

Mechanical Engineering Department

Use of the two 3D printers in the ME Department was problematic in their first semester (Fall 2014). By Spring 2015, most of the issues had been resolved. The additional capacity in Spring 2016 also increased usage (Table 1).

Table 1 - Usage statistics for the Mechanical Engineering Department printers, by semester.

	# of prints
fall 2014	96
spring 2015	298
fall 2015	351
spring 2016	905

Maker Commons

Due to the nature of the facility (it's in a library!) and the resources available to it, the most detailed data on usage are available for the Maker Commons.

As of mid-October, 2016, 865 unique Penn State Users have made use of the 3D printing capabilities in the Maker Commons (Table 2). The first 8 months of use have resulted in 19,335 hours of print time allocated across 2,435 successful prints. The success rate is holding steady at approximately 73%. The rate of usage has slowed since the initial influx, but demand is still steady.

Initially filament usage was free and unlimited, but it is now restricted to 30g for prints submitted outside of a class activity. The system was offline for much of August and September 2016 due to a filament shortage, and the library started limiting new printing requests for non-class requests to ensure that sufficient capacity is available for dedicated course usage. The actual average amount of filament per print remains at approximately 60g, an indicator of the large numbers of classes taking advantage of the resource. Each print requires, on average, 6 hours.

As described previously, since prints are submitted electronically, this resource is available to all 24 Penn State campus locations. Despite this and the free delivery of printed parts, the adoption rate at the 23 other campus locations has been low—only 20 prints had been submitted in the first half of the Fall 2016 semester.

Table 2 - Usage statistics for the Maker Commons since the February 2016 opening.

	March 2016	October 2016
# of unique users	469	865
hours of print time	6,640	19,335
# of successful prints	928	2,435
success rate	74%	73%
new requests / day	20	7
average filament / print	59g	60g
avg. duration of each print	6hr	6hr

V. LESSONS LEARNED

The development of Digi-net—and in particular making it broadly available—has resulted in a number of lessons learned and guiding principles. These include:

1) Standard and scale around low-end systems, but demonstrate utility and value of high-end systems. Do this even if it requires providing students with fewer options initially. Similarly, tailor instruction and coursework to different levels. For example, use 3D printing as an "on ramp" to making and manufacturing at the freshmen level and build on that in upper level courses.

2) Increase accessibility of the opportunity. When adoption isn't as expected, try to identify why. Reasons might include awareness, instructor needs, student capabilities, and availability of supporting materials (e.g., software).

3) Try to balance demand. For us this means staggering use in courses to prevent system overload at particular points in the semester. Restricting material access not also limits the size of jobs, but it restricts the kind of jobs that can be run, reducing overall demand.

4) The ability to do repairs in-house reduces down time. The Maker Commons is piloting a "Maker-in-Residence" program, hiring students on wage payroll (hourly) to help with repairs, harvesting, maintenance, etc. This keeps costs down and systems up and running.

5) Even in steady-state our "success rate" hasn't changed significantly. We started with great resources and tutorials for the students, but the system remains somewhat of a "black box" for the students. In the Maker Commons, for example, students don't "see" prints as they build…and fail, only after they get their part; so, DFAM learning remains somewhat disconnected. We need to identify ways to provide better feedback to students about how their parts are failing.

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Machine Refresher Guides: Promoting Trained User Autonomy in a Student-Run Makerspace

ISAM 2016
Paper No.: 35

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INTRODUCTION

This work discusses the potential benefits of using machine refresher guides, which are concise guides to machine operation, based on experience at the MIT MakerWorkshop. We discuss what the guides are intended and not intended to do. We believe other makerspaces would benefit from using refresher guides because of increased accessibility, a reduction in overhead for user supervision, increased user autonomy and participation, and machine longevity. Users of a makerspace benefit from an overall more pleasant makerspace experience resulting from improved autonomy, more productive use of time, a less stressful environment, and less load on the supervisors. We discuss two surveys we sent out to solicit feedback on how our refresher guides were being used as well as their usefulness. We conclude with our current guidelines on writing machine refresher guides.

Fig. 1: Location of refresher guides for (top) the lathe and (bottom) the CNC router.

REFRESHER GUIDE BACKGROUND AND BENEFITS

A. CONTEXT: REFRESHER GUIDE DEVELOPMENT IN THE MIT MAKERWORKSHOP

This paper is written based on the experiences of the volunteer staff at the MIT MakerWorkshop, a student-run academic engineering makerspace launched May 2015, by the MIT Department of Mechanical Engineering and the Martin Trust Center for MIT Entrepreneurship to serve users of those communities. It is currently staffed by approximately 40 mentors, drawn from both the graduate and undergraduate communities, who each take 2 hour shifts every week supervising the shop, and also dedicate approximately 3 additional hours doing user training and machine maintenance. The mentor staff are organized into machine teams, each supporting maintenance and training on each of the major pieces of equipment in the space, and are free to develop their own training protocol and rules of machine use. The space currently has approximately 800 registered users; users are required to take a general shop orientation, and then take machine-specific training on each of the major pieces of equipment on the shop. Since our space is relatively new, it has been a continual challenge to maximize the effectiveness of our volunteer staff while serving as many concurrent users as possible.

Our refresher guides were developed as a result of our mentors' experiences in other makerspaces around the MIT campus; our campus has an established tradition of hands-on workspaces such as the MIT Hobby Shop, which began as a student-run organization in 1938 [1] and the MIT Electronics Research Society (MITERS), a student-run shop which began in 1973 [2]. One of the challenges we students face is having many loosely affiliated makerspaces each of which has its own selection of machines; the machines vary between shops in make, model, configuration, and age, and we frequently encountered the situation where we had been previously trained on a machine months or years prior to using it again, or we were trained on a machine of the same type (e.g., a milling machine) but not the exact model or configuration encountered in a different makerspace (e.g., a Bridgeport retrofitted with a powered drawbar). We remembered in general how to use the machine and what the important safety issues were, but not the exact sequence of steps or specific location of controls that would result in a productive use of time and a good quality part. A frequent scenario was that we would need to find the shop supervisor and ask a simple question, but the shop staff would be busy helping or supervising another student, resulting in unproductive use of our time and also blocking access to the machine for others. Our mentors in the MIT MakerWorkshop were frequently being asked questions that we figured could be answered in a document, and remembering our experiences in other makerspaces, some of the machine teams set out to write refresher guides.

B. MACHINE REFRESHER GUIDE BACKGROUND

A machine refresher guide is a short document which primarily accomplishes three functions:

1. Reminds the user of critical safety issues
2. Instructs the users on proper startup/shutdown procedure
3. Has a step-by-step guide to make a successful part, without overwhelming a user with unnecessary detail

It is fairly common for consumer products to be accompanied with a "quick-start" guide; in general, the only consumer products which contain "quick-start" guides are products that are meant to be plug-and-play without any potential safety issues. Power tools, for example, do not generally contain quick-start guides and require the purchaser to read the manual before operating such that they are aware of potential hazards. Initially, we called our refresher guides "quick-start guides"; however, we realized the name "quick-start guide" gave the impression that an untrained user could operate a machine by using only the quick-start guide, and this is not a practice we wanted to encourage in our space. Refresher guides are meant to fill a training gap where a user has been previously trained but is not a frequent user of the machine, and does not remember the exact process for using the machine; or the user was trained on another variant of the machine which may have been slightly different. The refresher guide gives enough detail to guide a user completely through the making process, while reminding users of the important safety hazards both for the user and the machine. Table 1 gives a comparison of the different types of commonly encountered machine reference material and information typically contained therein.

Table 1: Information covered in different types of machine guides

	Guidelines	Checklist	Refresher Guide	Tutorial / Beginner Guide	Manual
Safety	X	X	X	X	X
Tips & tricks	X	X	X	X	X
Step-by-step instructions		X	X	X	X
Pictures for steps			X	X	
Labeled diagrams of machine			X	X	X
Useful tables & charts			X	X	X
Other basics (eg., tooling, fixturing, layout)				X	
Troubleshooting					X
Maintenance procedures					X

C. BENEFITS OF USING REFRESHER GUIDES

We argue that using refresher guides has several benefits in a makerspace:

- They improve user autonomy by allowing a user to independently make a part;
- They allow a user to be more time-efficient, and make the machine available for others to use;
- They reduce the stressfulness of using a machine, in the case where a student is nervous about potentially crashing the machine or scrapping a part due to operator error, by improving confidence;
- They reduce supervision load especially when the shop is near capacity; students can use machines without frequently having to pull staff from another user (which the mentor may not be able to immediately do), frees up the mentor to help another user who may need closer supervision;
- They reduce training overhead since students won't feel the need to take retraining when they only really need the refresher guide to walk them through the process;
- They prevent machine crashes and thus improve machine longevity, and reduce scrap rate.

REFRESHER GUIDES OR SIMILAR AT OTHER MAKERSPACES

Using a list of known makerspaces from Barrett et al. [3], we gathered online information on machine reference material they have available. This information is presented in Table 2.

Table 2: Summary of refresher guide or similar

	Guidelines	Checklist	Refresher Guide	Tutorials/training	Labeled machine pics	Pictures of steps	Charts	At machine
Other MIT spaces		X					X	X
U. Arizona Physics Dept. shop [4]		X						
Case Western think[box] [5]	X			X	X	X	X	
GA Tech Invention Studio [6]	X	X	X					X
Berkeley Supernode [7]		X						
Rice Design Kitchen [8]		X	X	X	X	X	X	X
Stanford create:space [9]		X						
UT Austin Longhorn Make studio [10]		X		X	X	X	X	
Washington State Fab Labs [11]	X						X	

Table 3: Initial survey to gather refresher guide feedback

Q1. Did you know about the existence of refresher guides in the shop?
Q2: Do you find the refresher guides helpful?
Q3: Do you find the refresher guides answer simple questions like where the ON button is?
Q4: For simple questions, do you prefer using the refresher guides or asking a mentor?
Q5: How often do you use the refresher guides?
Q6: Do you use the refresher guides out of necessity or as a way to double check what you are doing?
Q7: Do you find the labeling of the machines in the refresher guides useful?
Q8: Do you find the quick references, such as feeds and speeds charts, in the refresher guides useful?
Q9: Do you find visual references along with the typed instructions in the refresher guides useful?

In particular, we sorted their reference material into the types defined in Table 1. Many makerspaces had multiple forms of reference material. Further, we recorded whether the reference materials contained some of the key characteristics of the reference material also listed in Table 1. Lastly we recorded whether there was an indication that these reference materials were located at the machines in addition to being online.

REFRESHER GUIDE UTILITY SURVEY AND RESULTS

We conducted a survey to gauge the usefulness of our refresher guides, whether or not we should be publishing more of them, what we could do to improve them, and if our users were benefiting from their use. The survey was sent to the MIT MakerWorkshop user mailing list, which includes current mentors and users. The questions we asked are listed in Table 3.

After looking over the results of the first survey, we decided to gather more information on why students found the refresher guides useful, so we sent a second questionnaire; the list of the questions asked in the second survey are presented in Table 4.

The detailed results of both surveys are presented in Appendix A. We've drawn a few preliminary conclusions based on the survey responses; in general, users wanted or preferred:

- Additional reference charts (such as feeds and speeds)
- Detailed step-by-steps for common operations
- Pictures accompanying steps
- Simpler guides
- Notification of common mistakes other users encountered
- More refresher guides be published

Frequent complaints were that the users

- Did not know where the guides where

From this information, we conclude that users are mostly using the refresher guide as a sanity check or pre-flight checklist to make sure they're on the right track, as opposed to relying completely on the guides to use the machine [survey 1, question 6], which reinforces the idea that refresher guides are meant for users who only occasionally use the machine or may not recall every detail from the training. Users in general remember most of the training, but no user claimed to remember all of the details [survey 2, question 2]. Users find the refresher guides to be extremely effective at reminding them of details they've forgotten [survey 2, question 3]. Users overwhelmingly approve of having quick references such as feeds and speeds visible and available at the machine [survey 1, question 8], and overwhelmingly approve of having visual references along with typed instructions [survey 1, question 9].

Table 4: Follow up survey gathering information on refresher guide utility

Q1: How well do you feel machine trainings prepared you to use/operate the machines?
Q2: How well do you remember the content of the trainings (how to operate the machines, software, etc.) for the machines you've been trained on?
Q3: Do you find the refresher guides an effective tool to remind you about aspects of training you do not remember?

REFRESHER GUIDE GUIDELINES

Based on our experience, we present a few key points to keep in mind when writing machine refresher guides:

- It should be made very clear that the refresher guide is intended to be used by users who have been previously trained on the machine.
- The refresher guide should be visible at the machine.
- Include safety/hazards concisely at the very beginning if applicable.
- The refresher guide should have annotated pictures of the machine and screenshots of the control/layout whenever controls are referenced, in addition to written instructions.
- The quick-start guide could have contact information for the expert operators in case of difficulties.

The last point is meant more for a staffing model with many staff members, where each staff member may not have the expertise to troubleshoot every single machine. These practices will continue to evolve, and it is likely that there won't be a universal set of guidelines as every makerspace and machine is different.

CONCLUSIONS

Our survey has strongly suggested that refresher guides are a valuable addition to our makerspace. We have presented what have been for us the most useful practices for developing refresher guides and the context in which they have been developed.

ACKNOWLEDGEMENTS

The authors would like to thank the Richard H. Lufkin Memorial Fund, the MIT Department of Mechanical Engineering, the Martin Trust Center, and the MIT Project Manus initiative for providing funding for the MIT MakerWorkshop. The authors would also like to thank Prof. Martin Culpepper for serving as the faculty advisor (Maker Czar) for our space. Finally, the authors would like to thank all Mentors, past and present, for all their time and dedication into designing, building, and maintaining the MIT MakerWorkshop.

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APPENDIX A: SURVEY RESULTS

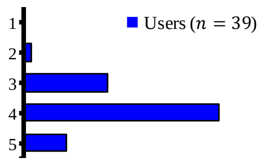
INITIAL SURVEY

Q1: Did you know about the existence of refresher guides in the shop?

	Number	Percent
Yes	32	82.1%
No	7	17.9%

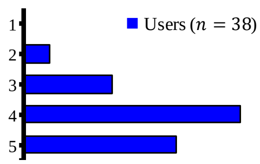
Q2: Do you find the refresher guides helpful?

		Number	Percent
1	Not helpful at all	0	0.0%
2		1	2.6%
3		10	25.6%
4		23	59.0%
5	Extremely helpful	5	12.8%



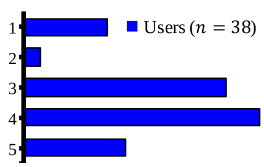
Q3: Do you find the refresher guides answer simple questions like where the ON button is?

		Number	Percent
1	No, they do not	0	0.0%
2		2	5.3%
3		7	18.4%
4		17	44.7%
5	Yes, they do	12	31.6%



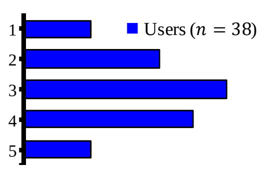
Q4: For simple questions, do you prefer using the refresher guides or asking a mentor?

		Number	Percent
1	Ask mentor	5	13.2%
2		1	2.6%
3		12	31.6%
4		14	36.8%
5	Use refresher guide	6	15.8%



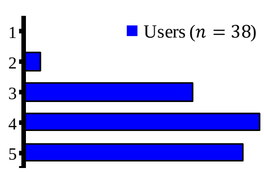
Q5: How often do you use the refresher guides?

		Number	Percent
1	Never	4	10.5%
2		8	21.1%
3		12	31.6%
4		10	26.3%
5	Everytime I machine	4	10.5%



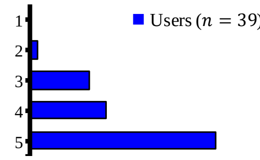
Q6: Do you use the refresher guides out of necessity or as a way to double check what you are doing?

		Number	Percent
1	Necessity	0	0.0%
2		1	2.6%
3		10	26.3%
4		14	36.8%
5	Double check	13	34.2%



Q7: Do you find the labeling of the machines in the refresher guides useful?

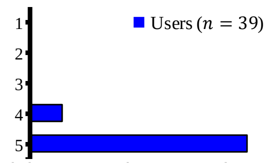
		Number	Percent
1	Not at all	0	0.0%
2		1	2.6%
3		7	17.9%
4		9	23.1%
5	Very useful	22	56.4%



[clarification: labeling refers to pictures of machine/software controls. Survey question was originally accompanied by example image]

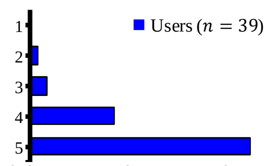
Q8: Do you find the quick references, such as feeds and speeds charts, in the refresher guides useful?

		Number	Percent
1	Not at all	0	0.0%
2		0	0.0%
3		0	0.0%
4		5	12.8%
5	Very useful	34	87.2%



Q9: Do you find visual references along with the typed instructions in the refresher guides useful?

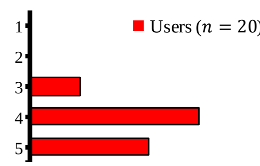
		Number	Percent
1	Not at all	0	0.0%
2		1	2.6%
3		2	5.1%
4		10	25.6%
5	Very useful	26	66.7%



FOLLOW-UP SURVEY

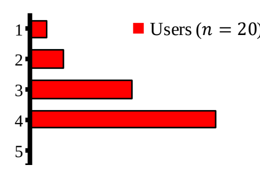
Q1: How well do you feel machine trainings prepared you to use / operate the machines?

		Number	Percent
1	Did not prepare me at all	0	0.0%
2		0	0.0%
3		3	15.0%
4		10	50.0%
5	Prepared me very well	7	35.0%



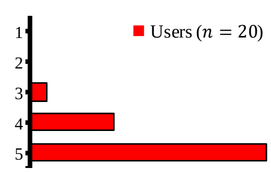
Q2: How well do remember the content of the trainings (how to operate the machines, software, etc.) for the machines you've been trained on?

		Number	Percent
1	Remember nothing	1	5.0%
2		2	10.0%
3		6	30.0%
4		11	55.0%
5	Remember everything	0	0.0%



Q3: Do you find the refresher guides an effective tool to remind you about aspects of training you do not remember?

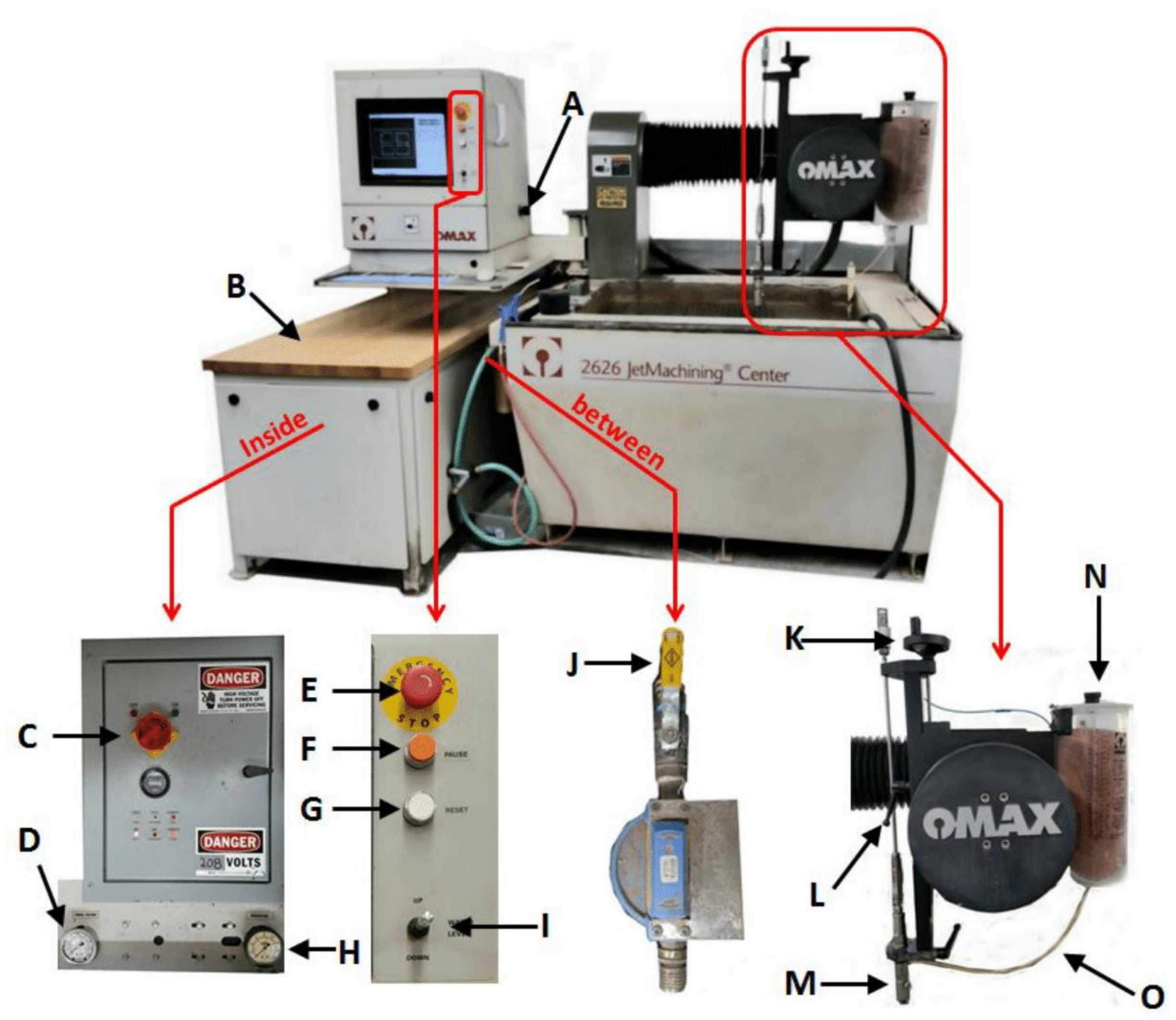
		Number	Percent
1	Not effective at all	0	0.0%
2		0	0.0%
3		1	5.0%
4		5	25.0%
5	Extremely effective	14	70.0%



APPENDIX B: MIT MAKERWORKSHOP OMAX 2626 REFRESHER GUIDE

Waterjet Refresher Guide

If you suspect the machine is not operating properly, contact mw-waterjet@mit.edu immediately!



A – Computer ON/OFF	F – Pause	K – Z Height Wheel
B – Pump Chest	G – Reset	L – Z Lock Lever
C – Pump ON/OFF	H – Prefilter Pressure	M – Nozzle & Guard
D – Final Filter Pressure	I – Water Level Control	N – Garnet Tube
E – Emergency STOP	J – Water Supply ON/OFF	O – Garnet Reservoir

Start Up

Turn On Computer Power

Turn Computer ON/OFF Dial to the ON position.

Turn On Water Supply

Turn the Water Supply ON/OFF Value to the ON position (**in-line** with the hose).

Air Supply - The air supply stays on and thus should be on already!

Turn On Pump Power

Turn the computer to the right away from the Pump Chest **(DO NOT HIT THE NOZZLE!).**

Pull up on the wood top to open Pump Chest and turn the Pump ON/OFF to ON position.

OMAX Layout

Import .DXF File

Click File >> Select Import from other CAD… >> Click Okay >> Decide if to scale to mm

Note: OMAX Layout assumes parts were drawn in inches & thus asks to scale to mm

Clean Up Drawing

Click Clean Button >> Check *Remove unnecessary "dots".* >> Click Start

Set Cutting Quality

Click Quality Button >> Click quality >> Select segments to be cut at that quality

OR

Select segments to be cut at same quality >> Right Click Quality Button >> Click quality

Note: The segments will be changed to the color of the quality selected.

Create Lead In / Lead Out Paths

Right Click Lead i/o Button >> Select AutoPath (Advanced & Configure)...

>> Select *Starting Corner* and *Method* number or Auto-Pick >> Click Go!

Create Tabs

Right Click Lead i/o Button >> Select Create Tab >> Enter desired *Gap Length* and *Leg Length* >> Click near a line in the drawing to create a tab extending to that side of the line

Create Cutting Path

Right Click Path Button >> Select Automatically Generate (Default)

A cursor will appear with *PICK START* >> Click start of your transverse (green) line

Check Cutting Path

(1) Check *Tool Offset to show* and enter desired tool offset if incorrect

(2) Make sure the kerf (thick red line) is on the outside of parts & the inside of holes

Send Cutting Path to OMAX Make

Right Click Path Button >> Select Open Path in Windows Make…

OMAX Make / Cutting

Enter Material Setup

Select material type & thickness on the 1st screen that appears when OMAX Make opens

Check Tool Offset

Check the *Tool Offset* and enter desired tool offset if incorrect

Make Multiple Copies of Part (Optional)

Click Nest >> Specify number of *columns*, *rows*, and *x* & *y* spacing >> Click Save

Click OK

Set Path Start (X/Y start)

Move the nozzle to the X/Y position to start cutting from >> Click **BOTTOM** Zero Button

Note: **DO NOT CLICK** the top Zero Button as that is the position of the bed's corner!

Set Z Zero Position

Unlock the Z stage (turn upward Z Lock Lever) >> Move nozzle (turn Z Height Wheel) to ~ 60 thousandths above the stock (thickness of metal spacer) >> Lock the Z stage (turn downward Z Lock Lever)

Check Toolpath Boundaries

Go To Spot On Path (Optional)

Right Click Begin Machining >> Click Go To Spot On Path… >>> Click on toolpath

Use to check toolpath boundaries as the nozzle will move to that spot on the toolpath

Dry Run (Optional)

Move the nozzle up 6" >> Click Go Home Button to home nozzle >> Click Begin Machining >> Right Click Start >> Select a dry run option >> Watch dry run >> Move nozzle down to zero height.

Actual Run

Cutting

Click Go Home Button to home the nozzle >> Raise water level to 1” below top of water basin >>Click Begin Machining >> Click Start >> **WATCH THE WATERJET CUT THE PART!!!!!**

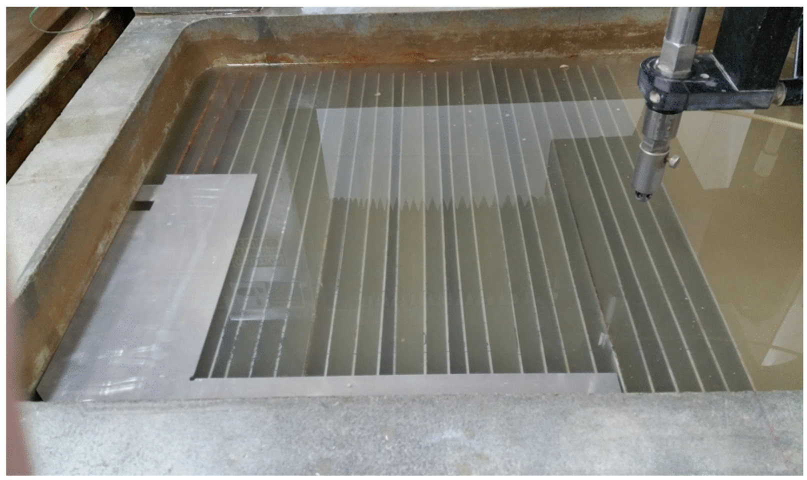
Pausing

Click Pause Button to stop the nozzle moving and / or cutting immediately

OR

Right Click Pause Button >> Select a stop option to pause while traversing

Shut Down



CLEAN UP!!!

- Move nozzle out of the way
- Hose garnet off corner plate
- Squeegee surfaces dry
- Put back clamps and weights
- When done, the waterjet bed should look like above.

Shut Down Computer

Note: We cannot turn off power to the computer until it is completely shut down!

Turn Off Pump Power

Turn the computer to the left away from the Pump Chest **(DO NOT HIT THE NOZZLE!).** Pull up on the wood top to open Pump Chest and turn the Pump ON/OFF to OFF position.

Turn Off Water Supply

Turn the Water Supply ON/OFF Value to the OFF position (**perpendicular** with the hose).

Air Supply - The air supply stays on and thus can be left alone.

Turn Off Computer Power

Turn Computer ON/OFF Dial to the OFF position.

* Safety and hazard information for this machine is not included in this refresher because safety/hazard info is present on another one-page document visible at the machine

Makers Managing Money, Machines and Their Mastery: The Mobius Makersystem App

ISAM 2016
Paper No.: 41

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INTRODUCTION

MIT created the Mobius Maker App via a collaboration between students, the administration, alumni, the Office of Environmental Health and Safety, facility managers, and other stake holders at MIT [1]. The app, shown in Figure 1, was created to address several barriers that dampened the speed of student access to maker tools and facilities. Specifically, the app enables students to search and find machines anywhere on campus, navigate the 40+ spaces where equipment is accessible, understand their entry requirements for each space, store their training credentials so that they have a trusted means of demonstrating their competency, and make payments for any use or material through their student maker account (MIT Makerbucks) or with a credit card. The app also enables facility managers to manage their machines, financial accounts, and have more information about students. The latter enables managers to make better and faster decisions such as how much training and oversight is needed for unfamiliar students, and this reduces time for both student and facility managers.

We have catalogued over 30 MIT spaces and students are able to search over 800 machines/resources within the Mobius database. The Mobius app is used by over 1,400 makers on campus and has been expanded to power the networking of people and machines for MIT's hardware accelerator, the Engine [2]. We are working on expanding Mobius into several universities within the Boston area, thereby creating a multi-campus network of makerspaces and maker resources.

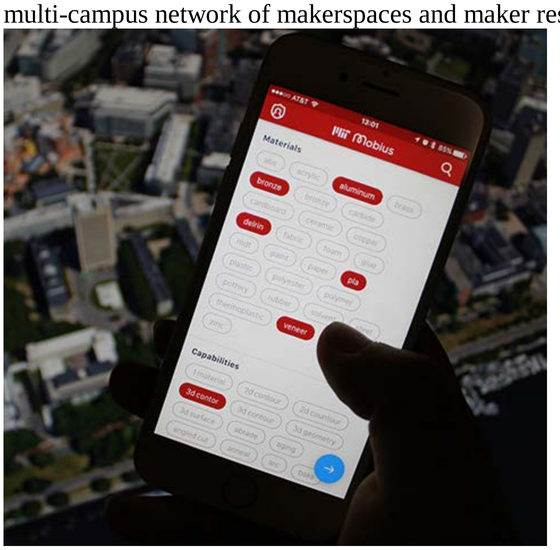

Figure 1. Mobius App for makersystem management.

The features of Mobius, and the database it runs on, enable different campus stake holders to have access to information they may use to make individual and joint decisions. It also provides a database that is trusted by all users, thereby fostering information-based decision making and fact-based decisions.

MIT MAKERSYSTEM AND THE NEED FOR AN APP

The MIT makersystem consists of over 40 spaces in which students may access equipment and expertise. Figure 2 shows about half of these spaces (all spaces cannot be shown due to space limitations in the image). This type of system is characteristics of MIT, people empowered to create their own spaces and run them as they desire. This yields many localized maker resources that are tuned for the local users. This can however lead to 'silos' that create barriers and prevent students from gaining access to many facilities.

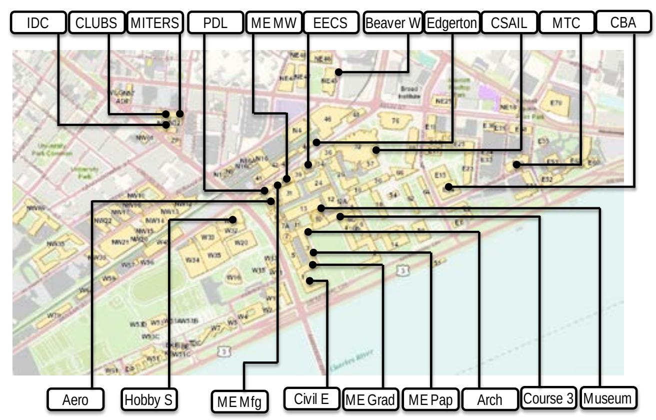

Fig.2 Half of MIT's design/build spaces within its makersystem

This issue is further complicated as MIT's long-range plan is to expand the access to maker resources beyond its boundaries, to include peer campuses. This type of network has the strength of diversity of spaces/approaches that is coupled with breadth of technologies available and depth of knowledge from many makers/technicians. The access to, and finding of equipment and technical expertise needs to be managed in some way. Many universities use web pages to help their students understand the resources that are available to them [3-8]. The Mobius app was created to do this. An app was selected vs. a web page because the app enables local use of Bluetooth and GPS which will (planned for a future release) be used to enable student's phones to unlock power to machines they have been trained on, and open doors to facilities after hours if they are authorized to be in the space.

The MIT network of spaces yields several barriers for our students. These barriers are shown in Fig. 3.

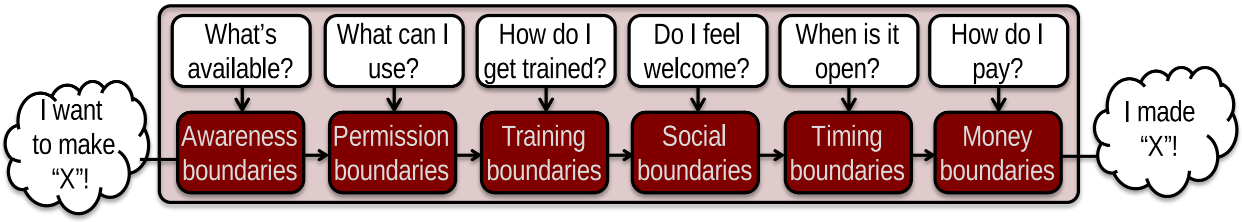

Fig.3 Barriers encountered when navigating the MIT makersystem

The MIT app has been designed to help our students easily navigate these boundaries, thereby having access to a wide network of spaces instead of one or two silos.

APP DATABASE, MANAGEMENT OF INFORMATION AND ACCESS TO INFORMATION

Mobius is more than an app. The Mobius system consists of the components shown in Figure 4. The power of Mobius is the database that has been configured to contain all the information required for each facility and piece of equipment. For example, make, model, CNC status, training requirements, materials allowed, accessible hours, capability, and more. MIT student can access the database via the app. Facility managers can manger their data (open hours, take machines offline, check training credentials of students, give training credentials to students, etc.). Facility manager may also manage their facility via a web portal.

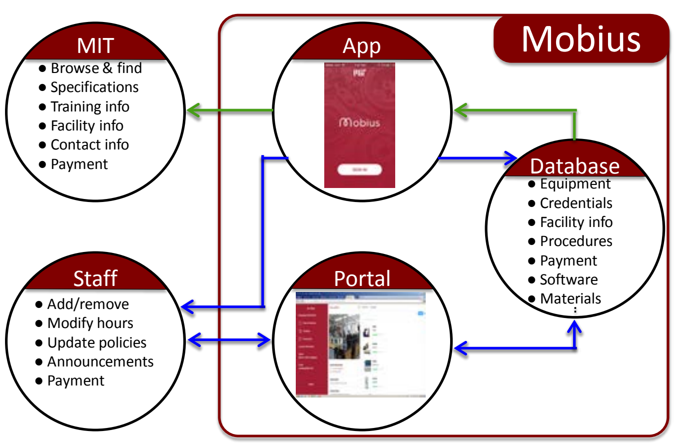

Fig.4 Mobius system architecture and components

ADDRESSING BOUNDARIES AND COMMON ISSUES WITH MOBIUS

In this section, we provide examples of how Mobius is able to address boundary issues for our students.

A. AWARENESS BOUNDARIES

Users can search for resources by browsing machines, materials they want to work with (buttons in Fig. 5), or machine capabilities.

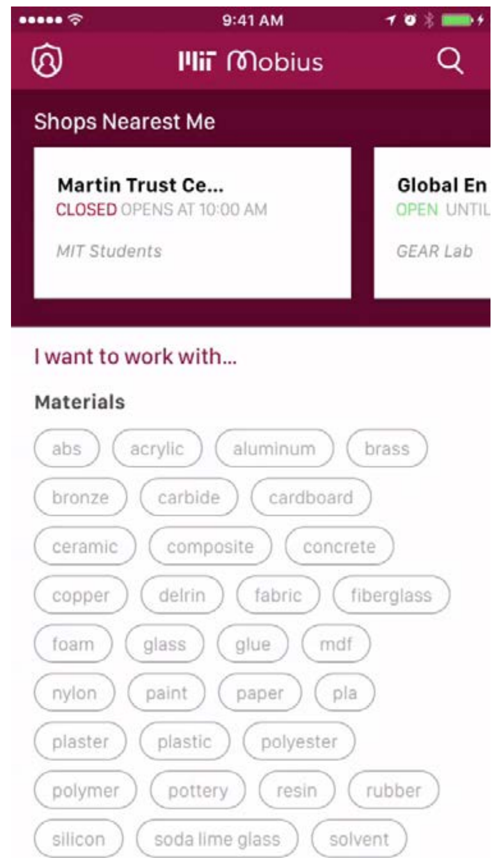

Fig.5 Users can search for resources by browsing "Materials", "Machine Capabilities" or "Machine Types"

Mobius also shows the location of the facility/resource and provides directions as shown in Fig. 6.

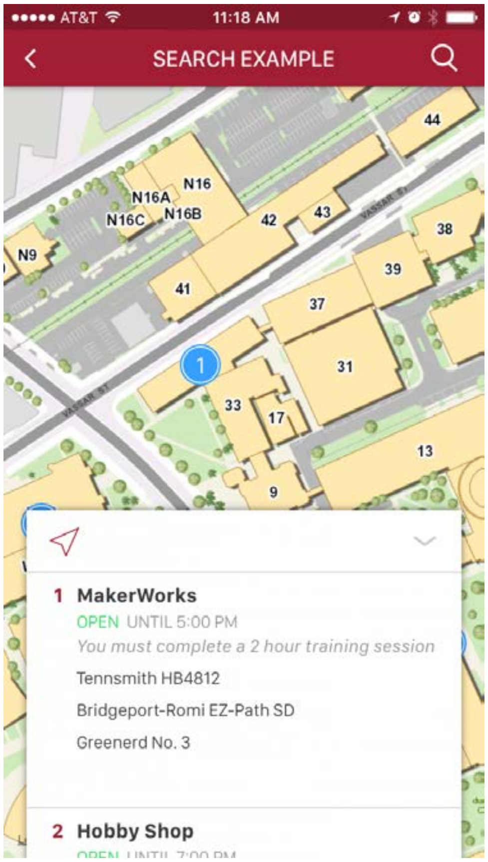

Fig.6 Locations of facilities of interest are displayed and walking direction may be obtained

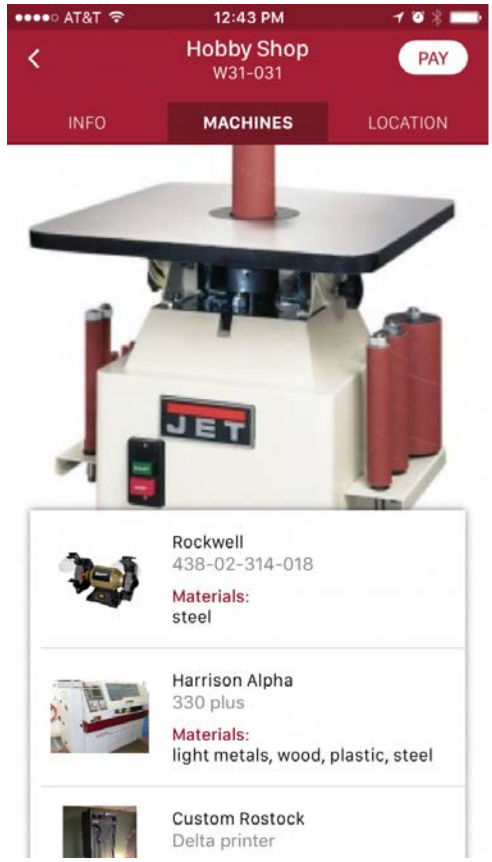

Fig.7 Users can look up specific details for each machine in a facility and view the manufacturers specfications

Users may also look up specific details for any machine by scrolling through the machine lists that appear when a student clicks on a particular makerspace name. Figure 7 shows the beginning of this process. If a student wanted to know more detail about the Rockwell bench grinder, they tap the image and are taken to a screen with detailed information and a link to the manufacturer's own specification sheet.

B. PERMISSION BOUNDARIES

Our students of do not know which facilities can accept them, perhaps because a specific facility may only be open to a specific research group or Department. There is no ambiguity now as Mobius points out requirements for access. For example Fig. 6 shows that access can be granted after training.

C. TRAINING BOUNDARIES

Students are able to store their training credentials in Mobius and show this to any facility manager. This is beneficial to the student as they don't have to worry about overtraining when the already have a base of skill. This is beneficial to the facility manager as they have trusted data from which they can make better decisions regarding how much effort will be required to bring this user up to speed on a specific piece of equipment. The credentialing page for a student is shown in Fig. 8.

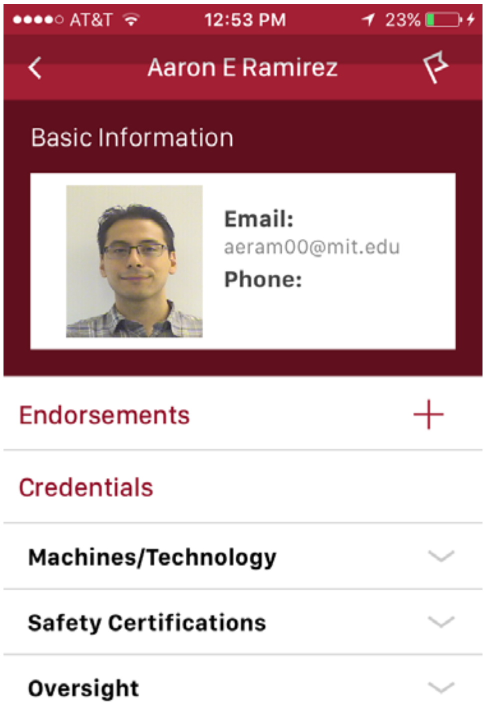

Fig.8 Students Mobius credential page

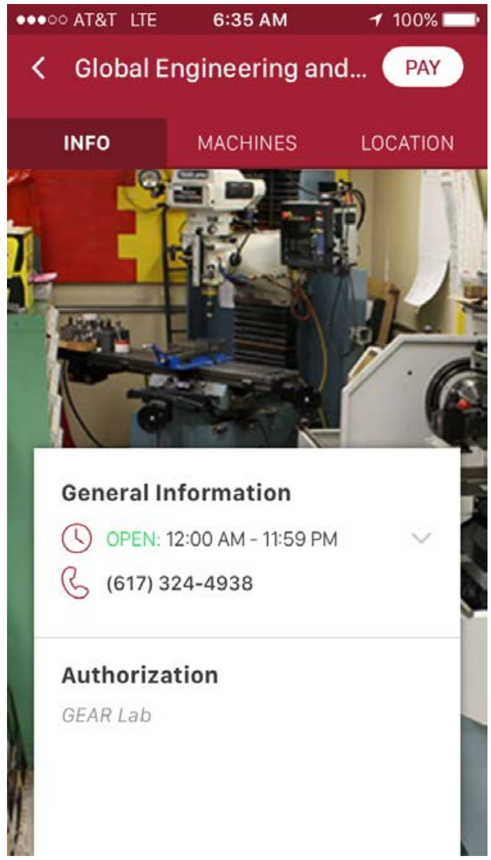

Fig.9 A facilities Mobius 'splash' page

D. TIMING BOUNDARIES

Students are able to view the hours of operation and contact information as shown in Fig. 9.

E. MONEY BOUNDARIES

Mobius may also be used to pay for materials, Arduinos, small electronics/fasteners, time on machines, etc… The pay button ono the upper right screen enables the student to key in the price to be paid to the facility they are in (in Fig. 9, this would be the Global Engineering and Research Laboratory). Payment is made from their student account to the facility, and a receipt is emailed to both parties. Students may also use credit cards to make purchases.

MOBIUS IMPACT ON THE MIT MAKERSYSTEM

Mobius enabled a new program that started at MIT in the Fall of 2016. This program, the MakerLodge program, enables every freshman (that wants it) to be trained in basic maker tech. After training, follow up competency testing and certification process administered through the MakerLodge, students receive the following:

- Tool box ($7/student) and set of tools ($18/student for wrenches, screw drivers, hammer, and other hand tools)
- Arduino micro-controller ($13/per student)
- $100 value awarded in Makerbucks (to spend via Mobius on materials and machine time)
- Mobius-recorded training credentials to show to facility managers to verify student machine competency and gain entry to a design/build space

- Ability to access 12 MIT maker facilities (Figure 4)

Ability to join a freshman maker community that provides social events, maker events, general life and class support at one of the 12 MIT maker facilities [10]

The MakerLodge Program, including the training, qualification, and certification components benefits many groups at MIT. From the School and Department perspectives, students are better trained and more fully capable in participating in early (freshman and sophomore level) hands-on education activities. This increases the programs' abilities to offer more advanced courses that focus on real world problems. The student mentors benefit from the skills they refine while teaching their peers, as well as 24/7 access to the space in return for their volunteer instruction. The resulting system has great value for MIT's administration as it addresses students' expectations of the 'mens et manus' experience they came to campus for.

The training workload for the facility managers has decreased with the centralized process, enabling more time to teach and assist students with more advanced needs. The verifiable training credential system reduces concerns associated with new users and helps customize additional oversight and training. Lab-based research programs have also benefitted from the initiative as students are better prepared to design and build experiments and equipment within these labs. Also, the MIT Office of Environmental Health and Safety (EHS) now has a standardized training program that enables a greater number of students to receive general safety training. As MakerLodge is in its first semester, data is currently being collected to measure the program's impact on many facets of the educational experience, and to document the benefits to the stakeholders.

The MakerLodge is currently running its first year of training for MIT freshmen at a rate of 50 students/week. In the spring, students will be trained at a similar rate on the other technologies (including, for example, glass working, CNC routing, band saw, drill press, and other machine tools).

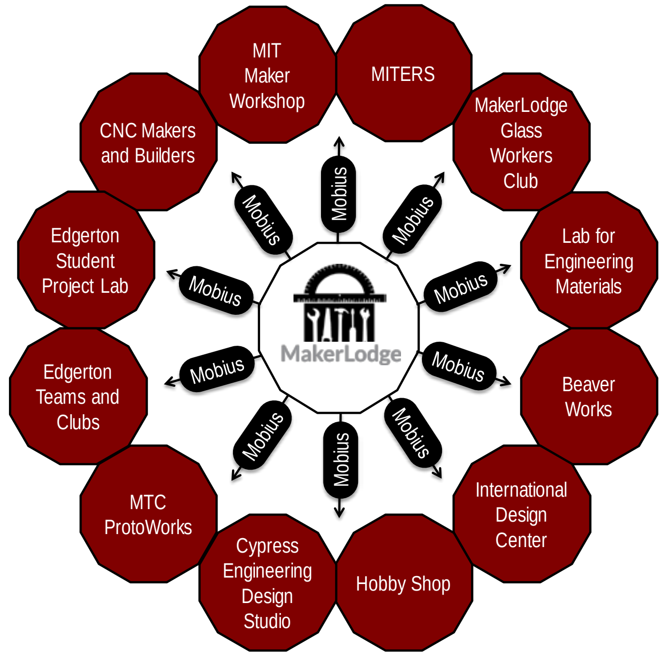

Figure 10. Collaborative network of facilities that accept freshmen graduates of the MakerLodge Training Program and Mobius' role in facilitating student 'flow' between these facilities.

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ISAM 2016 Paper No.: 36

A hierarchical system for purchase management in a student-run makerspace

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INTRODUCTION

To appropriately manage purchases in a makerspace run by 40+ student volunteers who have supervisory and management roles as "Mentors" to the community, it is important to have a well-defined purchasing system. There are several requirements for this purchasing system. We need an easy place for Mentors to request purchases. Additionally, we have a detailed policy that defines levels of purchase and the policy for each, preventing unnecessary discussion on small items, but encouraging participation from all Mentors and Users for new capital purchases. Finally, a system to track purchases allows us to monitor our finances across several accounts, and sort purchases by the several executive committee members who are qualified to make purchases for MIT MakerWorkshop*.

CATEGORIES OF PURCHASES

There are several needs for purchasing in MIT MakerWorkshop that group into four categories: capital equipment and one-time purchases, consumables (which include new tools to replace tools that are used up and stock that is available for purchase by Users, such as 3D printer plastic and acrylic for the laser cutter), items for mentor socials, and community socials including food.

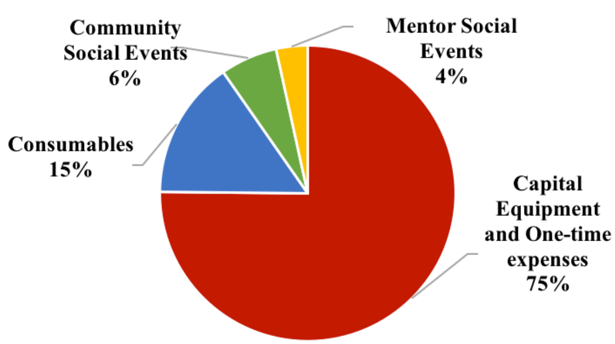

Fig. 1 The breakdown of the Y1 spending of the MIT MakerWorkshop. Note that Y1 refers to dates between July 2015 and July 2016. The bulk of the expenses were Capital Equipment and One-time expenses which include new items such as additional machine tooling. We anticipate spending in this category to decrease this year while we expect spending on Consumables to remain constant.

The method used to purchase and track our account for each is described below.

* Formerly named MIT MakerWorks

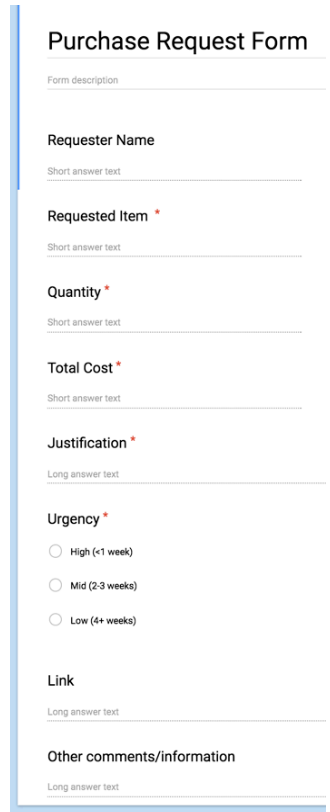

Fig. 2a The purchase request form (form 1) is used by any mentor to request a purchase. A member of the executive committee will check this form and make purchases typically twice a week.

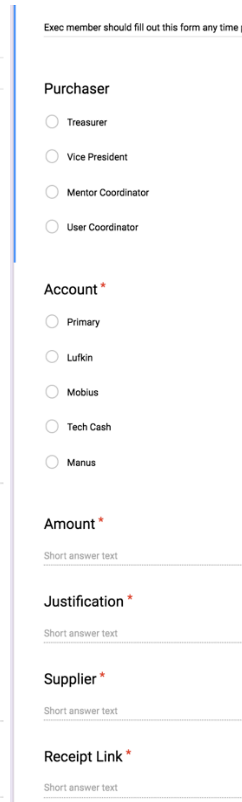

Fig. 2b The account tracking system form (form 2) is used when a purchase is made by a member of the executive committee. Google sheets formulas automatically short and display purchases by both purchaser, and by account.

1. Purchase request is entered into purchase request form (Fig. 2a).
2. Executive committee member (usually Treasurer) purchases item, and enters a record into account tracking system (Fig. 2b).
3. The account tracker spreadsheet (Fig. 2b) aggregates purchases based on account, and based on individual who makes the purchase.
4. The aggregated spreadsheet includes a section organized based on purchaser and is used for accounting and processing of MIT credit card charges.

5. The aggregated spreadsheet also includes a section organized based on account and is used to track the state of each account (as we only get monthly updates, and these do not account for charges that have been made, but not assigned to a specific account yet).

MACHINE TEAMS

In MIT MakerWorkshop, each machine or group of equipment is managed by a machine team that is headed by a machine master. The mill, lathe, laser cutters, 3D printers, CNC router, benchtop tools (drill press, band saw, sanders), electronics area, hand tools and hardware, and electronics and measurement tools all have a team that gives training on the machine and manages repair, maintenance and tooling stock. By assigning specific individuals, we can ensure that material does not run out without being noticed, and action is taken to maintain operation of the machines.

The machine teams make purchases for their machine by submitting a purchase request through a Google form. The Treasurer makes the purchases in groups twice a week and allocates the charge to the proper account. This hierarchy of machine management and purchase structure ensures purchases occur quickly, but prevents the same item from being ordered twice by mistake.

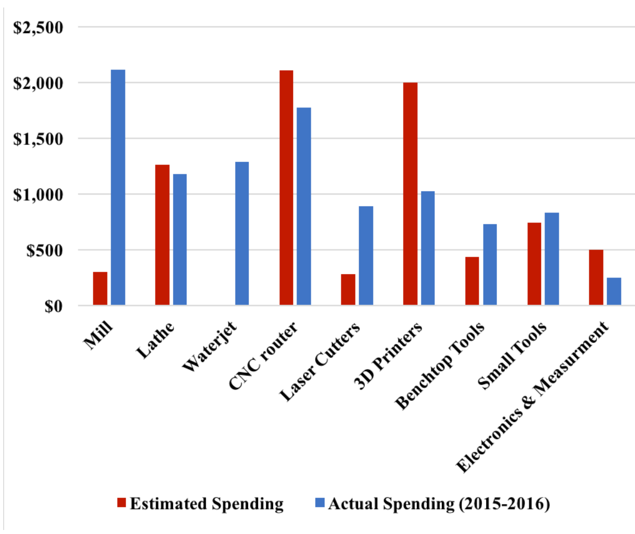

Fig. 3 This figure shows our projected vs actual usage rate for resources associated with each machine. Some estimates are high, as we built in the ability to buy new types of tooling into certain machines, to account for both tool damage, and expansion of our available resources. Since we started charging at cost for 3D printing, the usage rate dropped below what we predicted. We have also had success with not losing or breaking hand tools, as we have not needed to replace anything in the first 1.5 years.

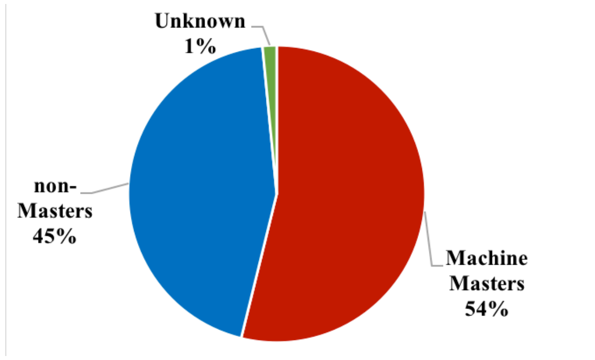

Fig. 4 This figure describes the purchase requests made by Machine Masters, non-Masters, and Mentors whose position is unknown. We see a nearly equal split between purchase requests from Machine Masters vs non-Masters. This shows that all Mentors are encouraged to help keep the shop running smoothly, which decreases the burden on the Machine Maters.

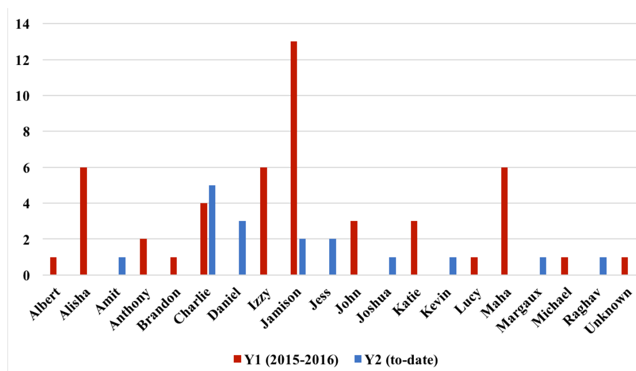

Fig. 5 This figure shows the number of purchase requests each year by different Mentors. Note that Y1 refers to dates between July 2015 and July 2016. Y2 (to-date) refers to dates between August and October 2016. The high number of requests in the first year by Jamison was for parts related to keeping the 3D printers running.

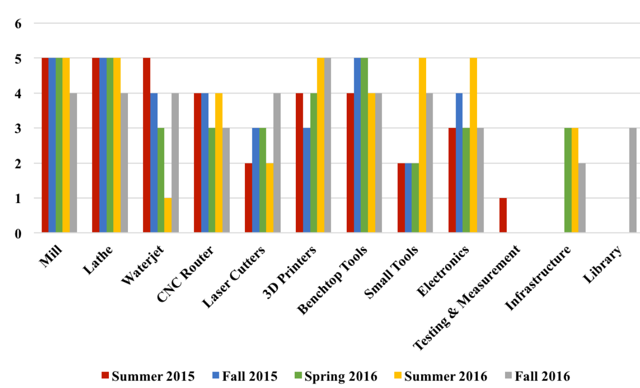

Fig. 6 Shown in this figure are the machine team sizes. Over the past 1.5 years, we have adjusted machine team sizes to keep up with need. For example, laser cutter team grew recently as we are in the process of adjusting our ventilation system. New initiatives have been started, including an infrastructure team, and a library tool check out initiative we are piloting for all of campus.

STOCK TO PURCHASE

Several things are paid for by use, including 3D printer filament, acrylic for use in the laser cutter, and garnet for the waterjet. When a User wants to use any of these machines and purchase these items, they can be charged by the MIT Mobius mobile application. This money goes to a discretionary account. When purchase of one of these items is made, the charge is applied to this account. This allows us to track the account over time, with the expectation that after our initial materials purchase, the funds in this account should not increase or decrease over time.

CAPITAL EQUIPMENT

There are three levels of purchase in MIT MakerWorkshop: less than $250, $250-$3000, and more than $3000. For items less than $250, the treasurer can make the purchase. Items between $250 and $3000 need the approval of the executive committee.

For capital purchases (items about $3000), all Mentors and Users are encouraged to give feedback about what tools and equipment they use in the shop the most, and what items they feel would be the most beneficial. Individuals are allowed to suggest any piece of equipment. We compile a list and send it out again to get specific feedback and rank on a variety of factors, which helps us to determine what would work well in MIT MakerWorkshop. Once a decision has been made, the executive committee must approve the purchase. From there, the entire mentor community must approve the purchase by a simple-majority vote. After being approved by the Mentors, the purchase is brought to the faculty advisor for the space (Maker Czar) who serves are our representative within the department, who must also approve the purchase. Once the purchase is approved, we can follow out the necessary steps to complete the purchase.

Purchase Level	Approval Process
<$250	1. Purchase made by Treasurer at their discretion
$250-3000	1. Purchase approved by executive committee by a simple majority vote 2. Purchase made by Treasurer
>$3000	1. Mentors and Users give specific feedback on suggested purchase 2. Purchase approved by executive committee by a simple majority vote 3. Purchase approved by the faculty advisor (Maker Czar) 4. Purchase made by Treasurer

Fig. 7 This figure details the levels of purchasing at MIT MakerWorkshop. The levels are delineated by dollar amount of spending, and require different levels of approval accordingly.

There are several reasons for this method. First, it establishes a system of checks and balances, where an ambitious treasurer cannot single handedly make large purchase decisions. Second, it allows Mentors and Users to have buy-in to the equipment we purchase. Finally, it gives the department a chance to give us input in what equipment will be beneficial to have in the space.

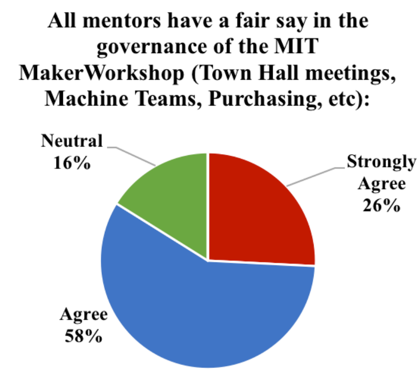

Fig. 8 Shown in this figure are the results from a survey sent to all the Mentors of the MIT MakerWorkshop in Fall 2016. Of the 31 respondents, the vast majority of them felt that they had a fair say in the governance of the space, including purchasing of equipment for the space. Note that no respondents chose "Disagree" or "Strongly Disagree" to this question.

CONCLUSION

The MIT MakerWorkshop is a unique makerspace on the MIT campus as it is run by 40+ student volunteers who have supervisory and management roles as "Mentors" to the community. To appropriately manage purchases for this space, it is important to have a well-defined and trackable purchasing system. We have made it easy for Mentors to request purchases, while also having a detailed policy to describing purchasing which prevents unnecessary discussion on small items, but encouraging participation from all Mentors for new capital purchases. Finally, we have system to track purchases allows us to monitor our finances across several accounts, and sort purchases by the several executive committee members who are qualified to make purchases for MIT MakerWorkshop.

Moving forward, a useful feature to add for the purchase tracker is a category section, where a selection can be made between capital equipment, one-time expense, consumable item, etc. This additional feature would allow for easier analysis of the purchases made for MIT MakerWorkshop.

ACKNOWLEDGEMENTS

The authors would like to thank MIT's Provost Martin Schmidt, the MIT School of Engineering, the Martin Trust Center, the Richard H. Lufkin Memorial Fund, the MIT Department of Mechanical Engineering, Prof. Dennis Freeman and the MIT Project Manus initiative for providing support, encouragement and funding for the MIT MakerWorkshop. The authors would also like to thank Prof. Martin Culpepper for serving as an amazing faculty advisor (Maker Czar) for our space. Finally, the authors would like to thank all Mentors, past and present, for all their time and dedication into designing, building, and maintaining the MIT MakerWorkshop.

ISAM 2016
Paper No.: 37
Invited

The Value of Data, Metrics, and Impact for Higher Education Makerspaces

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INTRODUCTION

The journey associated with designing, constructing, operating and managing a higher education makerspace in far from trivial, and is fraught with many challenges that require creative, team-based solutions. But, by far the most important management tool in the team's makerspace toolbox is 'data'. Data is a very powerful ally and difficult to ignore when used to; craft and promote one's makerspace story, support strategic decisions, measure and validate metrics and gauge impact.

DATA COLLECTION

The question frequently asked when operating a makerspace is - 'what data should be collected?' The answer is a resounding - 'as much as you can!' One can always be selective in which data set to use to tell a particular story, or assess outcomes, but if that data set has not been collected then one is left to tell anecdotes, which, without supporting evidence are easily dismissed. There are many different techniques and systems that can be used to collect data and these decisions will be very much a function of how a particular institution manages and operates their makerspace.

ID Card Readers: The majority of institutions adopt some form of campus ID card that is issued to students, staff and faculty. These have either (or both) a magnetic strip or use RFID technology to store and encode data that identifies the holder. These ID cards can easily be used as one of the major inputs in a data collection system where the holder would swipe their card when entering the makerspace. Fig. 1, shows a card reader unit located at the think[box] 'Welcome Desk'. For users who are not affiliated with the institution and therefore would not have a valid ID card, a government issued photo ID card (e.g. driving license) can be scanned. The data can then be mined to produce a wide array of reports and statistics.

Fig. 1. Card Reader Unit

Photo ID Scanner: For users without campus ID cards, data can be collected by photographing government issued photo ID card. Fig. 2 shows an ID scanner located at the think[box] 'Welcome Desk'.

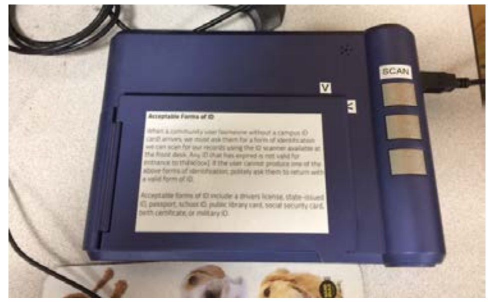

Fig. 2, Photo ID Scanner

However, this is only capturing an image of the ID and OCR software or human intervention would be needed to convert the image data into database format for mining and analysis.

Sign-in Apps: An alternative or accessory to ID collection data is to develop or purchase 'sign-in' application software that can be set up on an iPad or tablet. Using this solution provides ancillary data of any type needed by the makerspace or required by funding sources. This could also be implemented as a paper form at institutions without the needed support from IT services. A simple and quick solution is to create a customized Google Form which automatically populates a Google Sheet to store sign-in data. The form would be designed to capture whatever data is required to track makerspace users. Fig. 3, shows the iPad sign-in Google Form that is used in think[box]. Users are prevented from exiting the app thanks to a kiosk app and "guided access" (part of Apple's IOS). This Google Form captures the following data:

- Email
- Reason for the visit:
  - Tour
  - Course (with course ID)
  - Research
  - Entrepreneurship
  - Design Competition
  - Personal Project
  - Business/Corporate User
  - Other

The Google Sheet can then be mined for the data of interest, such as the number of courses utilizing a makerspace, or the percentage of users visiting to support their research projects.

Fig. 3, iPad Sign-in App

Gate Counter: Large groups, tours, VIPs, and certain other visitors often bypass the ID Scanner and Sign-In stations at makerspaces. In order to provide an estimate of these visits, some makerspaces employ a gate counter. The sensor can take many forms, from the traditional turnstile (Fig. 4) to a break-beam sensor (Fig. 5) or a thermal camera with image processing (Fig. 6). These sensors provide only an electric signal such as a relay which closes and opens again as a visitor walks by. In order to maintain a running count, this signal can be measured with a hobby microcontroller such as the commonly-available Arduino or Raspberry Pi, or through an industrial solution such as a totalizing counter (Fig. 7). The data can be displayed locally (Fig. 7), or sent to a server for addition to a spreadsheet or a dashboard application.

Fig. 4, Turnstile

Fig. 5, Retroreflective Break Beam Sensor

Fig. 6, Irisys Gazelle Thermal People Counter, and Interface

Fig. 7, think[box] celebrates 100,000th visitor in 2015
Red Lion EPAX0600 Display containing MPAXC020 Totalizing Counter

As an example of combining this data, Table 1 shows the total number of unique users as well as total visits to Sears think[box] over a three-year period.

Table 1 Total Users & Visitors

Fiscal Year	Unique Users	Total Visits
2014	903	17,982
2015	2,906	57,870
2016	4,150	66,235

The numbers in Table 1 were mined from the iPad sign-in station, Fig. 3, located at the think[box] Welcome Desk, as well as the gate counter (Fig. 7)

Registrar Data: Data from sign-in systems at higher education institutions is often merged with registrar data to allow deeper inspection of the types of users accessing a particular resource. This can be used to determine statistics on the breakdown of users in terms of percentage of undergraduates, graduate students, staff, and faculty using a makerspace, or as a breakdown of users by departments and majors (Fig. 8). Registrars at universities that receive at least some federal funding must also maintain gender and ethnicity information for each student using nationally-accepted definitions from the IPEDS program. Using this information, diversity information may be obtained for users to provide a picture of makerspace diversity in terms of gender (Table 2) or ethnicity (Table 3).

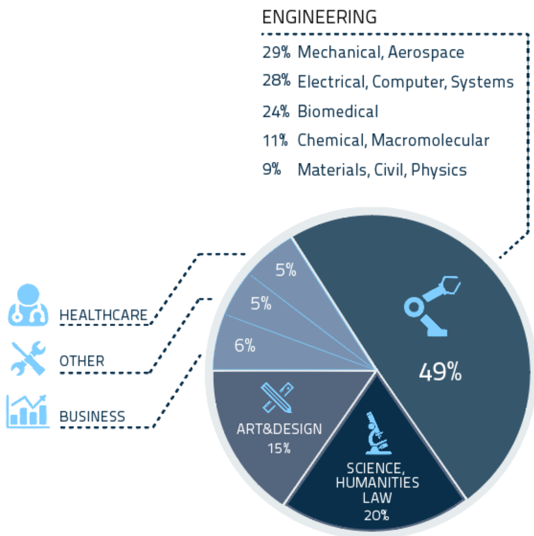

Fig. 8, User Breakdown by Background

Table 2 Gender of think[box] Users*

Female	Male
37%	63%

*CWRU student population is 50% female, 50% male, including both graduate and undergraduate students.

Table 3 Ethnicity of think[box] Users

Asian & Asian American	African & African American	Latino & Hispanic	White
28%	4%	6%	62%

User Surveys: Very useful for focused data collection, there are a number of online software survey/questionnaire products (e.g. Survey Monkey and Qualtrics) that can be easily customized to produce professional surveys and questionnaires. At CWRU we employ an annual student user survey for many purposes such as to see which equipment and services are most popular, to ascertain the quality of the user experience with staff and student workers, and many other functions. Through this instrument we were able to determine for example the percentage of student users who reported that think[box] was a significant factor in their decision to select CWRU as their destination university (Fig. 9).

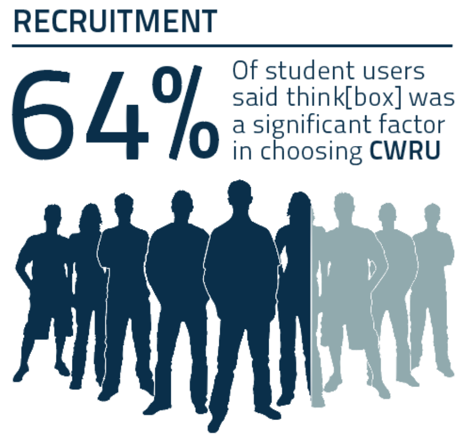

Fig. 9, Influence of think[box] on Student Recruitment

Noteworthy Projects: A great source of job satisfaction for university makerspace leaders is the quality of the projects that students and other users create using these facilities. These stories can be used to promote the individual makers as well as the makerspaces that were a part of the story. Some makerspaces employ project intake forms to catalogue the projects coming through the facility. Though logical, some makerspace leaders see forms and paperwork of this sort as barriers to access. At think[box], “cool projects” are identified at poster shows, start-up weekends, thesis defenses, routine lab walkabouts, and at every other opportunity. When staff and student workers identify projects that are technically challenging, novel, are being commercialized, or are noteworthy for another reason, that data is fed into two places. First, a photo is requested or taken, and that along with contact information and a title and description of the project are uploaded to the think[box] website (with the user’s permission) for public consumption. Projects are also promoted in a monthly newsletter, and selected exceptional projects are displayed as a rotating slideshow on large LCD screens on each floor of the building. Entrepreneurial-focused projects (possible commercial opportunities) are also added to a spreadsheet, and users are queried twice a year for totals on patents, jobs created, and funding obtained.

IMPACT

Decision Making: Most importantly, good data collection should support good decision making. Through user surveys and other metrics, makerspace leadership can determine which machines are overly utilized, to guide purchasing of additional units. With numbers on gender and ethnic background, as well as area of study, goals can be set to increase diversity and data-driven decisions can be made about which outreach programs are proving most successful.

Talking Points: Each institution and makerspace must generate their own “selling points” for use in student recruitment, alumni relations, donor engagement, and other purposes. Data can come from unexpected sources, and makerspace directors and managers are constantly searching for data that demonstrates impact – even of a corollary nature – of their spaces. For example, staff at think[box] attended a research showcase showing posters for 497 research projects at CWRU, and worked with research administration staff to produce a dataset of which posters used which “core facilities” on the campus. From this a talking point was generated when staff discovered that think[box] was the second most cited “core facility” at the University. Another talking point was generated when staff obtained data from the provost’s office on sign-in data from the gymnasium, library, health services clinic, and dozens of other student-centric facilities on campus, and discovered that think[box] was the third most popular student facility on campus after the gym and the library. Data may come from anywhere, and seemingly unrelated reports can be mined for valuable insights.

Grant Reporting: Foundations, government grant programs, individual donors, and other sources of funding commonly used by makerspaces may stipulate data collection and reporting in their terms of acceptance. Leadership at makerspaces can thus easily find themselves in the position of having to collect data for this purpose. Certain types of data can be more difficult to collect than others, and well-meaning foundations can sometimes ask for data which is overly difficult to obtain; however, terms of acceptance can often be modified, especially before the agreements are signed. By collecting data early and understanding this requirement, makerspace leadership can often work with foundations staff to ensure reporting requirements specify only data that is obtainable – ideally and most easily, data that is already being collected.

CONCLUSION

The collection, organization and analysis of data are an integral and critical part of developing, operating and validating an academic makerspace. As we have shown, data can be generated and/or collected in many ways, using an array of different systems and techniques. The power associated with disseminating information derived from these data sources in as many ways as possible cannot be overstressed. However, accurate and honest data collection is imperative; Most, Craddick, Crawford, Redican, Rhodes, Rukenbrod, and Laws (2003) [1] describe 'quality assurance' and 'quality control' as two approaches that can preserve data integrity and ensure the validity of results. In all cases, quality assurance (standardization of data collection protocols) and quality control (consistent, well documented monitoring, processing, and dissemination procedures) of data needs to be maintained before, during, and after data collection.

As higher education makerspaces are increasingly being integrated into mainstream academic programs, the opportunity for faculty to engage in pedagogical research using these spaces as their 'research lab' increases. In particular, NSF has issued an RFP in the form of an open "Dear Colleague Letter: Enabling the Future of Making to Catalyze New Approaches in STEM Learning and Innovation" [2].

Additionally, the VENTUREWELL organization [3] support faculty in developing programs that cultivate student innovators and promote institutional change through grants, workshops, training, and conferences. These VENTUREWELL programs provide grant support for faculty and students in the areas of pedagogical innovation and STEM entrepreneurship, and can integrate closely with the activities of an academic makerspace. The ability to collect data to validate outcomes from these programs would be critical.

Finally, data is the second (people being the first!) most important asset associated with running an academic makerspace; collect, process, and disseminate it wisely and it will repay with huge dividends.

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The Role of a Design Studio in a Mechanical Engineering Department

ISAM 2016 Paper No.: 38

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INTRODUCTION

Academic maker spaces, design centers, innovation institutes, and creativity labs of different kinds are becoming popular hubs of activity on many campuses – particularly within engineering colleges and departments. Some of these centers, such as Stanford's d-school and Penn State's Learning Factory [1], [2], have existed for over a decade. Others, such as Boston University's Engineering Product Innovation Center, are relatively recent developments [3], [4]. These spaces generally offer a physical location with fabrication resources and support for students to learn and work in a hands-on environment. However, they are more than just fabrication facilities: a key element of a maker space is the community itself. In other words, the people matter just as much as (or more so than) the machines. A participatory culture that encourages informal interactions between the communities the maker space serves is what distinguishes it from a facility used only for fabrication. Though each maker space has a unique purpose relative to its home institution, the spaces have all had an impact on embedding design experiences into the campus culture.

OVERVIEW OF THE DESIGN STUDIO

The Design Studio is a 5,500 square foot student-run maker space consisting of several interconnected rooms on the ground floor of a building primarily used to house mechanical engineering department offices and labs (Figure 1). It began in 2012 with just one room that was previously being used as a large storage space, and grew strategically as departmental needs evolved. Students helped design and build the space (Figure 2, left), and the grand opening was held in March of 2014.

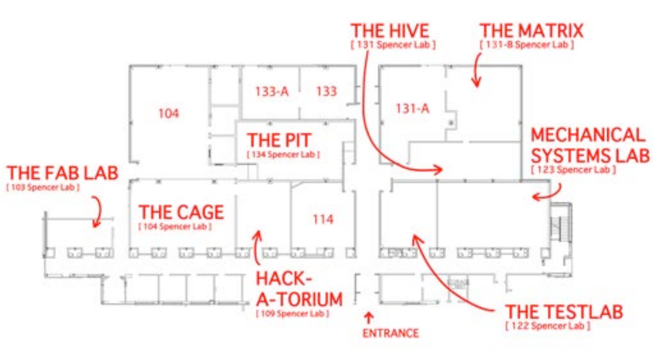

Fig.1 The layout of the Design Studio, indicated by the named rooms. The College of Engineering's student machine shop is conveniently located adjacent to the Design Studio in room 104 and encompasses part of The Cage. For reference, room 123 is approximately 47' x 27', or 1270 ft^2.

A. SPACE, EQUIPMENT, AND RESOURCES

The space and equipment are constantly growing and evolving to serve the needs of our students and department. The Fab Lab houses most of our digital fabrication equipment (three Stratasys uPrint SE Plus 3D printers), two electronics workbenches, and a variety of electronic rapid prototyping equipment including Arduino-based Sparkfun Inventor Kits and peripheral sensors. The Cage is home to all of our hand tools (e.g., portable drills, Dremels, sanding equipment, wrenches) and several benchtop tools (e.g. belt sander, drill press), as well as prototyping space. The Universal VLS4.60 laser cutter lives in the Hack-A-Torium next to a fume hood, several large work tables, and a lot of project storage bins. The Pit has room for group work and a wall lined with desktop computers, as well as two lounge areas for more casual collaborations. The Test Lab houses our sensor inventory and two large tension testing rigs, and the Mechanical Systems Lab is home to three out of four of our laboratory courses. Finally, the Hive is primarily used for teaching assistant (TA) office hours and tutoring, and the Matrix is a design lab with animal tissue storage and testing equipment controlled by the biomedical engineering department.

Fig.2 (Left) A student helps build out the Design Studio, (Right) The Mechanical Engineering Student Squad (MESS) hold a pizza and Legos night in the Design Studio

B. FUNDING AND EXPENSES

Initial funding for the renovations came from several key alumni, as well as contributions from the mechanical engineering department and the Office of Economic Innovations and Partnerships (OEIP). The first room of the space was outfitted with tables and hand tools for just \$5,000, and the initial investment by the alumni and department came to about \$80k along with in-kind donation of two 3D printers by OEIP. Several grants were awarded in the last year that will cover machine shop and space upgrades as well as consumables for student projects. Ongoing support will come from the mechanical engineering department (primarily through sponsorship fees from our well established senior design program) and targeted development efforts including grants and alumni donation campaigns.

C. USAGE

The resources and physical space of the Design Studio are used to support a wide range of curricular, extracurricular, research, and outreach activities.

Curricular Support: The Design Studio is used extensively to support the curriculum. Several courses have required activities that make use of the resources and/or space in the Design Studio (Table 1). For example, our sophomore level Computer-Aided Engineering Design class requires student teams to 3D print components after modeling them in Solidworks. Several courses are physically held in the space, including all of the laboratory courses and two technical electives.

Table 1:Courses directly supported by the Design Studio (*Indicates courses that are physically held in the space)

Required Classes	Required Labs	Electives
Introduction to Engineering	*Vibration and Control	*Integrated Design
Computer-Aided Engineering Design	*Fluids	*Applied Controls
Machine Design – Kinematics and Kinetics	*Thermal Fluids	*Maker Series
Machine Design – Elements		
Senior Design		

Extracurricular Support: The Design Studio is used by several registered student organizations, including the Society of Automotive Engineers, Engineers Without Borders, and a department level service organization called the Mechanical Engineering Student Squad (MESS) to design, build, and test their projects as well as hold events (Figure 2, right). Additionally, The Perry Initiative, a non-profit program that runs hand-on outreach programs to inspire young women to be leaders in the fields of orthopaedic surgery and engineering, makes heavy use of the space and draws volunteers from the student community. These organizations actively share the workspace throughout the year, promoting an interdisciplinary and cross-curricular exchange of ideas throughout the four undergraduate years that students typically use the space.

Research and Outreach: Many undergraduate and graduate research assistants utilize the Design Studio to support their work. We have a strong summer undergraduate research program and summer engineering internship program for high school students, and many of these students call the Design Studio home. The Design Studio is also home to past, present, and pending NSF-funded Research Experience for Teachers (RET) and Research Experience for Undergraduates (REU) programs, and allows the department to easily host first year graduate students before their alignment with a lab and advisor.

D. INTELLECTUAL PROPERTY

According to the University of Delaware Policies and Procedures Manual [5]:

> "It is policy of the University that all inventions and discoveries, together with any tangible research materials, know-how and the scientific data and other records of research including any related government protections (collectively "Intellectual Property"), which are conceived or reduced to practice or developed by University faculty, staff, or students in the course of employment at the University, or result from work directly related to professional or employment responsibilities at the University, or from work carried out on University time, or at University expense, or with the substantial use of University resources, shall be the property of the University."

Since the majority of the students that use the Design Studio are undergraduates who are not considered employees of the university, and use of the Design Studio is not considered substantial use of University resources, students retain the rights to their own ideas. Undergraduate research assistants, graduate students, staff, and faculty who are employees of the University may be considered differently depending on the project on which they are working.

ACCESS, STAFFING, AND MANAGEMENT

While the student machine shop is only open during normal business hours when the full time machinist is in, the Design Studio is open to students 24/7. It is primarily student run. While it is loosely managed by two co-directors that are also full time faculty, a team of ~10 hourly paid undergraduate TAs do most of the day to day work in the space. At least one of the co-directors meets with the team of students weekly to discuss ongoing maintenance, space usage, upgrades, and problems. Each of the TAs is assigned a specific role within the space that ranges from managing the 3D printing queue to general organization and restock, and these roles are detailed in a responsibilities document that is reviewed with the TAs once per semester. This allows us to be very responsive, and we can immediately implement lessons learned from curricular engagement, events held in the space, etc. into our operating procedures. For instance, in our freshmen Statics courses, we have been able to reinforce particular concepts that students may be struggling with, e.g., internal forces and moments, using hands-on build-test group exercises with less than 1 week notice to our TAs. We have also used TA support to train students en masse on new fabrication equipment that arrived mid-term, e.g., vacuum former and laser cutter. Staff support is also critical. A laboratory coordinator is in charge of major safety, maintenance, and facilities-related requests. Several other department administrative staff help support purchasing efforts in the space as well as direct students to the appropriate contacts and resources.

A. SAFETY AND TRAINING

The student machine shop requires formal safety training and is staffed by a full time machinist with an office inside the shop. The students are required to attend an in-person basic shop safety demo, review the online shop operating procedures, and then complete the online basic shop safety quiz with a grade of 100%. The students have to retake this online quiz each fall semester. As for the Design Studio, injury risk is mitigated by locking down all machines that reside permanently in The Cage area. Only TAs trained by the co-directors have keys to unlock the equipment. Students are introduced to the tools and equipment that can't be locked down throughout the curriculum. For example, the freshmen might only need to use PVC cutters and sand paper, while juniors are expected to be able to use the band saw and drill press for fabrication tasks. These tools and skills are taught to students in small groups by Design Studio TAs during class time as needed.

IMPACT ON STUDENTS

While we conducted numerous, informal formative evaluations of the student population during the development of the Design Studio - mainly to assess whether the physical plant and equipment infrastructure met their needs – our primary, summative evaluation of this effort thus far has been conducted with our alumni population. There are several benefits, from an experimental design perspective, to using an alumni population. First, we can clearly segment this population into those alumni who utilized the Studio and those who did not; and, second, alumni are in a better position to comment on the value of their Studio experience to their practice as engineers. With this in mind, we assessed the impact of the Design Studio on our undergraduate population as a subcategory of outcomes in our Department's standard alumni survey, which is administered approximately every five years as part of the ABET accreditation process. In fall 2015, an online survey was distributed to all alumni of the department, both graduate and undergraduate, with active email addresses (N=2301) via repeated emails (Constant Contact) with links to an online survey (Qualtrics). Responses were solicited for a two-week period from mid-September to early October 2015.

The survey began with questions about our current curriculum and our alumni's satisfaction with their overall level of preparation for their respective careers. This was followed by questions about self-perceptions and the importance of three core areas of emphasis for our undergraduate program: Active Learning, Professional Development, and New Technologies. Assessment items for the Design Studio were embedded in the Active Learning section, which included ratings of the quality and importance of undergraduate laboratory and design spaces, design projects, in-class demonstrations, and open-ended laboratory experiences. Survey items were mapped to a 5-point Likert scale, with higher values corresponding to more positive outcomes. To assess the impact of the Design Studio and associated curricular changes, the survey cohort was segmented by graduation year into pre (<2012) and post (2012-2015) Design Studio creation. The Design Studio was the only major change to our undergraduate curriculum from 2012 onwards. Pre versus Post Design Studio comparisons were made using one-way ANOVA (JMP Pro v12).

A. SURVEY RESULTS

The survey response rate was 6.6%, with respondents representing a wide range of graduation years (2015-1945), with concentrations in 2010-2015, 1992-1995, and 1980-1982. Only undergraduate alumni who completed the survey were included for further data analysis (N=132).

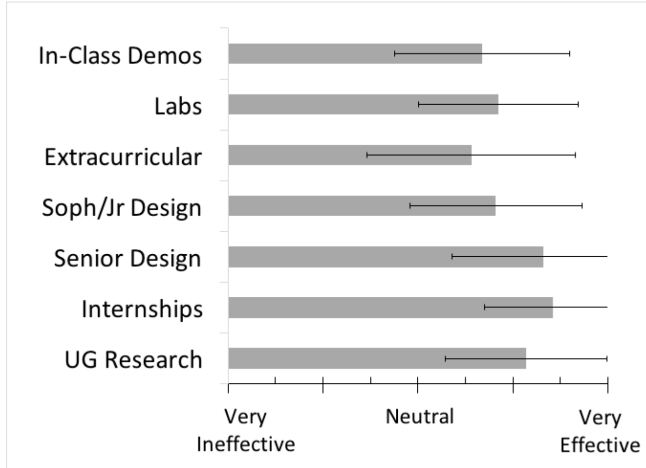

Fig.3 Results for entire survey cohort for survey questions: "Please rate the effectiveness of the following Active Learning strategies for you during your time in the UD-ME program." Bar represents mean with whiskers ± 1.0 standard deviation.

In general, alumni were satisfied with all elements of Active Learning in our program (Figure 3), and the creation of the Design Studio only improved the level of satisfaction (Table 2). Comparing Pre versus Post Design Studio cohorts, Senior Design, which heavily utilizes the Design Studio resources, was ranked as significantly more effective after the creation of the Studio ($p < 0.01$). Similarly, there was a significant increase in effectiveness for "In Class Demos" ($p = 0.03$) and "Sophomore/Junior Design" experiences ($p = 0.04$).

Table 2: Results for survey question related to Active Learning: "Please rate the effectiveness of the following Active Learning strategies for you during your time in the UD-ME program." Results scored as 5-pt Likert with 4=Very Effective and 0=Very Ineffective. Mean and ± 1.0 standard deviation are shown for pre (<2012) and post (2012-2015) Design Studio alumni cohorts. Pre vs. post results compared with one-way ANOVA. P values presented, and for p<0.05 effect sizes (d) are also shown.

	Pre (<2012)	**Post (2012-2015)**	**Pre vs. Post ANOVA p-value (d)**
In-Class Demos	2.58±0.91	2.96±0.90	0.03 (0.39)
Labs	2.84±0.87	2.85±0.77	0.95
Extracurricular	2.45±1.06	2.95±1.15	0.07
Soph/Jr Design	2.67±0.94	3.11±0.75	0.04 (0.44)
Senior Design	3.17±1.05	3.78±0.42	<0.01 (0.61)
Internships	3.32±0.72	3.62±0.67	0.11
UG Research	3.10±0.85	3.25±0.85	0.50

CONCLUSIONS AND FUTURE WORK

Although the Design Studio is a work in progress, we are happy with the results we have been able to measure so far. Aside from ongoing facilities and equipment maintenance, there are several near term changes we are exploring. A facilities upgrade will allow student ID card swipe access to all rooms, so we are looking at implementing a membership structure to the Design Studio such that access is limited by the types of training a student has taken. We are also looking for ways to make staffing more predictable to manage student demand for training on particular equipment ranging from sewing machines to power tools. In order to have a staff that can help address this, an application system was setup to identify future TAs that have either existing experience or the propensity to learn particular skills. Furthermore, as we integrate more hands on work into our curriculum, we will need to carefully balance the usage of the space for curricular, extracurricular, and research and outreach uses.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Dr. Suresh Advani, George W. Laird Professor and Chair of Mechanical Engineering, for the support of the work that led to this publication.

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Understanding the Impact in University Makerspaces

ISAM 2016 Paper No.: 39

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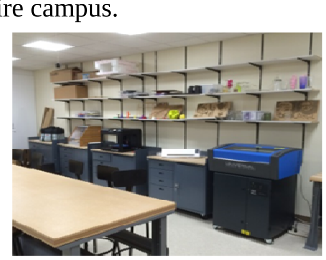
INTRODUCTION

Across the globe, the Maker Movement has gathered momentum such that university campuses are scrambling to develop makerspaces for recruitment purposes, for classes, and for leisure time / personal projects. Numerous universities and their donors are investing tens of millions of dollars to build new university makerspaces and renovate existing ones [1-3]. Proliferation has also been fueled by significant claims for the impacts of these spaces. Unfortunately, little empirical or quantitative research on the impact of academic makerspaces has been undertaken. The anecdotal evidence supports the potential for these spaces to tremendous impact the engineering [4-9].

RESEARCH METHOD

A five-year longitudinal study on how makerspaces influence students' retention, retention in major, design self-efficacy, and creativity is currently being performed. Data collection is occurring at three different universities in three very different makerspaces. The schools include James Madison University, a regional undergraduate focused institution, Georgia Institution of Technology, a research-focused university, and Texas State University, a Hispanic-serving institution. The spaces have very different characteristics providing a rich source of data. Texas State's Bobcat Made is a new makerspace not housed in an engineering building and open to the entire campus. James Madison has multiple makerspaces across their campus including ones for class only use and others that have broader use for both classes and personal. Georgia Tech is an example of a well-established makerspace housed within the department of mechanical engineering, but open to the entire campus.



Texas State-Bobcat Made

Fig. 1 Bobcat Made, a fledgling maker spaces at Texas State.

Georgia Tech's Invention Studio

Fig. 2 The Invention Studio is a well-established university makerspace at Georgia Tech.

Fig. 3. The maker spaces available to students at JMU are distributed across a variety of different facilities.

At Georgia Tech we are following a cohort of mechanical engineering students from the time they enter as freshman until they graduate as seniors. Each year we survey students regarding the time they spend in makerspaces, ask about the types of projects they work on, measure their Design Self-efficacy [10], and measure changes in their ability to generate ideas [6, 11, 12]. The survey also measures demographic information and collects data on their tool use and experience prior to entering the university. Students are being tracked longitudinally so that the makerspace's influence on retention, GPA, and retention in major can be measured.

To understand the flow of students through the makerspace we have also installed three commercially available Clear-Count Active Automatic People Counters (APCs) at the entrances of the 3d print room, laser and waterjet room, and the woodshop. This is a non-obtrusive approach to measuring the number of students entering the rooms. It allows usage data to be collected without adding any barriers or deterrents to use of the space. Through observational or survey data, linear regression may be used to estimate the relationship between automatically collected count data and other information such as the number of unique users per day and demographic information [12, 13]. APCs allow for the prediction of usage to be obtained and planned for. APCs also provide a means to determine how the changes in a space affect usage.

And finally, to provide context for the results being obtained by the design self-efficacy survey instrument and the APCs, we are following an ethnographic approach, where students at all three universities are being trained as ethnographers [14]. Our student ethnographers, enter the spaces, work side-by-side with students in the spaces, and observe, listen, interview, and describe the what they hear, see, and feel while in the spaces.

RESULTS

A. DESIGN SELF-EFFICACY

A survey measuring student participation in makerspaces was deployed in Fall 2015, and students' self-efficacy for design related tasks was also measured [10]. As shown in Figure 4, freshman who show a high level of participation in the Invention Studio have greater motivation to complete design tasks (p=0.002) and also show lower levels of anxiety about design tasks (p<0.001). Their expectation for success and confidence for design tasks shows similar levels [6, 12]. A high level of participation was defined as using the Invention Studio for activities unrelated to class. Some freshman classes require the use of the Invention Studio. This data is only correlational and does not demonstrate causality. It is very likely that the students who are highly motivated to do design activities and have low anxiety levels about design are choosing to participate more in the Invention Studio. It is also very possible that engagement in the Invention Studio may increase students' confidence, motivation, and expectancy of success when engaging in engineering design activities. Their anxiety about engineering design activities may also be reduced. The longitudinal data will further explore these issues and the impact of makerspaces.

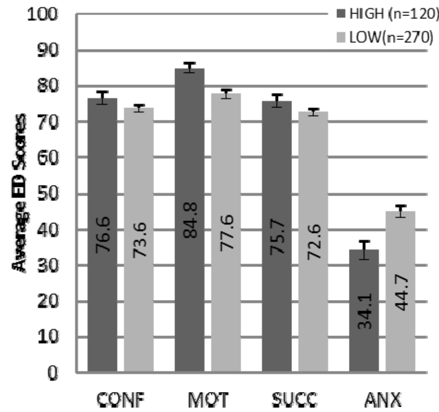


Figure 4: Comparison between high and low participation for design self-efficacy. Engineering Design (ED) Scores comprise a set of questions related to Design Confidence (Conf.), Motivation (Mot.), Success (Succ.), and Anxiety (Anx.).

B. AUTOMATIC PEOPLE COUNTER RESULTS

The APCs are allowing data on the room usage to be collected. The data is continuously collected throughout the entire day, seven days a week. Fig. 5 shows the raw usage data for three different rooms of the Invention Studio. The APCs were only recently installed, so only about a month, and a half of data is available. What is most surprising is the very high numbers of users from July 26th to August 27th even though the Invention Studio was closed for summer break between semesters. Two groups of students have 24-hour access to the space: students who volunteer and run the Invention Studio and the Prototyping Instructors. A limited number of students from the student competition teams such as Solar Car also have access.

Fig. 7 shows the estimated number of individual users who used the 3D print room in Fall and Spring. Cameras were used to observe the number of unique users entering and leaving the 3d print room. Through linear regression, this data was used to estimate the number of unique users. For the 3d print room, it is common for students to enter, start their print, leave and then return a few hours later to pick up their part. There is less usage on the weekends because the Invention Studio is only open to the Prototyping Instructors and students from the competition teams on the weekends. The Studio is not open to general users due to a limit in the number of available volunteers. As expected, spikes in usage are observed just prior to class project due dates like Capstone Expo. Another interesting increase in usage occurs on February 12th, the last day the Invention Studio was open to general users prior to Valentine's Day. It is very common to find a large number of students working on personal projects and gifts just prior to the holidays. Personal projects are another opportunity for students to apply their design and engineering skills, and they often motivate students to learn a wide range of concepts such as electronics, mechatronics, and about various prototyping and manufacturing techniques.

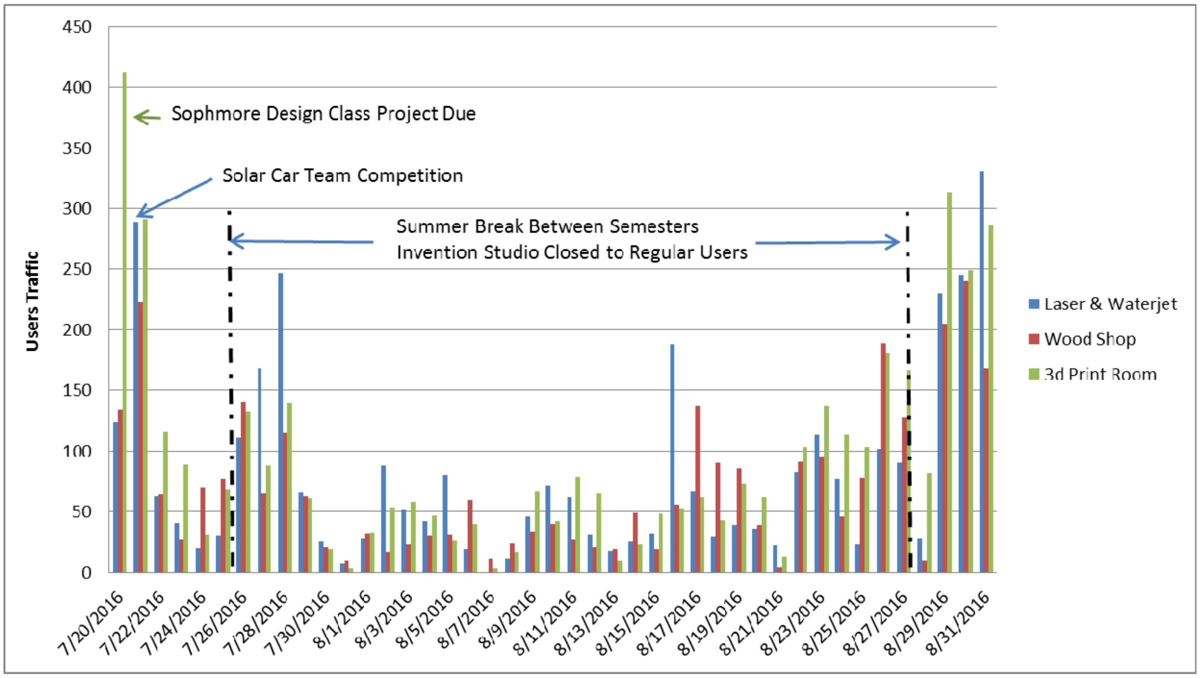


Fig. 5. Daily counts for the Wood Shop, Laser & Waterjet Room, and the 3d Print Room at Georgia Tech since APCs were installed.

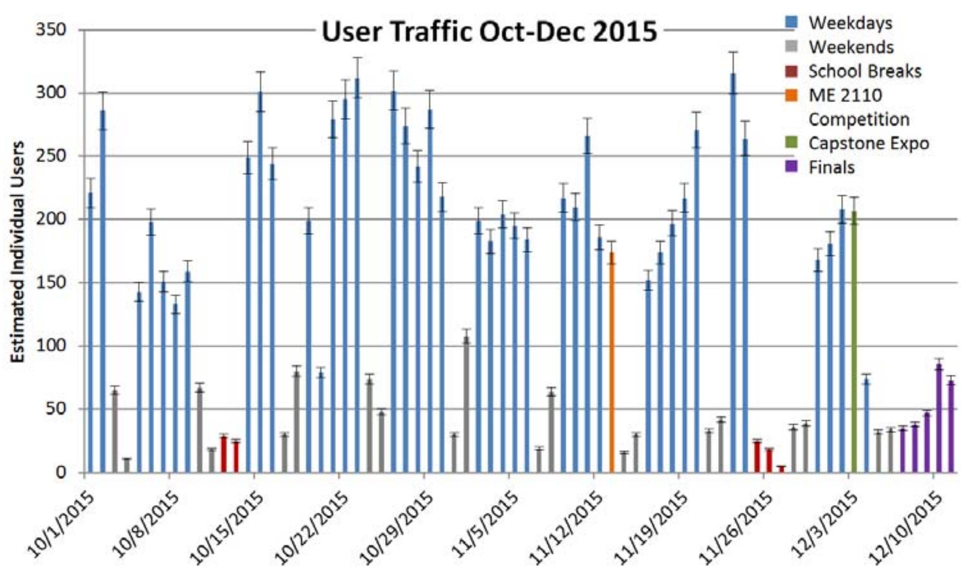


Fig. 6 User traffic flow in the 3D Printing room. The error bars represent ±1 S.E. [15]

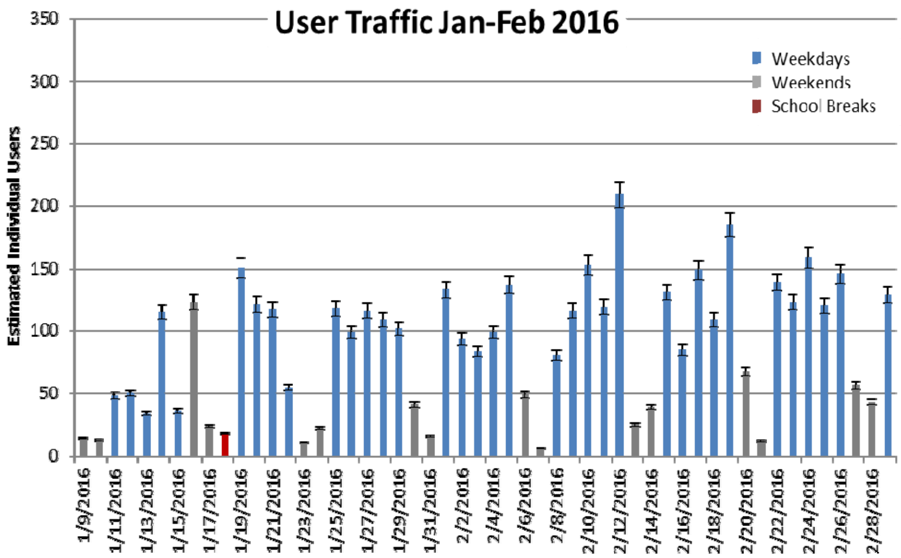


Fig. 7 User traffic flow in the 3D Printing room. The error bars represent ±1 S.E. [15]

C. ETHNOGRAPHIC STUDY RESULTS

The initial ethnographic studies of makerspaces are uncovering emerging themes including: access, proximity, and gender roles. With respect to access, we are finding that there are emerging sub-themes within the category of access, such as the role of visibility into and out of a space, the impact of locked doors, and the importance of appropriate signage. We have noted that the simple act of going into a maker space for the first time can evoke emotions ranging from insecurity to anxiety to fear. With respect to proximity, we have noted that barriers to entry might be as simple as a few flights of stairs, and with respect to gender roles, we are seeing differences in initial perception of a space between male and female student ethnographers. These results are beginning to paint a picture for how students find, access, and engage in making on our University campuses, and when considered with the design self-efficacy student we can begin to understand why the changes in design self-efficacy are occurring.

DISCUSSION & CONCLUSIONS

The emerging interest and installation of makerspaces on university campus internationally with only a limited understanding of their impact on student learning, demonstrates hope and promise that these spaces will provide new experiential opportunities across a wide array of disciplines. For us, this has demonstrated a need to understand the impact on student learning, retention, and inclusivity such that best practices may be identified and applied and that access may be ensured.

The three studies described herein—measuring student's design self-efficacy, monitoring the flow of students through a space, and exploring the cultural norms of a makerspace—provide a first step and understanding how these spaces, when placed in an engineering program, influence students' motivation, anxiety, confidence, and retention as well as provide initial insight into the informal learning occurring through the community of users in a makerspace.

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Failure Modes of Academic Makerspaces

ISAM 2016 Paper No.: 40

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INTRODUCTION

A successful academic makerspace allows for engaging learners in creative, higher-order problem-solving through hands-on exploration, design, construction, iteration, and entrepreneurship. Administrative support and fostering creative communities within these spaces are the keys to perpetuating a culture of safe, fun, educational, and responsible use. Through an international Googledoc brainstorming session, we identified several key elements that academic makerspaces must take into account for future success.

STARTING UP

Experienced fab lab managers all agree that the culture of a makerspace and the individuals involved are far more important than the technological capabilities. Without students making things, makerspaces become equipment museums. Spaces must thus attract people with diverse technical capacities, and provide mentorship for inexperienced attendees while encouraging exploration and tinkering.

To cultivate these attitudes, the first step is finding a solid team that enjoys working hard on ambitious (and perhaps seemingly intractable) goals. Creators should also consider what kinds of projects their makerspace should pursue before they actually design and create their space, as makerspaces depend heavily upon their local cultural, economic and social contexts.

If the team decides to purchase expensive digital fabrication equipment, this should be the most suitable thing for that particular space— and not because part this bill of materials is part of some established template or grant funding. Outside of high-tech cities, many academic and corporate institutions still have little or no exposure to innovation spaces, and may not be aware of their own misconceptions; it is thus important to communicate extensively with experienced makerspace creators and staff before embarking on a new endeavor.

We have noticed many misconceptions about the role of makerspaces and the perceived dangers of working with tools. Peruvian university-educated engineers tend to be more concerned about soft skills rather than technical knowhow, as the aim of engineering education is to train managers rather than hands-on engineers. Digital modelling and fabrication may be perceived as acceptable, whereas vocational skills such as metalworking and auto-mechanics (which are equally important for makerspaces!) can be considered dangerous and lower-class. In Peru, the university UNSA in Arequipa features many more practical courses than Lima's more prestigious Universidad Nacional de Ingeniería (UNI), where parents and university faculty at UNI are afraid that students will endanger themselves with tools. This provided an additional hurdle to creating the Fab Lab at UNI.

ENSURING ADMINISTRATIVE SUPPORT

Although makerspaces are difficult to initiative without a passionate start-up team, it is also key to win both top-level and mid-level administrative support early in the process of creation.

Due to a series of poor administrative decisions, Fablab UNI has been forced to close temporarily. One reason behind Fablab UNI's early success was dedicated financial and political support from the university's top-level administration. They initially thrived by allowing students open and unrestricted access to its facilities—and has thus attracted a variety of creative students and successful projects. Yet the lab did not have enough autonomy to maintain their own machines, approve community outreach projects, or purchase new materials. They were entirely dependent upon their hosts at the school of architecture. Autonomy is essential for a makerspace, as spaces are often required to take important decisions in short timeframes.

Quebec's Fab Outaouais (2013-2014) provides a more grassroots example in which student makers failed to gather enough faculty support for their initiative. The student founders were all too busy with their own schoolwork to focus on sustainability, and so the nascent fab lab fell apart upon their graduation—even though they could have potentially found grant funding to grow the project. This led co-author Thongsouksanoumane to build a framework for gathering more institutional support for fab labs and figuring out how to involve all stakeholders from the outset.

BALANCING ACCESS, SAFETY, AND FINANCES

Another key factor for success is access to equipment and facilities. While safety is of utmost importance, we have found students' level of engagement to be considerably higher when they can experiment and interact with machines without excessive oversight. Makers have to be in a trusting environment where they feel free to share, learn and fail.

When makerspaces fall under specific departments, or are used primarily for certain classes and/or sanctioned extracurricular activities, we recommend a strong open-access policy to ensure that students across the institution can have equal access. In Brazil, some students from the Federal University of Rio de Janeiro travel two hours to Olabi Makerspace to explore citizen science and biohacking because they cannot access their own university laboratories without a project or connection to some specific class. On the other hand, the design department of the Pontifical Catholic University of Rio de Janeiro is well known in the city for allowing their students to experiment and interact with their makerspace in a more project-based rather than subject-based style. Rio's European Institute of Design is another example of how people can learn more when they can freely interact with machines; their lab allows students across the institute to learn and build their own projects.

Through working closely with Brazilian universities, co-author Agustini found that when university lab managers relax their top-down control and stimulate a freer process of creation, students are better to engage in makerspaces and follow their own curiosity. Without determined efforts to allow machine access and provide students with qualified mentors, many well-equipped university makerspaces have spent the majority of their time empty.

When resource-constrained institutions get access to particularly expensive equipment, some administrators may become excessively concerned about damaging machines or running out of expensive feedstock. One library makerspace in North Carolina lost their community when they started charging for 3D printer filament—and students moved their printing projects to the local university makerspace instead. Both IIT Bombay's first makerspace and the Centre for Innovation in IIT Madras severely restricted student access for fear of damaging their expensive equipment. To gain access to IIT Bombay's first 3D printer several years ago, students had to first request and be approved for makerspace access, and then they had to be approved for 3D printer access, and then they needed to catch the person with the key to the 3D printer closet at the right time—as the closet was always locked. IIT Madras's Centre for Innovation lacked mentors to train students on equipment, and there is general disinterest for such endeavors among the university faculty and administration to spend time/resources on maintenance.

Yet makerspaces cannot afford to be too generous with their equipment and supplies; another reason behind Fablab UNI's closure was their failure to appreciate the fragility of many of their machines. Most makerspace machines are built for prototyping rather than industry, and therefore cannot sustain continuous unlimited use. Fab lab materials all generate a considerable economic cost that must be analyzed properly. Following Fab Academy classes at Fablab UNI and FabLab Tecsup, both makerspaces suffered significant economic losses that should have been better anticipated.

In resource-constrained settings, locally designed and fabricated solutions (DIY 3D printers, CNC machines, and even laser cutters) may remove barriers such as access to equipment, expertise, and advanced skills. Although making one's own machines can provide an excellent learning opportunity and an affordable way to build up a new space, homemade equipment is much more prone to failure and safety issues. One Australian fablab equipped their space with cheap laser-cutters, and then had to build their own safety mechanisms to ensure that the laser-cutters would stop running when the lid was opened.

INTERNAL ECOSYSTEM

A successful space blends experiences from faculty, graduate students, and undergraduates so they can learn together in a kind of 3rd place— where learning and hanging out go together. This context allows for new collaborations for both casual learning, and the invention of new, cross-disciplinary technologies. Successful makerspaces also foster opportunities to commercialize and/or release resulting projects as open-source.

One best practice from Newton Conover Middle School in North Carolina, USA is that all of the teachers had to incorporate a physical example of something constructed in the makerspace into their classroom curricula. That edict transformed that entire school into a makerspace-- rather than limiting maker activities to just one classroom or department. MC2 STEM High School in Ohio, USA takes an even stronger approach; topics are integrated across every subject taught in any given term, and every class culminates in a capstone project in which students are encouraged to use their extensive makerspace facilities.

Spaces must also work to communicate and share their projects with the larger community, in order to gain new members and gain more support from the administration—interaction and social media are crucial to a successful makerspace. The now-closed Fablab UNI, for example, would invite 3000 Facebook members to events but only 15 would attend; the problem was, the fab lab lacked a team that was specifically dedicated to bolstering community presence and engagement.

BROADER ECOSYSTEM

Finally, these makerspaces must also be connected internationally—which is a requirement for any space in the fab lab network. Significant collaboration spans multiple semesters and even multiple rounds of graduating students, and creates opportunities for global makers and academics to meet and exchange ideas. Local context is also very important; a small town off the coast of Iceland proved to be the perfect place for high school students from Vestmannaeyjar Fab Lab to build an interactive park to educate people on local history—but this sort of "civic hacking" project might be much trickier to pull off in downtown New York or Mumbai.

Academic makerspaces must also interact with their surrounding community and local industry, as this allows for the creation of strategic alliances, commercial exchanges, project development, financial support, and inspiring new makers and engineers. Industry partnerships also support makerspace sustainability, as companies can promote relevant industry training and cultivate the next generation of engineers and entrepreneurs.

CONCLUSION

By making a solid commitment to community-building, allying with friendly administrators, and ensuring openness while being cognizant of the risks, we believe that academic makerspaces can thrive in any environment— from Peru to India to the USA.

Don't GUESS, It's Easy to Get the Information That Lets You KNOW How to Create and Run Your Makerspace and Makersystem

ISAM 2016
Paper No.: 42

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INTRODUCTION

The *intent* of this paper is to demonstrate that "easy to get" data can be helpful in the planning and decision making process when one is creating or modifying campus makerspaces. This is *important* because this data makes it possible to know the truth of the situation, and thereby make sure that all stakeholders understand the situation. Given that makerspaces are resource intensive (cost, space, staff, maintenance, etc.). The most important cost is the negative educational impact upon all of the student users' that will use a facility that is not properly designed to meet their needs. In extreme cases, even the best of intentions in creating a makerspace can yield spaces where millions of dollars in construction and equipment costs don't attract students. The positive *impacts* of having this data is increased ease of getting stakeholders to sign on, a better educational experience for students, and satisfied alumni/donors among other things. This impact can be measured in many ways, for example work done in Georgia Tech's assessment of its Invention Studio [1].

MIT learned a great deal from the previous assessment efforts and surveys of several makerspaces [2], however we found we needed more/different information. MIT's Project Manus office (campus maker advocates) collaborated with Provost's office, MIT's Institutional Research Office and the Chancellor's office [3], to create a survey that would enable general university makerspace stakeholders to understand the state of making on campus and thereby know how to (i) set a strategic plan for the campus and (ii) invest resources that deliver the makerspaces our particular university needs. This team invested over two weeks creating a survey with questions that were properly phrased and properly designed to elicit the data that is useful in decision making. The time and expertise required to do this is often a barrier to obtaining this data. MIT believes it is important for any student, whether at MIT or not, to have access to the best possible makerspaces and maker resources. Toward this end, *MIT has made this survey freely available to other universities so that it is easier for them to obtain this information*. More information about survey results is provided on the MIT Project Manus Homepage [4]. They may use the survey in whole, or in part, or with adaptations to suit their specific universities resources/needs.

The following provides a case study of the how a sample of this data was used to design MIT's new flagship makerspace. We show example questions that provided the insight needed to program and design a 20,000 ft^2 makerspace [5] that would require over 25 million dollars for construction and equipment. This new makerspace will be MIT's flagship makerspace, and therefore data was required to make sure that the invested resources would provide the intended impact upon the students' educational experience. The survey is too long to reproduce in its entirety within this document, however it may be obtained by emailing *project-manus@mit.edu.*

A. ABOUT THE SURVEY

The survey consists of 35 questions that cover topics ranging from equipment, expenses, training, open hours, and more.

The survey was conducted during the summer of 2015, which is not the ideal time to conduct a volunteer survey, i.e. when students are away from campus. This was necessary as decisions regarding the design of the makerspace were quickly approaching. Despite the summer timing, the response rates shown in Table 1 were obtained.

Table 1: Survey Pool Characteristics

Group	# Invited	#Participated	Response Rate
Undergrads	3,358	729	22%
Grad students	4,902	640	13%
Overall	8,260	1,369	17%

B. ABOUT THE STUDENTS

Table 1 does not include input from the incoming freshman class (typically 1,100 students) as they had not yet been on campus and therefore had no experience with the MIT makerspace system. Figure 1 provides more information on the students that elected to take the survey.

Answer	Bar	Response	%
Graduate: Doctorate		375	32%
Graduate: Masters		154	13%
Undergraduate: Year 1		0	0%
Undergraduate: Year 2		201	17%
Undergraduate: Year 3		203	18%
Undergraduate: Year 4 or later		227	20%

Fig.1 Results of Question: Which Year Are You?

C. EXAMPLE DATA REPRESENATIONS

Given the size of the graphics, it is best to switch to the single column format for a portion of this paper. In the following we provide several figures for the reader to examine without narrative. We then pick up the discussion after the figures and explain the import of this data on the decision making for the 20,000 ft^2 Victor and William Fung Metropolitan Warehouse Makerspace [5].

Answer	Bar	Response	%
Where I live: My bedroom or common space		697	55%
Wherever my laptop is		691	54%
Off-campus		251	20%
Other department-based shop or research lab		226	18%
Edgerton Center Student Shop		154	12%
Media Lab		142	11%
Where I live: Shop or hobby space in the building		140	11%
Hobby Shop		128	10%
Pappalardo		117	9%
Architecture shops (Fab, Wood, etc.)		102	8%
Student Art Association		90	7%
Other student group spaces		80	6%
D-Lab		75	6%
Edgerton Center Area 51 CNC Shop		73	6%
ME Maker Works		66	5%
Other		64	5%
MITERS		63	5%
Lab for Manufacturing and Productivity		59	5%
Glass Lab & Forge/Foundry		58	5%
Gelb Laboratory/Shop		55	4%
CSAIL Machine Shop		54	4%
I have not made things at MIT or off-campus		49	4%
SUTD International Design Center		48	4%
Cypress Engineering Design Studios		33	3%
Beaver Works		28	2%
MIT Museum Studio		26	2%
Bioinstrumentation Lab		22	2%
CEE Student Machine Shop		14	1%
Grad Student Machine Shop (AMP Lab)		10	1%

Fig. 2 Results of Question: Where do you make?

This led us to understand that most campus spaces were not the first choice for students compared to off campus resources. On-campus resources often had too many barriers, or barriers that were too high. Through further analysis, to be described at the symposium, this *led us to the realization that our students needed a community-type makerspace*. This also led to several other MIT programs that have been put in place to enable easier access to spaces on campus.

Answer	Bar	Response	%
None		112	9%
Up to 5 hours		594	47%
6-10 hours		223	18%
11-15 hours		103	8%
16-20 hours		86	7%
21-25 hours		43	3%
26-30 hours		19	1%
More than 30 hours		87	7%

Fig. 3 Results of Question: During a typical week in the last academic year, how many hours did you spend building, making, or creating?

This led us to the conclusion that our new space needed to fit into a system that could absorb several 10,000s of person-hours per week of making. A large, new makerspace would not be the panacea solution to our students lack of access problems. A sinigle large 20,000 ft^2 space would not be able to handle the shortfall between demand and that the existing 45 facilities (120,000+ ft^2) could deliver. As a result, *the solution to our campus' access problems lay in a makersystem (fixing the existing system of 45 spaces) that could integrate the large new building, and thereby handle this load as opposed to one giant makerspace*.

Answer	Bar	Response	%
Software, code, programming, etc		837	62%
Electronics, Arduino, etc		555	41%
3D printing, rapid fabrication and prototyping, etc		555	41%
Hardware, machining, etc		490	36%
Art, painting, graphic design, etc		476	35%
Culinary arts, creative cooking, etc		407	30%
UI/UX, web design, etc		362	27%
Product design, etc		347	26%
Woodworking, carpentry, etc		332	25%
Papercraft, origami, etc		321	24%
Cinematography, animation, photography, etc		278	21%
Clothing, knitting, sewing, etc		272	20%
Metalwork, smithing, foundry, etc		200	15%
Jewelry, soldering, enameling, stone setting, lost wax casting, etc		192	14%
Sculpting, ceramics, glass blowing, etc		122	9%
Architecture, drafting, etc		112	8%
Cosplay, costuming, etc		89	7%
None of these		77	6%
Other		71	5%

Fig. 4 Results of Question: In the last year, have you built, made, or created in any of these areas? Please check all that apply.

This helped us understand the equipment and programming needs for the space. There were several unexpected insights that came from this information. For example, culinary arts and art and painting are more commonly done than wood or metal working. This was not expected given MIT's reputation as fostering mostly a 'gritty' maker/builder community. This was important to changing perceptions among faculty, staff and administrators. Specifically, the *new makerspace should contain technologies that are not commonly found in spaces at MIT, e.g. technologies that are artistic in nature*.

		Overall	Undergrad	Grad	Female	Male
Thinking about your own schedule during the school year, would you use maker spaces during any of...	Between 4-7 PM on weekdays	35%	33%	37%	38%	32%
	Between 7-10 PM on weekdays	42%	46%	38%	43%	42%
	Between 10 PM-1 AM on weekdays	19%	24%	14%	18%	20%
	24 hours a day	26%	29%	23%	24%	28%
	Other, please specify:	2%	2%	3%	2%	3%
	8 AM to 4 PM is usually sufficient	7%	3%	12%	6%	7%
	I would use maker spaces on weekends	51%	55%	46%	56%	46%
	Total	100%	100%	100%	100%	100%

Fig. 5 Results of Question: Thinking about your own schedule during the school year, would you use maker spaces during any of these times if they were open?

We learned that 24 hour access to every type of equipment/technology was desired but not absolutely needed for a large portion of our students. This had been a major point of contention at meetings with stakeholders and this data enabled us to move past that argument. Through negotiations with stakeholders, our *approach settled on providing access to some technologies (3D printers, laser cutters, waterjets, and similar) 24/7 while access to lathes, mills and similar equipment would only occur between 6am and midnight*. It is also interesting to note how one can break this data down further. For example, looking at differences in responses between graduate and undergraduate students, and between women and men. The yellow highlighted sections of this figure show where statistically significant difference occur between compared groups. For example, the use of a makerspace on weekends is more attractive to female students than male students. We are in the midst of trying to understand the reasons for these differences.

Answer	Bar	Response	%
$0		239	19%
$1-50		277	22%
$51-100		186	15%
$101-150		120	10%
$151-200		77	6%
$201-250		65	5%
$251-500		157	13%
$501-750		48	4%
$751-1,000		28	2%
$1,001-1,500		23	2%
$1,501-2,000		9	1%
Over $2,000 a year		27	2%

***Fig. 6* Results of Question: Approximately how much of your own money do you spend each academic year on the resources, raw materials, tools, etc. for things you make at MIT?**

The understanding of how much students spend out of their own pockets *led to the creation of a program wherein students could earn 'maker bucks,' via maker community activities* [6, 7], that could be used at parity with US currency.

Answer	A	B	C	D
3D printers	619	277	38	5
Metal cutting tools	567	160	32	3
Woodshop tools (e.g. planer, lathe, router)	547	189	41	3
Laser cutting tools	544	248	23	5
Sanders/grinders	515	151	40	6
Computers with design software	494	181	65	23
Electric fab	374	185	92	14
Waterjet	334	289	72	20
Sheet and tube metal working	273	244	91	8
Foam cutting tools	236	268	122	15
Welding tools	232	343	96	13
Paint booth	213	296	153	37
Bike repair tools	193	262	180	87
Light and photo equipment	181	280	184	62
Plastics fab	175	286	119	20
Silicone/plaster molding	120	284	158	22
Textiles and vinyl	118	235	194	59
Metrology equipment	93	89	229	110
Composites	92	197	132	21
Wet lab	88	192	207	87
Jewelry making tools	71	228	226	116
Glass making and shaping tools	63	291	219	64
Other:	56	9	3	3
Forge	51	227	222	57
Foundry	44	217	223	55

***Fig. 7* Results of Question: If you could design your own maker space, which tools, technologies, and equipment would be essential, nice to have, or excluded? The rightmost columns represent responses of - A: Essential, B: Nice to have, C: Excluded, and D: Ambivalent**

This question helped us to understand which specific tools our students want as part of their own makerspace. This information directly influenced the layout of technology areas and the selection/number of pieces of equipment. For example, a bike repair area and paint booth were not originally planned for the building. After this survey, these elements were added in. We had also planned on having a small forge and foundry, but these plans were discontinued, in part due to the low expressed desire for them in the figure.

D. INTEGRATING THE MET INTO THE MIT MAKERSYSTEM

As mentioned previously, the MET would best help if it was integrated into the MIT makersystem. This integration enabled us to address some of our access issues by better placing our resources in solutions that have larger impact on access. The decision to make the MET a community makerspace changed the balance of space on our campus as shown via contrast of Figs. 8 and 9.

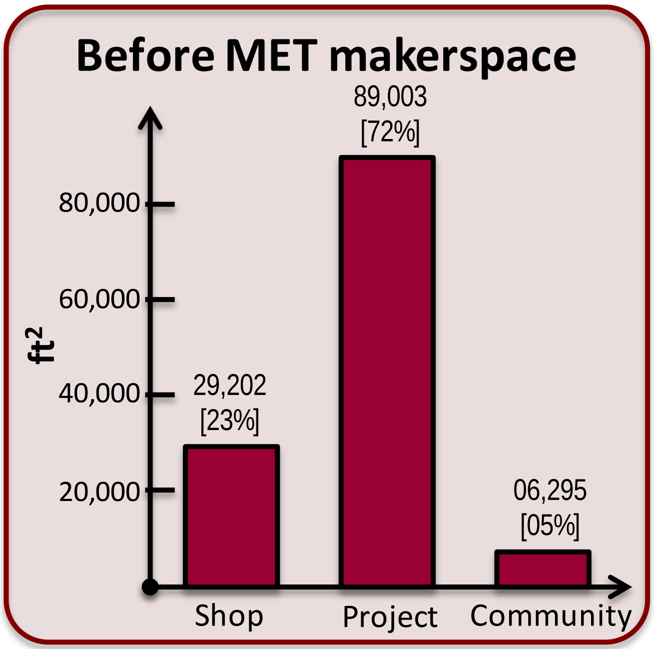

Fig.8 Initial Distribution of the Types of Spaces on the MIT Campus

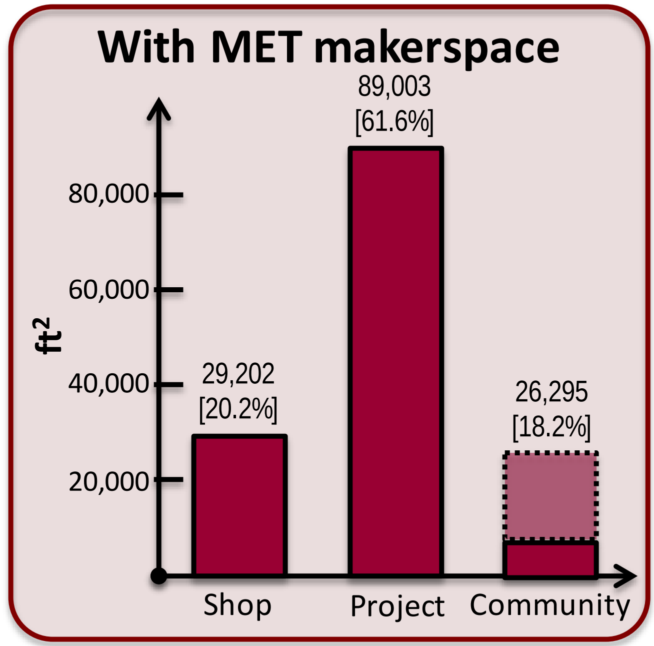

Fig.9 Planned Distribution of the Types of Spaces on the MIT Campus

Prior to our information collection, the plan had been for the space to become a hybrid between a machine shop and a project space (used only for classes.) This design was found to be at odds with the conclusions from the data in Figs. 2-7. The time spent on better understanding our student's needs and the deficiencies in our existing spaces was a good investment. This led us to knowledge that helped to fit our student's needs to a type of space that would satisfy them.

In our presentation at ISAM, we will delve deeper to explain facts and information that were used in combination to come to the conclusions we have highlighted after each Figures 2-7.

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Evolving maker and entrepreneurial resources to support the growing aspirations of student innovators

ISAM 2016 Paper No.: 43

Invited

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INTRODUCTION

This paper describes the methods and strategies of the MIT Innovation Initiative, a university-wide effort to strengthen the entrepreneurship and innovation (E&I) networks and pathways available to students at the Massachusetts Institute of Technology (MIT).

A. INTRODUCTION

In October 2013, MIT announced plans to launch an Innovation Initiative, with the goal of strengthening resources supporting E&I across all five schools. Over the course of the following year, the Initiative conducted an extensive feedback process engaging the MIT community – including faculty, staff, students, and alumni – to deliver a set of recommendations for evolving the Institute's E&I educational programs, infrastructure, and research.

B. FEEDBACK AND DESIGN PROCESS

The Innovation Initiative utilized a variety of tools to solicit feedback on MIT's E&I landscape and suggestions for new ideas. These included:

- **Institutional Research Surveys**: The team reviewed multiple years of institutional survey data from incoming and graduating MIT students (at both the undergraduate and graduate levels).
- **Informal Surveys and Questionnaires**: Additional research conducted by the Innovation Initiative Student Committee elicited over 300 comments and suggestions from the student body.
- **Faculty White Papers**: An open call for ideas generated 16 white papers (including one from MIT Lincoln Laboratory) describing multidisciplinary research ideas and novel research activities that MIT could pursue.
- **Public Presentations:** Initiative faculty and staff solicited feedback throughout over 75 public presentations to MIT alumni groups, universities, and corporations in Cambridge, MA and around the world.
- **Individual Conversations**: Staff and faculty also conducted over 200 individual meetings and interviews with students, faculty, alumni, and external partners.

The feedback process culminated in the release of a preliminary report to the community in December 2014, followed by an additional window of commenting and release of a final report in January 2016.

C. KEY TAKEAWAYS

The research process revealed a community eager to celebrate the past successes of MIT's E&I landscape and make suggestions for continued growth. The process elicited a wide variety of insights, challenges, and opportunities for the MIT community, among them:

- **E&I Aspirations of Students**: Anecdotally, both students and faculty sensed growing interest in E&I on campus. This was confirmed by reviews of institutional research, student club data, and qualitative interviews. Table 1 shows the entrepreneurial interests of incoming freshman in 2014 and 2016. Table 2 presents the 2014 freshmen cohort's self-identification along a variety of dimensions. Figure 1 presents the growth of entries into the MIT $100K Business Plan Competition. Figure 2 shows the evolving career choices of MIT students post-graduation, with a steady increase in joining startups as founders or early employees.
- **Letting a Thousand Flowers Bloom – Then Navigating the Garden:** Research and feedback surfaced over 80 different on-campus centers, programs, prize competitions, and student groups that self-identify as supporting E&I activities. It was widely acknowledged that the de-centralized, free-flowing culture of the MIT community was key to enabling a diverse portfolio of resources, and needed to be preserved. However, it also emerged that students, faculty, and external partners sometimes struggle to find the resources most relevant to their projects, and would benefit from a standardized, consistently updated interface for exploring their options.
- **Barriers to Entry:** Upon finding an appropriate resource, the community noted challenges to entry due to misalignment between program content and their own prior knowledge, or concerns of holding back due to feelings of 'imposter syndrome'.
- **Cross-campus Collaboration:** Students from all five of MIT's schools expressed a desire to deepen links for engaging, team building, and knowledge sharing across school boundaries on the MIT campus.
- **Tailored E&I On-ramps:** Despite the rich landscape of resources on campus, students sought initial opportunities more tailored to their own context and level, as an on-ramp into other campus opportunities. As examples, undergraduates desired a minor in entrepreneurship and innovation that could be taken ahead of enrolling in advanced MBA-level courses; graduate engineering students desired more leadership curriculum; and postdoctoral researchers desired opportunities to explore commercialization activity linked to their research in the lab.

Table 1 Percentage of incoming freshmen responding as somewhat interested or very interested in starting a business during their undergraduate years at MIT. Data from 2014 Survey of New Students and 2016 Survey of New Students.

2014	45%
2016	52%

Table 2 Percentage of incoming freshman in 2014 self-identifying in the following categories. Data from 2014 Survey of New Students.

Innovator	52.8%
Maker	37.7%
Entrepreneur	23.2%
Inventor	22.2%

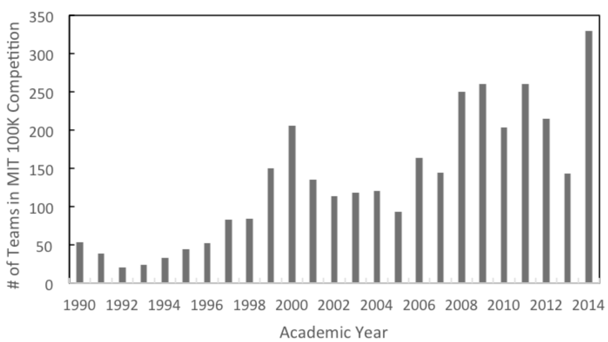

Fig.1 Team entries to the MIT $100K Business Plan Competition

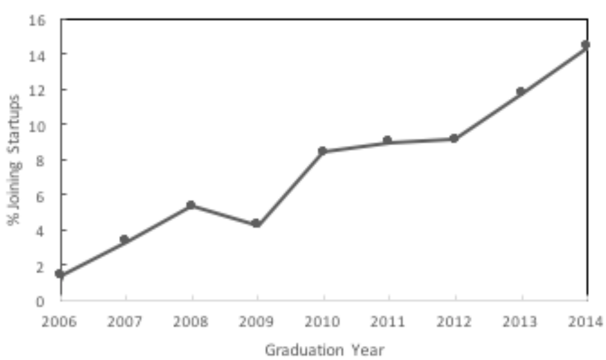

Fig.2 Percentage of graduating MIT seniors joining VC-backed startups, of total entering full-time employment in the private sector. Data from Kim (2016).

D. ORGANIZATIONAL DESIGN AND PRIORITIES

The final Innovation Initiative report outlines the feedback process, takeaways, and suggested priorities for evolving MIT's E&I landscape. The Initiative organizes its activities in the following categories:

- **Education and Practice**: The Initiative supports a number of existing programs to adapt curriculum and reach more students and partners, while also creating new educational offerings that fill key gaps in the landscape. The Initiative also curates an ever-changing online E&I resource guide for students, alumni, and potential external mentors.
- **Research and Policy:** The Initiative's new MIT Lab for Innovation Science and Policy engages experts from across MIT and partner institutions in cross-disciplinary research that studies the policies, programs, and organizations striving to catalyze innovation, and translates findings into useful tools that inform the design of MIT's own programs and are shared broadly with entrepreneurs and policymakers.
- **Infrastructure and Community**: The Initiative is cultivating enhanced communities and infrastructure to support the aspirations of students to bring ideas to realization, and understand complexities of transitioning to production at scale. Efforts include Project Manus, focused on evolving MIT's entire maker system and community, long-term planning for E&I hubs in the Kendall Square area surrounding the MIT campus, and creation of the MIT Hong Kong Innovation Node.

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The Power of Investing in Building Relationships, Collaboration and Ownership

ISAM 2016
Paper No.:
44

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INTRODUCTION

Makerspaces and their Communities exist within a living system; a Makersystem. This System evolves from three core values; the Makerspace, Community and Culture. Makerspaces follow the fundamental concept of Supply-and-Demand. In which, there is a demand from the Community, for resources and/or space; and the Makerspace serves this requirement. The manner in which they operate and interact within the System is defined as Culture. The promotion and encouragement of Makersystem Culture, drives Community well-being and development. These variables and their variable subsets, are dynamic and susceptible to change. As a result, it's rare to find or determine complete failure, on the integration of a Makersystem. Alternately, finding a formula for success, is futile. However, encouraging fundamental practices in collaboration, will stimulate growth of your Community, and create an innovative Culture that welcomes change.

If Makersystems are dynamic, we must promote a sense of modularity and flexibility within our Community. Showing our Community that we are open to innovation, evolution, and change. If we plan on promoting this sense of modulation, we must encourage our Community to participate in decision-making, problem solving, and discussions on solutions. If we are to do this efficiently, we must build relationships with our local Community, while engaging our external Community. Ultimately, the impact on Makerspace Community & Culture, is most effective through building relationships, collaboration, and promoting ownership.

BUILDING RELATIONSHIPS

Building relationships is essential to efficient and innovative collaboration. When building relationships, we are creating a support system for collaboration to occur. While a Community is all we need to build this system- some collaborators are more essential than others. It's important that we are able to find these elements, and encourage their participation as a foundation for future collaboration. The majority of our Maker Community, will not act as foundational elements for collaboration; however, providing methods and setting examples on how these groups can get involved, and encouraging their transition into vital roles is still of primary concern. Building relationships allows us to learn about each other individually, but it also allows us to learn about each other as groups. Understanding how individuals operate, will provide insight on how best to include individuals on collaborative teams. Understanding how groups operate, will provide better insight on how best to collaborate between groups. The important values in building and maintaining relationships, are specifically related to the methods you promote. Engaging multiple people or teams, and creating a formula for their voices or ideas to be equally heard; while determining best practices on engaging those who are *not* invested in your initiative, are simple tasks if you understand your audience.

INTERNAL COMMUNITY

Within the Makersystem's internal Community, relationships are easily formed; as they gather, meet, and discuss items of similar interest. These Users are considered *Stakeholders*, people from your Community that have interest or concerns in your system's development. Based on their involvement, Stakeholders can be divided into the following categories: *Passive, Proactive,* and *Administrative.* These categories will create a better understanding on their level of interest, and how they fit within your initiative.

ADMINISTRATIVE STAKEHOLDERS

Administrative Stakeholders, are usually uninvolved with the day-to-day usage of the Makerspace(s), but they still have a general interest (or participate) in the development of the Makersystem. Presidents, Provosts, Deans, and other Administrators may be some of the individuals you'll find within this group. Their role already dis-includes them from understanding more completely, the needs of the Makersystem. However, their interest in the system still exists. It's only natural that these groups may feel unable to fully participate, but finding ways to include them will promote a sense of teamwork within the Makersystem. Learning about their backgrounds and areas of expertise, will prove useful when assigning these individuals or groups to collaborative teams. This group is always willing to help; they are happy to participate in any on-going project. However, their most unique quality is their willingness to *not help*- stepping aside when their talents, or expertise are unnecessary.

The *Integrative Design, Arts & Technology* (*IDeATe*) Facilities, located within *Hunt Library* at *Carnegie Mellon University*; supports rapid prototyping and making through multiple spatial and equipment resources. The IDeATe Administrative and Technical Team, oversees all aspects of Curriculum and Facility. Although the majority of the Administrative Team has limited experience on working within the IDeATe Facilities; their inclusion and consulting on several projects have proven useful. The Dean of Libraries and Director of Emerging & Integrative Media provided input on the formulation of a Borrowing/Lending System for Makerspace Technical Equipment and Resources. IDeATe's Project

Manager and Project Coordinator, primarily serve as Student Advisors and Event Coordinators. Their capabilities extend far beyond these roles, as they offer writing, communication and graphic expertise in managing day-to-day Digital Signage updates, Web Content, and social communications to our Community. While these contributions seem small, building relationships with these individuals or teams, will ensure efficient operations. Keep in mind, these individuals are *not* valuable simply because they contribute; they are valuable because of the Networks they bring with them. Your Community is accustomed to collaboration between Faculty and Students. However, finding unexpected participants in collaboration; specifically, those that have a separate, primary function, sends a powerful message. Administrative Stakeholders participate in any way possible, for the overall well-being of a community, culture and space. A truly selfless act, when we take into consideration these individuals will never fully experience the impact of their participation.

PASSIVE STAKEHOLDERS

The most populated group, is *Passive Stakeholders*. This group includes those who are more concerned, but still interested in the development of your Makersystem. Typically, this grouping will include those whom experience, and use the Makerspace and resources. These Users are affected by the Makerspace, and their natural response is to report their concerns with limited comments on their interests or possible solutions. Passive Stakeholders are brutally honest and straight-forward, offering no room for misunderstanding. While frustrating at times, this group drives quick change. The most interesting quality of this group, is their conflicted understanding of Community. They believe that their problem is the *only problem*, and they are the only User experiencing the problem. They believe that their input is the *only input*, and they will push to have the issue addressed immediately. Most notably, they want someone else to come up with the solution. This attitude, is derived from negative experiences, or simple lack of time.

More frequently, we are finding dictatorship-style administration within University Groups. Students, Staff, and Faculty form Committees to present issues and guide Department Heads and Deans; but the solution and final decision still reside with the upper-level administration (Department Heads and Deans). This procedure begins an acceptable form of Culture; where one may present their concerns with solutions, through the proper channels, and nothing happens. Repeated or single experiences will drive Proactive Stakeholders into a state of passivity. In which, they believe their concerns matter, but will most likely go unaddressed. Over time, they find when they speak louder and over-react to these issues, people begin to listen.

Alternately, we find some individuals within this group, do not have time to deal with the problem. In Academia, this is commonly the case, where Students or Faculty are constantly in a rush. They are upset over unreliability and inconsistency within the system.

Passive Stakeholders are accustomed to failures within the Community & Cultural aspects of their environments. When dealing with Passive Stakeholders, you must find ways to recondition their natural response to failures in the system. First and foremost, eliminate your natural and emotional response to their concerns. Frustration, will lead to aggressive and inappropriate replies. Always follow-up promptly, and show these Users that their concerns matter. Additionally, it’s important to encourage their participation in a more proactive format. A great way to get Passive Stakeholders involved may require the integration of a cultural policy:

No one from the Makerspace Community may complain, without (5) proposed solutions.

While the populous of this group will always exist, finding ways to turn Passive Stakeholders, into Proactive Stakeholders creates a system for transition. It begins to form positive practices uncommonly experienced within Academia.

Within the IDeATe Community, we have several Faculty that provide Interdisciplinary Courses on various methods of Making. Their participation is vital to the Makersystem, as it generates interest across our Campus Community. The variety of Faculty, has brought about many issues, as they are each accustomed to their *own* Department’s cultural norms. In many ways this is frustrating, as they request changes on Policy or Procedural elements that are embedded in our Makersystem. For instance:

Your Passive Stakeholders are upset, because you do not offer Materials for purchase, within your Makerspace.

One might find advantageous aspects, born from their concerns and incubated in practice. More specifically, when you have multiple individuals, explaining how *their* department operates; it becomes more clear which scenarios may fit more efficiently in *your* operation. For example:

Department (A) does not charge their Students for Materials, because it deters Students from risky experimentation. Department (B) charges their Students for materials; arguing that the Student must understand how to work efficiently, and work within a budget.

Instead of adopting one Policy over another; we can find balance by combining these suggestions:

Makersystem will begin providing some of the more common Materials requested by Maker Community. Each Full-Time Student will receive a monetary stipend every semester for material purchases. Unused funds will expire at semester-end. If Student uses the entire allowance, any further material purchases will be billed to the Student, separately.

In gathering input, we can more easily find common solutions. These solutions cannot evolve without the collective suggestions from our Passive Community. Their involvement is limited because they feel their input is not taken seriously. When we take this feedback and include these individuals in developing innovative and effective solutions; we are encouraging proactive participation, not *passive*.

PROACTIVE STAKEHOLDERS

Proactive Stakeholders are those that have interest and concerns, but also offer solutions and feedback for realistic improvement. These are the people in your Community that you want on your team. They are essential to the health of your Makersystem, and the collaborative efforts that will evolve from Community involvement. Every structural system includes foundational elements; from which, additional structural branches begin to form relationships. For example:

Common building structures, include vertical foundation walls and columns, from which are horizontal steel I-Beams. These I-Beams, support concrete floors with rebar steel running throughout. The concrete floors support walls, which are supported by wall studs that eventually support a ceiling grid.

When we build relationships with Proactive Stakeholders, we're looking for our figurative *foundation walls and columns*. These individuals or teams will support every other element of our Community, while promoting the Cultural aspects we deem most valuable. These individuals are rare, consequently, the group is small. Finding ways to increase this population, is directly related to the methods you promote and encourage when dealing with Passive and Administrative Stakeholders. As this group grows, they will adopt the methods and practices you initially encouraged when building relationships. Further expanding the understanding of Passive and Administrative dealings, and increasing your Proactive Community, *exponentially*. Proactive Stakeholders serve as an example to your Community, on how to become more involved. Making certain that these Proactive Members play a visible role in your Makersystem, is vital to your Community's Cultural amelioration.

IDeATe features a unique network of core Faculty. These individuals serve split appointments within the University, as they teach IDeATe Courses, but are also providing instruction in other programs across the Campus. Their most valuable quality is derived from their connections to Industry Leaders. This creates a platform for support requests involving Materials, Consumables, Equipment, or funding to support on-going Makersystem initiatives. But, also informs the manner in which they support collaboration. They offer the most conceptual solutions, but their ideas tend to be brushed off as unrealistic. This way of thinking evolves from their experience with a seemingly unlimited funding source in the commercial sector; inspiring the negative response from those that are accustomed to the limited funding available in the not-for-profit sector.

For the majority of those who work in Education; formation of solutions typically begins with thoughts on the amount of funding allocated to a project, rather than the highest quality solution. This ideation process, begins with realism or pessimism, and the final solution reflects just the same.

The IDeATe network of core Faculty, are not acquainted with this practice. They are more familiar with building ideas on the highest quality product, *first;* focusing on the other variables, *second.* This form of thinking, encourages positive outcomes. The argument that realism is a *requirement* in this process, still holds true; but it should not be where we begin our collaborative efforts. Building relationships with Proactive Stakeholders will become highest priority in your Community's development. Making certain that these individuals adopt and promote best practices in building relationships and collaboration; sets a standard for continued Community growth, outreach and engagement.

EXTERNAL COMMUNITY

While building relationships can be relatively simple within your Maker Community; finding ways to engage the external Community is more complex. This form of outreach can be beneficial, as the infant stages of team-to-team Collaboration reflect wonderfully toward your Maker Community. Building these external relationships, will increase your Community's size; thus, increasing demand, exposure, and value.

Before building external relationships, make sure your existing Makerspace Community is taken care of. The increase in Community size, will create increased traffic. If the Community is affected negatively by the increase of external and/or new Users, your Community will respond similarly; rejecting the newcomers and external collaboration.

Setting aside bandwidth issues, building relationships with Student Organizations, Departments, Programs, Associations, Clubs, Alumni or other initiatives on-campus, is a great way to gain positive exposure. As long as these interactions result in positive experiences, your Community will continue to grow. This growth, is something that can be recorded or measured; providing useful metrics that illustrate increased demand. The data, can be useful in generating higher levels of interest, funding or support with Stakeholders.

Administration at Carnegie Mellon University, attempt to dedicate a block of time to the Student Community. Course meeting times, are disallowed between 4:30 and 5:30pm. During this hour, many student-run organizations or events take place. With the hope of increasing interest and diversity among our Makerspace Community; IDeATe provides 1-2 Student Makers to the external campus community seeking assistance with any laser cutting or 3D printing projects.

As a separate, yet similar initiative, we've implemented one-unit *micro-courses;* providing quick training for equipment or other popular processes like laser cutting, 3D printing, soft fabrication, or Arduino in 2-3 Lab sessions. Every micro-course, reserves (5) seats for Faculty or Staff.

As a result of these systems, our Community has grown in size and diversity, as shown in Appendix A, Fig. 14 & Table 1; promoting a Culture that is distinctly different from our various departmental communities.

Successful platforms for building these external relationships will create a network of effective, efficient, and innovative Stakeholders. Creating a method of transition for non-stakeholders to become a *participating stakeholder* in your Community, will most likely require some form of *trade.* Finding the common elements in your initiative, and their existence; creates a device for discussion. Beginning to build a relationship, will involve discussing how your Communities operate and intersect. Specifically, what they get from working with *you*. While this may appear as selfish, it promotes self-worth, and should not be viewed negatively. Although, building relationships shouldn't involve trade-off in the form of payment or transference of funds; it *should* take on the form of bartering. Finding common ground that provides mutual benefits for both groups is essential in creating these relationships.

Implementing systems that encourage building and development of internal and external relationships, will ensure an efficient operation with a steady supply of proactive individuals and teams. A strong focus on your internal advocates and stakeholders, will show your Community that *they* come first. Increasing your efforts in this area, will establish a Culture that is accustomed to distinctly different ideas and open-source knowledge. Identifying and supporting your Proactive Stakeholders, including your Administrative Stakeholders, and creating pathways for your Passive Stakeholders will only promote a participatory Culture. As this system develops, engaging external Communities and formulating methods for non-stakeholders to become a part of your Makersystem will strengthen the sense of Culture already embedded in your existing Community. In building relationships, we set the framework for Collaboration to occur, while expanding our Community and formulating a Cultural standard on proactive participation and innovation. Indirectly, rapid growth, interest and diversity will increase the systemic value.

As an example, a comparison on non-diverse community growth (*Fig. 1*) versus diverse community growth (*Fig. 2*).

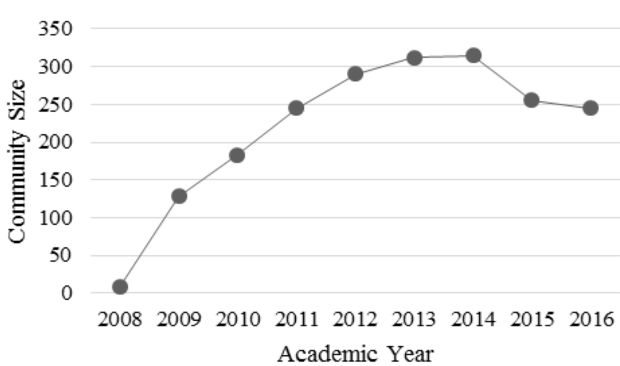

Fig. 1 Community Growth per Academic Year

In Fig. 1, we find the common trend in Makerspace Community Growth; where the Community Size begins to normalize. In many ways, these numbers reflect bandwidth issues, thus limiting any involvement with external groups or individuals. These Makerspaces were built for *one* Community; as a result, they grow slowly until they reach maximum capacity. Slow growth will reflect as slow interest. In addition, this facility was directed by two individuals, whom managed all aspects of the system, and minimized external participation.

When we include external Groups, and focus on building relationships throughout the Campus Community, we find undisputable evidence in Community Growth per Academic Year. Fig. 2 provides data on a separate Makerspace, focused on its Community and building relationships, before the idea was even promoted or approved.

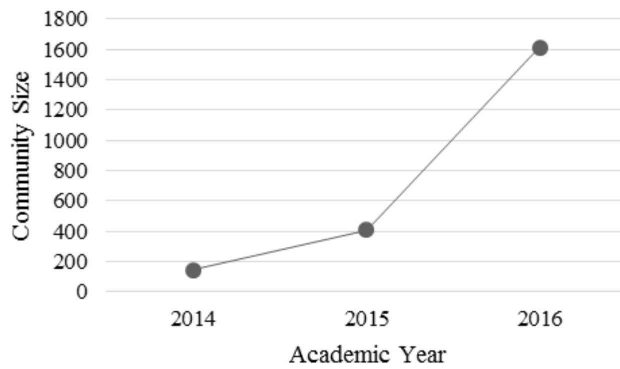

Fig. 2 Community Growth per Academic Year

Fig. 2 shows the value in building relationships, and how this can affect rapid growth. The most interesting metric in this data, is not indicated: The Community has exceeded the Makerspace bandwidth; they've essentially outgrown this resource in less than two years. However, because this facility is open and available (24) Hours a day, (7) Days a week; the Community has tailored their work habits to eliminate traffic issues.

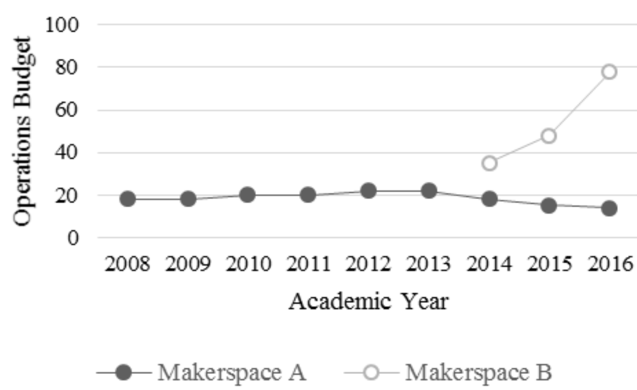

Fig. 3 Operations Budget per Academic Year

In addition to the diversity-community relationship, this data was helpful in generating support for our Makersystem. Listed in Fig. 3, we see a comparison in Operating Budgets for Makerspace (A) from Fig. 1; against Makerspace (B) Fig. 2. Operating Budgets (*$k*) include funding dedicated toward student staffing and equipment or facility maintenance.

Makerspace (A), received limited increases from 2008 (*$18k*) through 2013 (*$22k*). The increases were specifically directed toward student staffing, as the Community increased in size. A drop off occurs in 2014 (*$18k*) through 2016 (*$14k*); this decrease is attributed to the elimination of student staffing. The dismissal of student staffing resulted in a decrease in Community size, shown in Fig. 1.

Makerspace (B), has received steady increases since inauguration in 2014 (*$35k*); essentially doubling by 2016 (*$78k*), due to the increase in interest and diversity of our Community.

COLLABORATION

Collaboration remains one of the most rewarding and remarkable experiences in *any* Community. For a number of years, this practice has been encouraged; however, encouragement never seems to be enough. Only recently, are we truly beginning to practice collaboration through community and human experiences. With the birth of Social Media, our upcoming generations are more aware of the value in working together for a common goal. While this progress is exciting, it eliminates human interaction from the equation; arguably important for any healthy human experience. Makersystems, are built around the human experience. Creating tools or platforms for your Community to come together, will encourage collaboration; but, our primary mission should focus on the collaborative experience and promoting a culture that is casually diverse and innovative.

The IDeATe Student Community, is provided access to a web-based project gallery. This resource, is used widely throughout our interdisciplinary courses, as a documentation, portfolio and networking tool. Faculty can create *Pools*, in which students may submit documentation of their various course related projects. The student, maintains complete control over what is publicly visible, and what is private.

In addition, many of our Students are either building a portfolio, or haven't the resources or sense to do so. In the interim, their process, documentation, and images typically reside on a hard-drive, unseen and unknown. Even if the gallery does not act as their final portfolio tool, it provides a place of residency where others can still see, and comment on their work.

The most valuable element of this gallery, is the ability for others- inside *and* outside our Community to find individual proficiencies. Allowing others to browse and find members from our Maker Community, that have expertise in specific areas. Ultimately, acting as a prime example of platforms for bulding relationships and collaboration.

Collaboration is commonly misunderstood as *only* working with a team of individuals. In which, the team of individuals ideate, experiment, and formulate solutions as one. The more uncommon form of collaboration, involves teams working with other teams. Team-to-team collaboration is often a secondary thought, because it is already difficult enough to get individuals to work together, let alone teams. Although this form of collaboration can be challenging to coordinate; not only is it a requirement within Academia, the results are overwhelming effective, innovative and inspiring to the external Community. Encouraging these interactions, begins with selective team-building and promoting best practices within your Makersystem teams. Before venturing into the realm of team-to-team Collaboration, we must focus our efforts on getting individual teams to work efficiently. This will require a firm grasp and understanding of each participants' role.

A working example on the roles of collaborative team building, can be found in the sports-world. Before making this comparison: we assume the most involved person in the Makersystem initiative, is a scout. Building relationships, and learning about your Community's proficiencies, tendencies, and operations; finding the best players for the positions that need filled. When scouting, we'll find certain individuals are better-suited for specific roles. In Soccer, there are positions that deal strictly with offense, others that are defense, and hybrid positions like mid-fielder, where the position supports offensive and defensive positions. In Hockey, we find wonderful comparisons on collaboration, where team dynamic and individual proficiency begin to form *lines*, or groupings of players that play in shifts. Building relationships and scouting, will allow us to form these efficient teams, where every individual can contribute in their own, most proficient way.

More importantly, we begin to find out who can coach. Proactive Stakeholders, should take on the role of *Coaches of Collaboration.* When we implement a network of coaches, and provide guidance as *scouts*, collaborative culture will become automatic. When collaboration becomes a part of your Community, a platform for addressing collective concerns and deploying collective solutions becomes a part of the Makersystem. When this occurs, your Makersystem, becomes *our* Makersystem. Even still, we must promote values that encourage problem solving and outreach within each of these teams, to create a Culture that is innovative and efficient.

INNOVATION

In most ways, collaboration may be regarded as a form of democracy, in which the *majority* rules. However, effective collaboration will use democratic solutions only as a last resort. Majority versus Minority voting, may indicate that a large portion of your Community's concerns, will go unaddressed. This is neither innovative, nor does it convey efficiency. Quite often, we find collaboration terminating at the very first instance of resistance or friction. When your team lands on these limitations, problems, or bottlenecks, it's important to write them down, and continue the discussion (if possible), on separate topics that do not cause negative reaction. In short, follow the path of least resistance. The topics that are difficult to solve, are not solved easily in a one-hour meeting. While it's imperative that they are not forgotten, collaboration should have an extreme focus on problem-solving, not *problem-obsessing*. In most cases, one person is the only person who was aware of the problem. This person was also dealing, troubleshooting, and experiencing the problem on their own. By eliminating this issue from the current discussion, it will allow other members of the team to think on the subject between your team meetings. Regardless of methodology, it is important to make progress in your collaborative efforts by proposing solutions. We can have concerns and issues with proposed ideas; but we must find alternative and innovative solutions that address these bottlenecks. This form of collaboration ensures that there are not divisions of majority vs. minority in the community. It promotes a culture of inclusion, where all opinions and concerns matter; in finding solutions that cover the majority *and* the *majority-of-the-minority.*

In 2014, we found a common concern among our Community, in the form of how one of our spaces was resourced. To make the situation more difficult, the space served a hybrid function, as a classroom and a project-build space. Some Faculty, wanted more dry-erase boards, others were looking for pin-up space, and a select few were looking for Projection areas. When polling the Students, they offered split decisions on several subjects, but also agreed on a few others. They asked for rolls of paper, to be placed on all table-tops, allowing them to make messes and clean up faster. Others requested cleaner work spaces, for electronic prototyping. They asked for modular mounting systems, to hang projects from walls and ceilings; more accessible power and data outlets. Located in the library, our neighbors wanted us to sound-proof the rooms, to eliminate excessive noise. Essentially, the request became:

We want clean space, and messy space. We want dry-erase walls, pin-up walls, and projection screens. We want more power, more data, and more infrastructure. We want to be loud, but we need to eliminate noise pollution.

These requests reflect contradictory needs, which also indicates how diverse our Community can be. The solution was not easy, but through innovative collaboration with our Community, we were able to address the *majority*, and the *majority-of-the-minority.*

ModWall is a cost-effective solution that provides function, while promoting engagement from the Community. The Wall is a completely reconfigurable, dry-erase, pin-up, or projection surface, increasing the structural integrity of the existing wall, and dampening sound. The ModWall is made from wall studs and multiple sheets of plywood, cut into Panels on a CNC router. ModWall begins with horizontal wall studs, being mounted to an existing wall within the Makerspace. Dry-erase board and rolls of ¼" thick cork, are glued to multiple sheets of Russian Birch Plywood. Once dry, these sheets are placed on the CNC router, and cut into their final panel sizes. Other sheets of plywood, are cut into vertical structural and fastening elements. The vertical studs, receive captive bolts and pressure fit dowel pins in specific areas; then mounted to the horizontal wall studs, as illustrated in Fig. 4.

Fig. 4 ModWall Studs, Pins & Bolts

The hybrid birch/dry-erase and birch/cork panels, easily slide over the exposed captive bolt threads and dowel pins, shown in Fig. 4. Two thumb screws, fasten each panel to the wall. Each panel can be removed, flipped and refastened. Flipping a panel will reveal either a dry-erase, cork, or birch surface. Access to power and data outlets, is still maintained throughout the wall. The double-layer, horizontal and vertical wall stud structure, increases load capabilities and allows the User to run cables behind the wall, to any location they like, while keeping the cables hidden from view. Users can take panels to a desk, and use it as a clean surface, messy surface, or sketch surface. Aluminum Strut channel runs along the top of the wall, allowing Users to hang projects, or projection screens. The modification of panels, is not prohibited, but encouraged. Students are given the CNC File, to cut or modify panels into whatever they like. Creating touch sensitive light panels, hidden desktops, or embedding computing hardware into the wall. Finally, the wall creates an additional level of sound dampening that reduces noise leaving the space, but also prevents noise from entering the space.

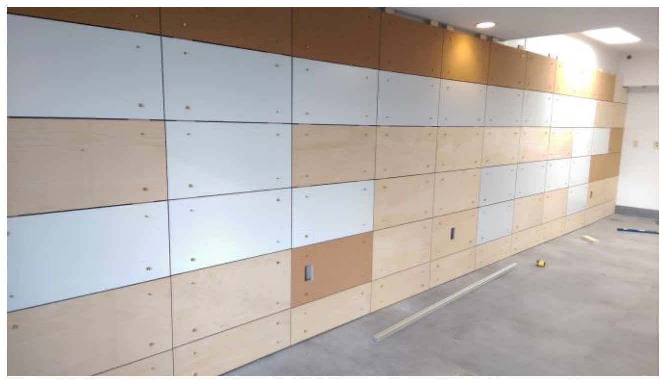

Fig. 5 ModWall fully assembled

This solution, was only conceived through Collaboration, but exists as a primary example of innovative thinking. Issues were presented and discussed further, not *presented and forgotten*. In working past our opposing stances, we were able to formulate a solution that applied to the majority of the Community's needs; while addressing the needs of the minority as well.

This final product also provides a great example on how building relationships and collaboration can generate interest with external communities. In 2015, our team was approached to discuss the layout, design, and deployment of a new makerspace, in a dormitory. The Student Housing Team's interest, was elevated when they saw the ModWall solution. As a team-to-team collaborative effort, with Campus Design & Construction and Environmental Health & Safety included; we worked together on equipment selection and spatial layout. The wall was provided as a resource in a multi-purpose space. This is called *external collaboration,* where we engage our external communities.

EXTERNAL COLLABORATION

Finding innovative ways to engage and include the external Community in collaborative efforts, will happen naturally; *if* you've established relationships with external non-stakeholders. In some cases, external teams will ask for your team to collaborate. Other instances, may require your team to reach out and ask external teams to collaborate. Either of these instances, will require that your internal collaborative teams are aware of each other's roles and initiatives. Working with these groups, rather than separately or without; will set a new standard within the Campus Community and beyond; while communicating accessibility, value and efficiency to your existing Maker Community.

COLLABORATIVE ENGAGEMENT

When an external department, institute, group, or team contacts a team within your Makersystem, they are looking for your help. If they've contacted the right team, then you are already doing something right. Our Campus Networks have evolved in a limited fashion with social technologies. We heavily rely on word-of-mouth, email, and meetings within our little worlds, we call departments. It's evident, the upcoming generations are much more efficient at seeking out assistance. Students in Academia have a much larger network on Campus and beyond. This is largely inherited through the social media tools they've grown-up with. Many Faculty, Staff, and other Administrative Personnel are too consumed with their day-to-day interactions, to continue actively engaging external groups. They prefer casual encounters, wherein they meet new members of the Campus Community. If a team outside of your Makersystem seeks you out and was able to easily find you, then your Makersystem is operating correctly. This indicates that your teams are building relationships and collaborating with external groups. Which equates in increased exposure. Exposure is a great tool, however, depending on how well your teams are working, will determine whether this exposure is positive or *negative*. When teams outside of your organization ask for help, it's important we expose them to our cultural standards. Making certain that we stimulate the growth of these relationships through positive experience, will create positive exposure. When this type of collaboration occurs, we continue to expand as a supportive Community, we see a rise in level of interest, and optimization within the campus community teams.

The IDeATe Makerspace, serves as a resource to the entire campus community. It didn't come as a surprise, when the on-campus Environmental Health & Safety (EH&S) Department took a higher level of interest in our space and practices. What *did* come as a surprise, was the new level of interest in working *with* our team. We formed relationships in setting safety standards for the entire campus community, and other makerspaces.

Specifically, EH&S was concerned about the 24 x 7 access to Laser Equipment, without constant supervision from Administrative Personnel. Together, we were able to formulate a solution to our opposing stances, in the form of an educational partnership. EH&S offered to provide training sessions on fire extinguisher identification and use. As a token of our appreciation, we offered one of our spaces to act as a 25-person classroom for these training sessions. EH&S typically provided training courses in their own classroom, which only allowed for (10) trainees, so this was a very appealing offer. With the hope of standardizing this training for all laser equipment users across our campus, they were unable to commit to the policy, unless they had a larger classroom. Through our collaborative efforts, the training sessions were made available to the entire campus community; while promoting safety and increasing impact on our Maker Community. While discussion of this training occurred before the IDeATe Makerspace was developed, our combined efforts allowed EH&S to provide this training in greater numbers, in a more local, and recognizable space on campus. Fig. 6, illustrates the increase in trained, Laser Equipment Users within our IDeATe Community between 2014 and 2016. This initiative, and its impact, becomes evident when the training began; in Fall Semester of 2015.

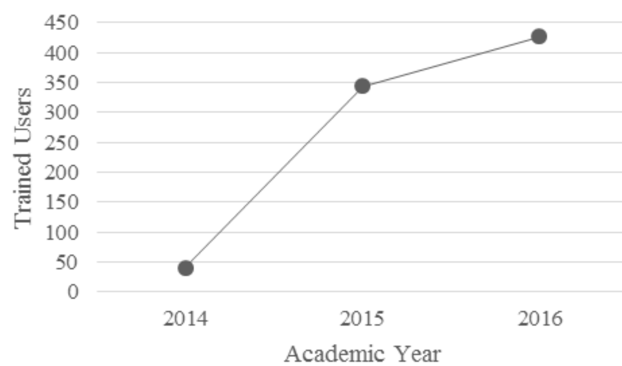

Fig. 6 Trained Laser Equipment Users per Academic Year

COLLABORATIVE OUTREACH

Asking external teams to collaborate with your teams, typically evolves from building relationships with external individuals or groups. Their networks, become an extension of your network. This is most common within University settings, but still an extremely underutilized resource. On Campus, asking for help, has become more difficult than figuring it out on your own. This is due to the overwhelming amount of work, the under-staffed campus community fits into one academic year. Common sense, would indicate that these teams or individuals would be unwilling to help, because they are already overloaded with tasks. However, it may be the case, that these teams have not been efficient in their existing operations. Inviting external teams to participate in troubleshooting, should give them a *taste* on how your community works *with* each other. Showing expedited results and offering assistance between your networks, will benefit both groups. Overall, enforcing the cultural standard you've set from the beginning in your Community, and permeating throughout the ranks all over the University.

The IDeATe Community has access to several equipment resources, large and small. Several IDeATe spaces include local resources, readily available for the Community to access and operate. Other resources, equipment, hardware, supplies, or materials are made available from IDeATe Lending. The lending booth provides some of the more universally utilized items, like DSLR Cameras, Tripods, Microphones, Electronics and various other items related to making. Most notable, is the inventory of mobile computing platforms; over (25) Tablets, (10) Tablet PC's and (40) Macbooks make up what is called the Virtual Cluster. The mobile computing platforms include all the software required by any of our IDeATe courses.

In providing this resource, we found an immediate need for computing and technical support. Our team initially gathered to discuss solutions on deploying software to our multiple computer devices; before realizing there is a group on campus that does this type of work every year. We asked Computing Services to provide consulting on mirroring our laptops; in doing so, they became very excited in learning about our laptop lending system. It turns out, Computing Services was also looking to create some form of mobile computing lending platform, with the eventual transition away from clusters of dedicated desktop computers. Unfortunately, their discussions on such a transition, repeatedly brought about concerns on theft, damage and protection of student data. With our request, we invited to trade information and act as their beta deployment; where they could more easily test, experiment, and learn best practices on developing such a system. In exchange, they would offer software deployment and support on imaging our laptops. This relationship, specifically addresses the *trickle-down-impact*, collaboration can have on a community and its culture. Our Maker Community is presented with a reliable resource for borrowing, and our Staff is not overwhelmed with constant management of software and systems development. The overall operation is extremely efficient; these qualities directly affect our Community. Although an unseen operation occurring in the background, our Community begins to understand the standard we set as *administration through collaboration*; where we provide quality experiences by including the most proficient individuals and groups in our internal and external decision making.

COLLABORATIVE RELATIONSHIPS

Encouraging community engagement or outreach, will require a heightened awareness and understanding of your teams' roles and proficiencies. This will reduce redundant efforts between your teams, while creating a sense of consistency when organizing efforts with external groups, or within your Makersystem. Promoting this practice, typically requires more face-time and conversation between your teams and leaders. Finding ways to increase casual conversation and encounters with your Proactive Stakeholders and their teams, will establish quality relationships. Although difficult, multiple examples are found throughout the Commercial Industry. Keeping these individuals in close proximity to each other, is one incredibly effective way many Companies support this practice. Rather than email, text, or phone discussions as a means of distance communication; keeping your cohort near each other will allow for short distance communications. Asking questions, getting input and finding feedback become easier qualities to maintain when we eliminate the distance. With these repeated face-to-face interactions comes casual conversation, and personal relationships begin to evolve. These relationships will build over time, and your leaders will fight, argue, and find friendship. While the fighting and arguing may seem unnecessary, it indicates that your team is passionate. When they maintain close proximity, they are encouraged to work past these issues.

Even still, this group needs to know about each other's on-going projects and initiatives. When you increase their face-to-face encounters, they begin to develop this awareness. While this second-hand involvement will work temporarily, as your Community continues to grow, this will have lesser impact. As a suggestion, facilitating bi-weekly or monthly meetings, where one or two leaders provide an informal presentation on what they are working on, will keep your Community informed. It is essential that these meetings are less formal, and a sense of relaxation is evident in the group's demeanor and attitude. So frequently, we are seemingly *forced* to focus on work; very rarely do we have time to stop and actually listen to each other. Sending out invites, supplying food, and allowing a few members from your community to present their most recent work or information they care to discuss, will encourage engagement between your leadership. Further promoting collaboration between your teams, and creating platforms for relationships to mature.

Within the Hunt Library, the IDeATe Office resides on the second floor. This large office, supports the IDeATe core Faculty, and Administrative Staff. Providing shared office space, for our most involved Stakeholders, keeps this group informed and communicating on a daily basis. A shared island of desks, near the center of the room acts as a collaboration zone, while their storage lockers double their function as dry-erase surfaces. In addition to the office, Faculty meetings are held on a monthly rotation. During these Faculty meetings, 2-3 Faculty are selected to provide presentations discussing on-going work, research or initiatives they care about. In one meeting, a Faculty member presented a simple slideshow, on the recent birth of their child, homeownership, and marriage. While this information was irrelevant to our shared interest in IDeATe, this presentation brought us closer as a group, by sharing more personal on-goings, it allows for more casual relationships to form. Establishing a sense of comfortability in your relationships with Stakeholders, will encourage their feedback, and participation in future interactions.

Carnegie Mellon's Campus Deans, provide another example of comfort and collaboration. Presently, Carnegie Mellon University's Deans, are communicating and collaborating, more than ever. Traditionally, these upper-level administrative personnel, are reluctant to work with each other. When discussing the reasons *why* our Deans are more willing to work *with* each other; their answers are similar. Each year, the Deans gather for their retreat; flying to an off-campus location to discuss formal business goals, in an informal business setting. They attribute their recent improvement in relationships, to the free time they've spent together during these retreats. Typically, in a restaurant/bar setting, these individuals come together and relax their constant discussions on business, and begin to communicate more personally. As their informal discussions continue, they begin to formulate a more precise understanding on what initiatives are important to each of their prospective Colleges, Departments, or Programs. When they return to campus, it's back to business; but their relationships have improved from the time spent together, and their congenial conversation on topics they truly care about. In short, creating platforms for relationships to build; will evolve into an increased willingness to participate and collaborate within your Makersystem, and beyond.

OWNERSHIP

The impact of building relationships, and collaboration will be evident in the Culture your Community adopts. These are undeniably essential values in the formula; however, they are *nonmaterial* elements. Ownership, stands as the single piece of *material* evidence, from which relationships were built, and collaboration occurred. This variable, can make or break the Community, as it directly affects their willingness to participate, while also communicating the type of Culture your Makersystem promotes.

SUPPORTING OWNERSHIP

The steady and arduous task of building relationships and collaboration will become easier as your Makersystem Culture takes hold on your Community. Continually pushing these groups, while encouraging and preaching fundamental practice, will only get you so far. Creating platforms for these efforts to grow and evolve is certainly admirable, but the most vital variable your Community will find most valuable, is the *final product*. The final product is the sum of any team's collaborative efforts. It's important there are defined methods in implementing final solutions, and this is relative to your team's understanding of other teams and their roles inside your Makersystem. The final product may require assembly or funding; or maybe it's completely electronic and requires coding and development. Whatever the scenario, it is *essential* that the final product does not *die*, *fizzle-out*, or *lose traction*. Allowing projects to fail, will leave your team bitter and upset with the hypocrisy of the Makersystem Culture. If we are to preach efficiency to our collaborative teams, we must be vigilant in following through with their final solutions. When we allow projects to extinguish, we are pushing our Proactive Stakeholders toward a state of passivity. In short, Makersystem Culture grows gradually, through building relationships, forming teams, and collaboration; but there is nothing more vital to this process, than supporting the final product.

An example, is communicated through the frustrations of a Student: A Student Action Committee was formed, to act as the *voice* of the Student Community within a Makerspace. The Committee met with Administration, on a monthly basis, to communicate their interests and concerns. One issue, they found most detrimental to the Makerspace, was the lack of branding. They formulated an action plan, nominating their Leader to begin developing logos, branding, and wordmark content. This group worked together, with limited guidance from one faculty member, to create and communicate branding for the Makerspace. In another meeting, they presented their work to Administration, showing examples of business cards, t-shirts, signage, web content and graphics. The presentation was professional, and the product was equally admirable. After this meeting, summer began and the project died. Administration never followed up on the completion of the project. Their lack of response to this project, has proven extremely destructive to the Student Community, and their willingness to participate.

The Students did everything right: they presented their concerns in the proper forum, built relationships, formed teams, and provided solutions. When presented with the final product, the Administrative team failed to support their work. As a result, the Student Community is less inclined to work on any solutions; as they've transitioned from proactivity to passivity.

COMMUNITY OWNERSHIP

While conveying a sense of ownership to those who participate in developing the final product is important; it is equally relevant to those who have limited involvement. The term, *ownership*, is not a conveyance of individual ownership, but *ownership of the Community*. The ability to pull a team of individuals together, communicate a need, collaborate on solutions, and deploy the solution- is the full scope of ownership. Without ownership, there is no realization of completion. Ownership, shows your Community *physical* examples, and the results of building relationships and collaboration. Without these examples, building relationships and collaboration are only speculative and unproven. When a Community can see actual examples of collaboration, it begins to take full form. It shows that they have the ability to participate, and change the elements of the system. The only requirement when encouraging this sense of culture, is continued understanding of modularity, flexibility, and revision.

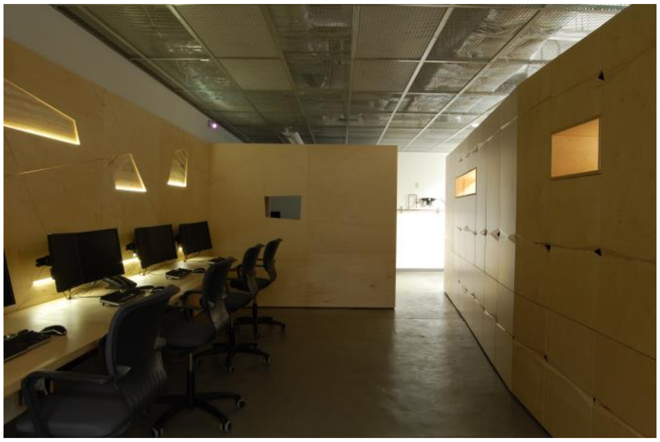

Fig. 7 Digital Fabrication Lab, School of Architecture, Carnegie Mellon University, 2008

In a sub-basement level, we find a remarkable Makerspace dedicated to the School of Architecture. When this Makerspace first began, Architecture Students were enlisted to help in designing and building the space. The results were beautiful, with custom designed, and custom cut Russian Birch Panels surrounding the environment. The project was built by students, in a space that would be populated by students. When the Student Community used the space, a sense of ownership was evident, as they were surrounded by their colleagues' efforts. This increased the level of interest in the space and throughout the Student Community; in knowing they were able to assist or participate in the continued development of the space.

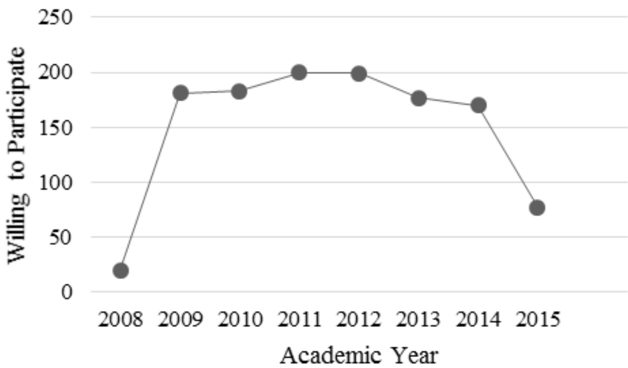

Fig. 8 Willingness to Participate per Academic Year

In Fig. 8, the data represents the level of interest in the Student Community, in participating on the physical evolution of the space. The students were polled every semester for (7) Years, on their level of interest and willingness to participate in the continued development of the space. They were asked to rate their level of interest on a scale of from *0 – Not interested* to *10 – Very interested.* Any student who responded with a value of 6 through 10, was included in the data. We see a spike in the level of interest among this community from 2008 to 2009, this is when the Students designed and built the space; directly related to the increase in interest. Unfortunately, under poor direction, this participation was not encouraged. We see the level of interest growing, then equalizing throughout 2013. In 2014, the space began new modifications under separate leadership. The Student Community was not included, and we see evidence of their response in the data spanning from 2014 to 2015.

When this space began, a level of Community Ownership was promoted with the Student Community's involvement on developing and building the space. Throughout the years, this level of interest was neither encouraged nor supported. In 2014, modifications were made without the consent of the Student Community. As a result, the cultural understanding of communal or collective ownership, was dismantled.

EVOLUTION

Any systems that are deployed, as a result of collaboration, must be made to be revised, updated or improved upon. Showing the results of collaboration is essential in the continued development of Community, but exhibiting results that are able to be updated and revised, is essential in the continued evolution of your Community. Branding, Signage, Websites, Displays, and publicly viewable systems related to your Community, should be developed with the understanding that they will be changed over time. Allowing your Community to see these items, will provide examples on how they can get involved, and spark ideas for improvements, upgrades and other suggestions. This a wonderful way to show the Community that this is *their* space, *their* system, *their* ideas.

We find examples of revisions throughout our IDeATe facilities. Each example provides a well-thought solution, to a common problem. But, the solutions are never deployed as a final product. They are built to be revised, modified, or improved upon.

Fig. 9 Laptop Cart

Our student staff were disappointed with our laptop storage. They needed something better, to track what was checked out, and provide easier recharging. They also needed something better, to deliver laptops and equipment to various classrooms throughout our spaces. Their solution involved slotted storage in the lending booth, and a custom designed laptop cart for course provisioning. Fig. 9 provides an image of the final laptop cart solution; capable of being modified to accommodate various course delivery needs. Even more remarkable, a second set of students are already creating a revision of these products.

Fig. 10 IDeATe Sign

More recently, a sign was installed in the stairwell entry to the IDeATe Makerspaces. We saw an immediate, positive response from our Community, but this sign was not meant to be the final product. A system was implemented, where the sign is redesigned by a Student, every 2-3 years. In the interim, we invite our Student Community to update or modify the signage in any way they like, as long as the modification is not permanent.

A Student modification is represented in Fig. 10 & Fig. 11. One-week after the sign was installed, we had multiple students ask if they could add their own *extra touch*. Their addition was not only supported; it was fully funded. In the process, the students learned how to program LED Lighting with an Arduino.

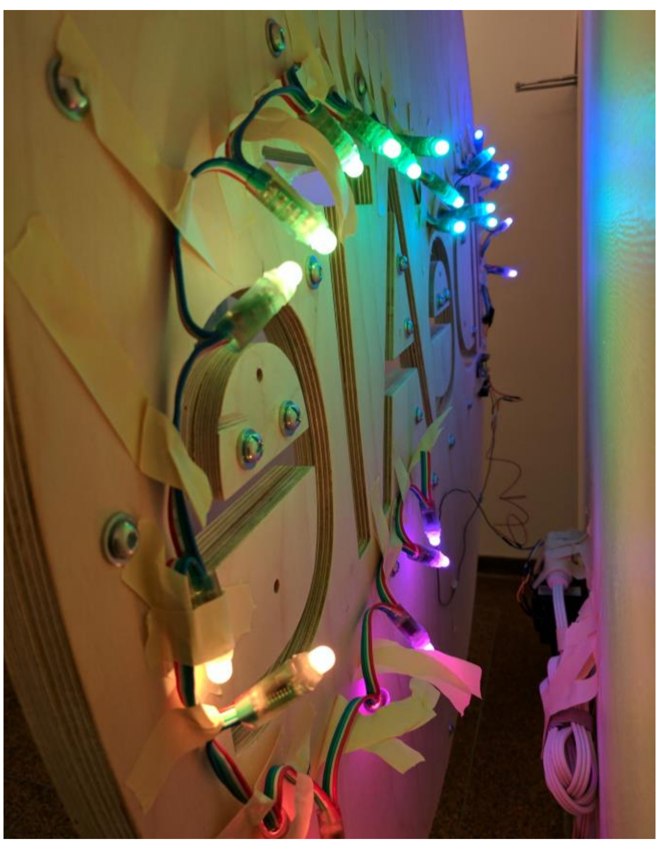

Fig. 11 IDeATe Signage Backlighting

Fig. 12 Beverage Shelf & Yellow Emergency Stop Cover

Other systems are found throughout the spaces, where Students are constantly creating and tailoring temporary solutions to improve the space. We find basic solutions, like beverage shelves near doorways that encourage the student to leave their drinking containers at the door; and 3D Printed Emergency Stop Covers- both of which are shown in Fig. 12.

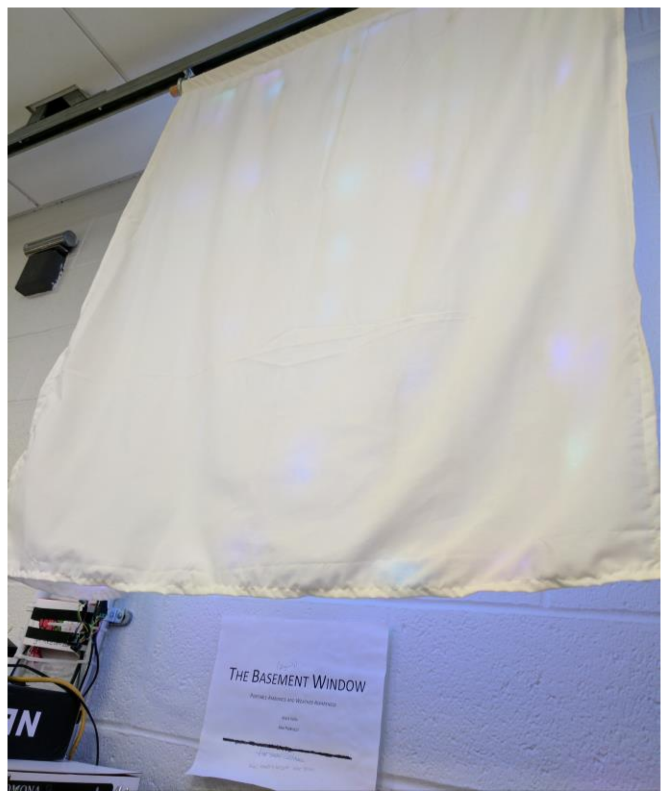

Fig. 13 The Basement Window

We find more complex solutions, like the *basement window* project in Fig. 13, that connects to an online weather channel feed, and changes color depending on the current weather conditions. We find digital signage solutions that connect to calendars, indicating whether or not a space is available for use. All of these solutions, were made by the Community, for the Community. In this understanding, the Community begins to feel a sense of ownership of the space.

CONCLUSION

This generation frequently references itself as the *second Industrial Revolution.* The Industrial Revolution deserves its place in history, as a single, radical instance that will never be repeated; as indicated by the term *revolution.* In many ways, the Industrial Revolution was not ideal, and we've continued as a society, to improve and evolve. Our generation deserves its own place in history, as the *Industrial Evolution.*

We must find ways to improve and utilize technology in the most efficient manner; encourage effective collaboration throughout our industries; and promote relationships throughout the ranks. This begins in the classroom, but is refined in post-secondary schooling.

If we continue to believe, that Makerspaces are the *only* element in a Makersystem; then we are certainly deserving of the *second Industrial Revolution* title. If we plan on making our mark in history, we must evolve and understand that our community, and the cultures they adopt, are essential in our generation's continued development as a whole.

Providing platforms for building relationships, will establish a participatory culture; where those who are interested will find ways to participate; *and those that are uninterested can find ways to participate.* While this effort in itself, will create a community that is accustomed to inclusion and open to conversation; developing strategies in collaboration will create a growing, proactive community; thus inhibiting a sense of collective ownership of the Makersystem.

When you include internal and external Communities, you are promoting ownership to those within your Makersystem; and those that were initially *on-the-outside.* Including these external Communities, will ensure that your initiative continues to evolve and grow. Increasing interest, efficiency, and value in the entire operation; but more importantly, conveying the core values we look to embody in our Students.

ACKNOWLEDGEMENTS

Thanassis Rikakis, for his perseverance, imagination and grandiose ideas.

Keith Webster & Susan Finger, for their constant support & mentorship in Collaboration.

Kelly Delaney & Gretchen Graff, for their un-endless strength & positivity.

George Minick, IDeATe Student Staff & Student Community, for their hard work and constant, unwavering belief in IDeATe.

IDeATe Core Faculty, for their embodiment of proactivity.

External Stakeholders, specifically Environmental Health & Safety, Computing Services, President Subra Suresh & Provost Farnam Jahanian.

Jeremy Ficca, for his guidance, mentorship & support.

Chaz Vance, for his expert guidance and selflessness that would eventually inspire this research.

Appendix A

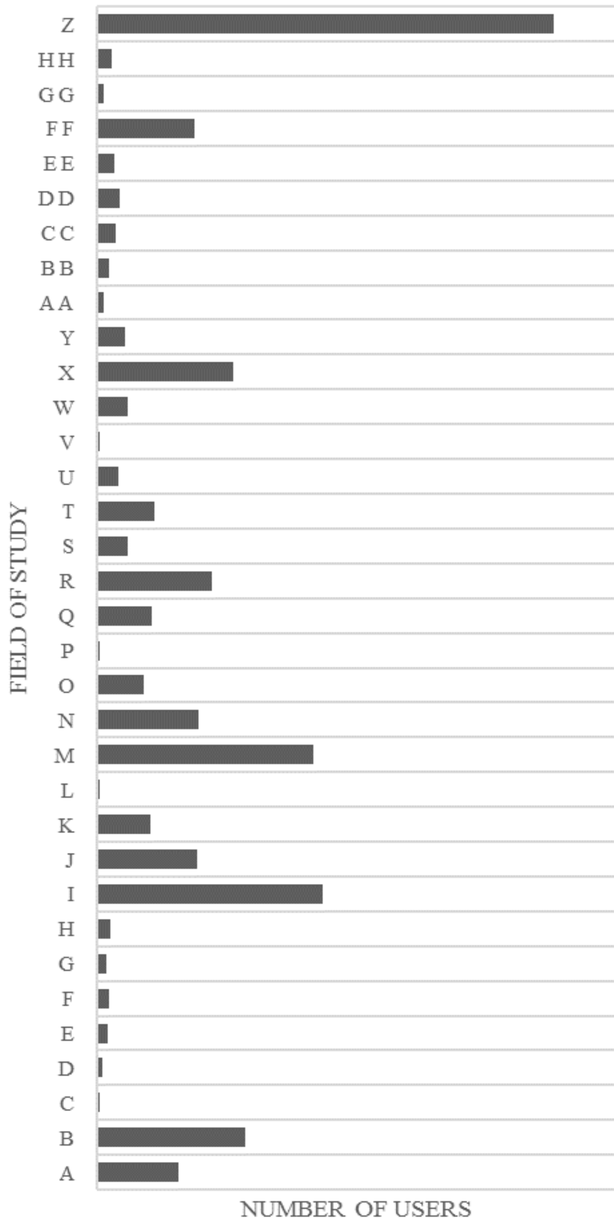

Fig 14. Community Diversity

Table 1 Community Diversity

A	Architecture	62
B	Art	114
C	Biological Sciences	2
D	Biomedical Engineering	4
E	Business	8
F	Chemical Engineering	9
G	Chemistry	7
H	Civil & Environmental Engineering	10
I	Computer Science	173
J	Design	77
K	Drama	41
L	Ecology	2
M	Electrical & Computer Engineering	166
N	Engineering	78
O	Entertainment Technology	36
P	History	2
Q	Human-Computer Interaction	42
R	Humanities	88
S	Information Systems	23
T	Integrative Design	44
U	Materials Science	16
V	Mathematics	2
W	Mathematical Sciences	24
X	Mechanical Engineering	105
Y	Music	21
Z	Undecided	351
AA	Philosophy	5
BB	Physics	9
CC	Psychology	14
DD	Robotics	17
EE	Science	13
FF	Social Sciences	75
GG	Software Engineering	5
HH	Statistics	11

Overcoming Barriers to Establishing Academic Makerspaces and "Tinkering" Culture

ISAM 2016 Paper No.: 45

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INTRODUCTION

The global maker movement has helped popularize the practice of DIY design, building, and "tinkering." The idea that anyone can make things is empowering, and makerspaces provide everyone from new to experienced builders a place to work in an environment where it is okay to explore. This model fits in well at a university, where engineering (and other) students benefit from the chance to apply theory to open-ended and personally engaging design projects.

Starting a makerspace on a college campus often poses challenges, however: resources are hard to come by, finding a space to work in is difficult, and opening access to students may pose safety or staffing concerns. In addition, the importance of an open space to work on non-academic projects is often not a priority amid other contenders for staff time and resources.

This paper explores the necessity of such a space for an engineering campus, as well as common barriers to starting a university makerspace. In addition, a case study of the efforts from students, staff, and faculty for a makerspace and "tinker culture" at Harvard will be examined, as well as lessons learned from the process which may be beneficial in overcoming barriers to such a space on other campuses.

FIRST: WHAT IS A MAKERSPACE?

A *makerspace* is more than just a room with tools; a makerspace connects a community of people.

Although it is important for a makerspace to provide both the space and tools needed for personal fabrication, the culture and community built up around the physical space is equally important. A successful makerspace should be open to student projects both in and out of the classroom, and allow students room to explore and tinker without fear of failure. A culture of "tinkering" encourages students to work on projects they find personally interesting and to direct their own learning. A strong makerspace community is important for bringing new users into the space, allowing students and mentors to learn from one another, and exposing students to new ideas and collaborations.

BENEFITS OF ACADEMIC MAKERSPACES

A makerspace is hugely beneficial to students at universities, particularly those in STEM fields. In addition to giving students a place to work on projects they find personally engaging, a makerspace allows students to apply the theories they learn in class to real-world problems.

At MIT, for instance, students in the Intro to Mechanics course learn how to calculate forces and displacements in

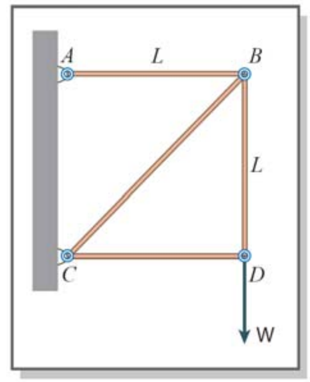

Fig.1 MIT Intro to Mechanics homework problem [1]

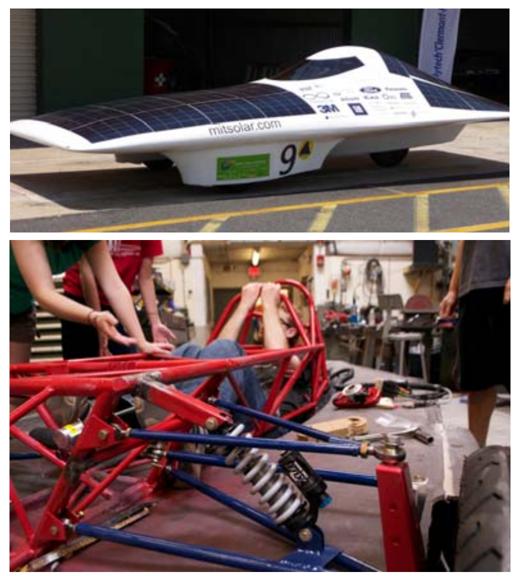

Fig.2 MIT Solar Electric Vehicle [2] and suspension [3]

problems similar to the one in Fig. 1. While this problem does teach basic theory, it is difficult to relate to a real-world scenario. On the MIT Solar Electric Vehicle Team, in contrast, students spend time outside of classes designing and building a solar-powered vehicle in one of the campus makerspaces. A student tasked with designing a front suspension for the car (Fig. 2) would need to use the same skills learned in an intro mechanics course. In this case, however, the student is applying the theory to a real-world design challenge, is more invested in the problem, and has a framework in which to apply theory to practice.

Research strongly supports the benefits of project-based learning (PBL). Students who engage in project-based learning have a deeper understanding of the subject material, and also retain that knowledge for a longer time.[4]

Open-ended projects also help students improve skills like critical thinking, creativity, teamwork, and problem-solving, which are much more difficult to teach in a traditional classroom. The community around a makerspace also provides huge benefits to students: working in the same physical space as people of many backgrounds helps expose students to new ideas and skills, and helps promote a collaborative culture of life-long learning.[5]

This sort of environment is critical for the success of engineering students – and critical for their ability to transfer engineering theory into good practice.

BARRIERS TO ACADEMIC MAKERSPACES

There are many obstacles to starting an academic makerspace, however. These may include:

A. RESOURCE LIMITATIONS

Universities must choose where to allocate a finite amount of space and funding. With research, coursework, and students all competing for limited resources, it may be difficult to find the real estate and capital necessary to host a makerspace.

This is particularly true in colleges with growing enrollment in STEM programs. In addition to an overall increase in the number of students attending college, the number of science and engineering majors has grown significantly in the last ten years.[6] Many schools with increasing enrollment lack adequate space for classrooms, student housing, and research labs; finding additional space for a makerspace may be impossible. Ideally, a makerspace needs room not only for its tools, but also for material storage, project storage, open workspace, and space for people to gather.

Similar issues arise with funding. Although expensive tools are not required for a makerspace, a well-equipped facility will give students access to a range of rapid prototyping equipment and other tools. This equipment can be costly; a single Epilog laser cutter costs between $8k and $45k, for example.[7] In addition to tool costs, a university makerspace may also require staff salaries, material and supply budgets, and maintenance of equipment.

The large financial and space resources required to start a makerspace often necessitate planning and approval at a high administrative level within the university.

B. SAFETY AND ACCESS CONCERNS

An effective makerspace allows students freedom to explore and work on their own. But machine tools pose safety hazards, and finding an appropriate balance between oversight and student freedom is often challenging.

Many makerspace users – particularly in a university – are new to machining and making. Threats of injury and misuse of tools must be mitigated with some sort of shop training program and supervision. While some schools may feel comfortable with undergraduate student supervision in a lab, others require graduate students or professional staff to be present at all times.

This relates to issues of access; if a makerspace is supervised by professional staff, student access may be limited to daytime open hours. However, students are often busy with schoolwork during the day; having time on the evenings and weekends for personal projects and for extracurricular teams to meet and build is often critical to their success.

Providing a mutually agreeable safety plan for students and staff is difficult: it must satisfy concerns about safety for both new and experienced users, while also satisfying student need for access and freedom to use the space independently.

C. "BUT WE ALREADY HAVE A MACHINE SHOP"

Many engineering programs already have machine shops, where students can either machine parts for class projects, or where a professional machinist can make parts for them. It can be difficult to get funding or the go-ahead for an additional space if the same tools already exist elsewhere on campus.

These spaces often don't fulfill the same need as a makerspace, however. A professional machine shop may be restricted to research or classwork, or may not allow students to use the fabrication tools themselves. Most importantly, a machine shop does not necessarily include the same culture and community required of a makerspace. Machine shops may allow students to come and build a part, without encouraging students to work on their own projects outside of academics.

While getting resources for a space may be difficult when those resources are already available, it is important to stress the difference between a machine shop and a makerspace, and the need for the latter when improving student outcomes in STEM programs.

D. ESTABLISHING CULTURE

Once a makerspace has been successfully started, there are still challenges to making it a successful space. For students who have never built anything, the fear of building without instruction or a specific project in mind may prevent them from participating in makerspace culture. Creating classes, programming, or a community of support is crucial to bringing new makers into the space, and making sure that students feel comfortable despite their lack of familiarity with new tools and with design.

OVERCOMING BARRIERS: HARVARD CASE STUDY

At Harvard, there is a huge push for more hands-on learning opportunities, including student access to makerspaces. While a number of hands-on facilities already exist on campus, students lack adequate space to work on personal and extracurricular projects. Members of the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) have been working on a number of different strategies to improve space available to students.

ADVOCATING FOR SPACE

Students, staff, and faculty have come together to discuss a need for a makerspace and community around tinkering. Students have been proactive about expressing these needs to the institution:

> "I know students would love the chance to work in the lab/shop on something other than what is required for school… [we] both have often wanted to use equipment for personal projects, but often we can't because of class use or equipment is off limits during non-normal hours."[8]

Despite the demonstrated need, space limitations at Harvard have made it difficult to find a quick solution. The engineering program at Harvard is growing rapidly: the number of undergraduates declaring a concentration (major) in engineering and applied sciences has almost tripled in less than ten years since the school was first launched.[9] Rapid growth in the school has left very little free space on campus, and finding a location to house a new makerspace is difficult. A larger engineering campus is currently being built just over a mile away, but will not be open until 2020.[10] This future campus includes plans for an impressive makerspace, planned in collaboration with a large number of faculty, deans, administrators, and students. Faculty and staff responsible for the higher-level makerspace planning have been proactive about involving all stakeholders in the planning process.

Despite this, current students still lack an adequate space to work on personal projects:

> "[We] have been interested in getting some dedicated maker space for SEAS. We know there are currently plans to have space like this at the new campus in Allston, but four or five generations of innovators will lose out on that opportunity in the meantime." [11]

EXISTING FACILITIES

SEAS has several machine shops currently open to students. In addition to a professional machine shop staffed by full-time machinists, there is an instructional machine shop where students can undergo a comprehensive training in proper machining practices, before gaining access to tools during business hours.

The Active Learning Labs (ALL) is also available to undergraduate students. The ALL comprises several machine shops and design spaces, as well as a full-time staff of engineers, whose goal is to support hands-on activities in all undergraduate classes in SEAS. The labs give students training and access to basic machine tools, as well as rapid prototyping equipment like laser cutters and 3D printers. They support classroom activities, as well as student capstone design projects and general project support.

Despite these resources for fabrication, many of these spaces are too restricted to satisfy the student need for a makerspace. Until recently, the ALL was only available to students when supervised by professional staff, mostly during business hours. Students could not use machine tools on evenings or weekends, and work on personal projects was discouraged due to the high volume of classes needing the space.

SHORT-TERM AND LONG-TERM SOLUTIONS

With students continually advocating for a space, and faculty already planning a makerspace in the new engineering campus, the priority turned to finding a solution for students in the interim. Since space is so limited at Harvard, the Active Learning Labs staff worked with students to develop an experimental solution: transforming the ALL into an open space for personal projects one night a week.

The new ALL "project nights" are advertised to the school as a "fun night of tinkering and community", and aim to bring students and other community members together on a night dedicated to personal fabrication. With open machine shop time and encouragement to come explore, these evening events attempt to start building maker culture and community in existing machine shops, even if a 24/7 makerspace is several years away.

The ALL has already had several successful "project nights": one staffed and run entirely by students, and another run by staff. Staff worked together with students and the lab leadership to mitigate any safety risks. An expanded safety training program for shop "super-users" was developed, to teach students how to staff the labs on their own, respond to safety violations or emergencies, and help address common problems in the shop. Other students attending a project night must complete machine shop training with ALL staff before using the shop after hours, but are then cleared to work under supervision of the shop "super-users," who can always contact the lab staff over phone at any time.

In order to improve accessibility to members of the community unfamiliar with working in a shop, the staff-run events also have a theme: the first of these was "bike night," encouraging students to bring in their bikes and learn how to fix and maintain them. The goal of a weekly theme is to give some direction to students who still feel uncomfortable in the shop or don't yet have a project in mind, but still want to participate in the culture and community.

Finally, staff and students are working together to collect data on project nights: who is participating, what activities they are interested in, what impact project night is having on them, and so on. Hopefully, this data will be useful in informing future makerspaces and programming.

CONCLUSIONS

Several takeaways from this ongoing experiment may be of general use to others attempting to overcome barriers to starting university makerspaces:

Students have a powerful voice when advocating for themselves to campus administration. Persistent efforts on the part of students made a huge difference in allowing project nights to happen, and the same students have been involved in meetings around future makerspace planning.

Collaboration among all stakeholders when designing a program or makerspace is beneficial. This ensures that student needs are met, while also satisfying the safety and resource constraints of an institution.

Building up a community is a key part of starting a makerspace – and culture can start developing before a space is fully realized. In fact, starting to build up a culture of making and tinkering helps demonstrate a clear need for future space

Small-scale tests of a program can help diminish risks and demonstrate its potential for success, as well as iterate on best practices. By holding weekly project nights and talking to students, ALL staff hope to iterate quickly to improve the community.

And finally, gathering data on open questions, such as who is using the space for personal projects, and what sorts of tools and resources are lacking, can help make data-driven arguments for space and community needs.

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Poison Pills, How Basic Analogies and Data Can Inoculate You Against the Nay-sayers

ISAM 2016
Paper No.:
46

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INTRODUCTION

The ***purpose*** of this paper is to provide insights that have been successfully used at MIT to remove unnecessary objections to makerspaces, maker tools or maker methods. This is ***important*** because unnecessary objections lead to unnecessary boundaries that limit the effectiveness of a makerspace and thereby its ***impact*** on the student educational experience. Usually, these objections are:

(i) couched in legal and regulatory issues and don't have any basis in legitimate safety concerns, and/or

(ii) based upon someone's feelings or philosophy and have little to do with factual information, and/or

(iii) due to people not having the proper perspective when it comes to makerspaces and maker activities.

When creating a makerspace, factual information is one of your best allies. For example, data and facts that show a maker activity is safe can enable that activity to happen. In the absence of that data, it is often useful to have (and easier to obtain) comparative means, e.g. anecdotes, analogies, examples or experiments to make one's point. This paper offers a nice balance to the quantitative data that you will see at ISAM. It reinforces the concepts that there is more than one way to address a problem.

In this paper we cover a few examples of how analogies, anecdotes and examples can be used to address common, unnecessary objections to makerspace activities. This topic does not lend itself to demonstration via data other than via explanation of how they made a difference in a real conversation. We have provided a few examples in the text, which should be enough for the reader to adapt the other analogies and anecdotes for their own purposes. We hope this also spurs thoughts on new analogies/anecdotes that readers will share via the newly launched MakerShare platform [1] and at ISAM 2017.

COMMON UNNECESSARY OBJECTIONS AND USEFUL RESPONSES

In the following, we provide matching sets of objections and responses for the author to read and consider before we return to discussion. Please note, that the appropriateness of these responses is situation dependent. The idea here within this text is to give examples that help the reader understand how this approach may work for them.

OBJECTION: I'm worried someone will get hurt if we have a makerspace?

RESPONSE: OK then, let's look at sports injury statistics... no one thinks twice about letting our football players onto the field. In fact, we often have ambulances there [2] because we expect injuries that may require medical care and hospitalization or lead to worse. Why is that OK and makerspaces not OK?

OBJECTION: I'm worried a laser cutter will start a fire! [3]

RESPONSE: Well, let's look at dorm oven fire statistics.

OBJECTION: I worry we can't trust these '*kids*' to be safe with things.

RESPONSE: Are you really going to tell that to students returning from military service?

OBJECTION: I don't feel that the ROI justifies this?

RESPONSE: The proof is out there [4, 5], you just need to find it. Start with the education research journals and then do an analysis of university program effectiveness that is correlated with availability of hands-on/design/making resources.

OBJECTION: I fear that we'll get sued.

RESPONSE: Do we plan to do something that is unsafe and/or unreasonable?

OBJECTION: We need policy documents to make things safe. They should be detailed (this means several pages long).

RESPONSE: Have you memorized your state's driver's manual? Students won't read long documents and won't remember them if they do.

OBJECTION: I don't feel comfortable with this much risk!

RESPONSE: How comfortable do you feel with students driving a 2 ton trucks at 65mph? Or perhaps riding on a motorcycle or bicycle on a busy city street. These activities carry elevated levels or risk, but you don't think twice about letting student do them.

THE POWER OF EXPERIMENTS

If someone is on the fence about proceeding with a plan, or there is no proof either way as to which direction is right… yours or theirs… perhaps you can 'try an experiment.' People find it hard to say "no" when someone is asking to learn more about the truth of the situation. In essence, you are making it hard to say no. In some cases, you might make it easy to say yes… that is if they are really interested in understanding the lessons that could be learned from the experiment regardless of whether or not they would reaffirm their position.

Example - The MIT MakerWorkshop

The MIT MakerWorkshop [6] was started as an experiment because many people on campus did not believe a student-run facility would work. This was a pervasive attitude despite example cases at peer institutions (and the MITERS facility at MIT). A compromise was struck wherein the facility would be run by graduate students and a handful of exceptionally talented/responsible upper class undergraduates. After 18 months, the experiment showed that this space could be run safely and effectively. This experiment made it possible for MIT to run the MakerLodge [7] program that aims to train MIT freshman (all that want to) in basic and advanced maker techniques. This facility uses volunteer undergraduates as the training staff. The Martin Trust Center ProtoWorks [8] was also launched in parallel with the MIT MakerWorkshop and functions as a safe and effective makerspace with a staff of undergraduates that act as monitors, design consultants, entrepreneurial consultants and training staff.

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Creating a Network of Community Colleges with Makerspaces: California's CCC Maker Model

ISAM 2016
Paper No.: 47

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INTRODUCTION

California's 2.1 million full and part-time community college students comprise the largest system of higher education in the United States. Sixty-seven percent of community college students are people of diverse ethnic backgrounds and roughly 53 percent are female [1]. As part of the "Doing What MATTERS for Jobs and the Economy" initiative and the Strong Workforce Taskforce recommendations to prepare students for high-value jobs in regions throughout the state, the California Community College Chancellor's Office (CCCCO) is investing $17,000,000 to grow a statewide network of community college-based STEM/STEAM-focused makerspaces over the next three years. This paper introduces the new CCCCO initiative named *CCC Maker* as an open-source model that will be used in community colleges throughout California. Community colleges are uniquely positioned to deliver makerspace benefits to its students, instructors, the regional business community, and government entities.

BACKGROUND

The California Community Colleges is the largest provider of workforce training in the state and nation, offering postsecondary technical education in 175 fields, and educating more than 100,000 individuals each year in industry-specific workforce skills. However, California's education pipeline is not keeping pace with the higher levels of skills and education required by employers. By 2025, 30 percent of all job openings in California – or a total of 1.9 million jobs – will require some form of postsecondary education short of a four-year degree [2].

In response, the California Community College Chancellor's Office (CCCCO) has developed multiple organizational structures and strategies to address these workforce needs. The Doing What MATTERS for Jobs and the Economy (DWM) framework, managed by the Workforce and Economic Development Division, is designed to supply in-demand skills for employers, create relevant career pathways and stackable credentials, promote student success, and get Californians into open jobs.

The CCC Maker initiative is an emerging action strategy under the DWM and Strong Workforce Taskforce system. It is the first statewide community college system effort in the United States that will intentionally 1) grow a statewide network of STEM/STEAM focused makerspaces linked to California Community Colleges to develop a workforce for the innovation economy, 2) develop a California Community College makerspace 'Community of Practice' to serve as a state and national model, 3) align 21st century skills with STEM/STEAM research and practice, 4) support work-based opportunities for California Community College students, and 5) disseminate information and resources to ecosystem partners and key stakeholders.

The initiative is built upon research and findings from a California Council on Science and Technology white paper, "Promoting Engagement of the California Community Colleges with the Maker Space Movement" [3]. The paper asserts that:

- "Making" offers complementary learning environments to the traditional classroom and helps participants develop skills that differ from those in traditional student projects and learn-by-doing classes" and
- Makerspaces should be part of a community college's instructional strategy to: 1) help students master 21st century and soft skill sets, 2) engage with business, industry and other ecosystem partners, and 3) establish their role as a key stakeholder in strengthening regional workforce development.

Concurrent with the publication of the white paper, the CCCCO released a Request for Proposals in April 2016, seeking qualified community college applicants to serve as fiscal agent and technical assistance provider [4]. Sierra Joint Community College District was selected and awarded in July 2016 by the Board of Governors. The CCC Maker grant is operational from July 2016 to May 2019.

THE MODEL: CREATING STANDARDS AND REWARDING CUSTOMIZATION

Fifteen California Community Colleges currently have operational makerspaces, and another 17 have committed to starting up a makerspace. These current and future spaces are and will be customized to the education and economic ecosystem in which they operate, but operate using existing and prototyped operational structures such as Fab Labs, Hackerspaces, Co-Working Spaces, and Makerspace models to deliver services to students. This is challenging to build from a statewide perspective – encouraging customization and experimentation, but holding colleges accountable for outcomes built around common metrics.

CCC MAKER DESIGN

The organizational structure [Fig. 1] is designed to accelerate the integration of makerspaces into California Community College educational strategies and operations. At the leadership level, an advisory committee is the voice and the inspiration for the CCC Maker initiative. Committee members bring in their unique perspectives to discuss progress, recommend strategies, aid in the tactics of building the ecosystem, and provide a voice to educate and influence. Dale Dougherty, CEO of Maker Media and the founder of Make Magazine and the Maker Faire, is chair of the advisory. As the leader of a California-grown phenomenon that has spread globally, Mr. Dougherty has a keen interest in engaging community college students and faculty in new ways of learning that will "lead to a truly innovative economy and society" [5]. Other advisory members include representatives of business, education, foundations, and government.

The Project Manager coordinates administrative operations and resources available to colleges including ecosystem mapping through the National Association for Community College Entrepreneurship (NACCE); Making Across the Curriculum faculty workshops by Zack Dowell at Folsom Lake College; 21st Century Skills workshops by the New World of Work; How to Start Up and Improve Your Makerspace workshops by Maker Education Initiative; Infusing Social Entrepreneurship into the Community College Experience workshops by Kiva, and more.

A Technical Assistance Provider (TAP) administers and manages a mini-grant application and selection process, facilitates the delivery of training and other resources to colleges, builds a makerspace communication network; and serves as a facilitator for building business/industry partnerships and student work-based experiences.

WHAT LESSONS HAVE WE LEARNED?

1. There are plenty of best practice examples in the higher education-makerspace world that can be deployed in this initiative. Many of the core CCC Maker components don't need to be recreated; they just need to be found.
2. Communication is the most important feature to successfully deploy this huge undertaking. There are many different stakeholders that need to be in the loop of communication. We are communicating on multiple fronts: face-to-face meetings, social media, an accessible website, on-site training and small conference gatherings. We intend to closely monitor what works and what doesn't work for communication channels, our success depends on it. We are deliberately seeking to create a sharing culture that uses the benefits inured from collective learning.
3. An engaged advisory committee with a wide range of perspectives is invaluable. Our first advisory meeting uncovered interesting and useful insights that came from this diversity.

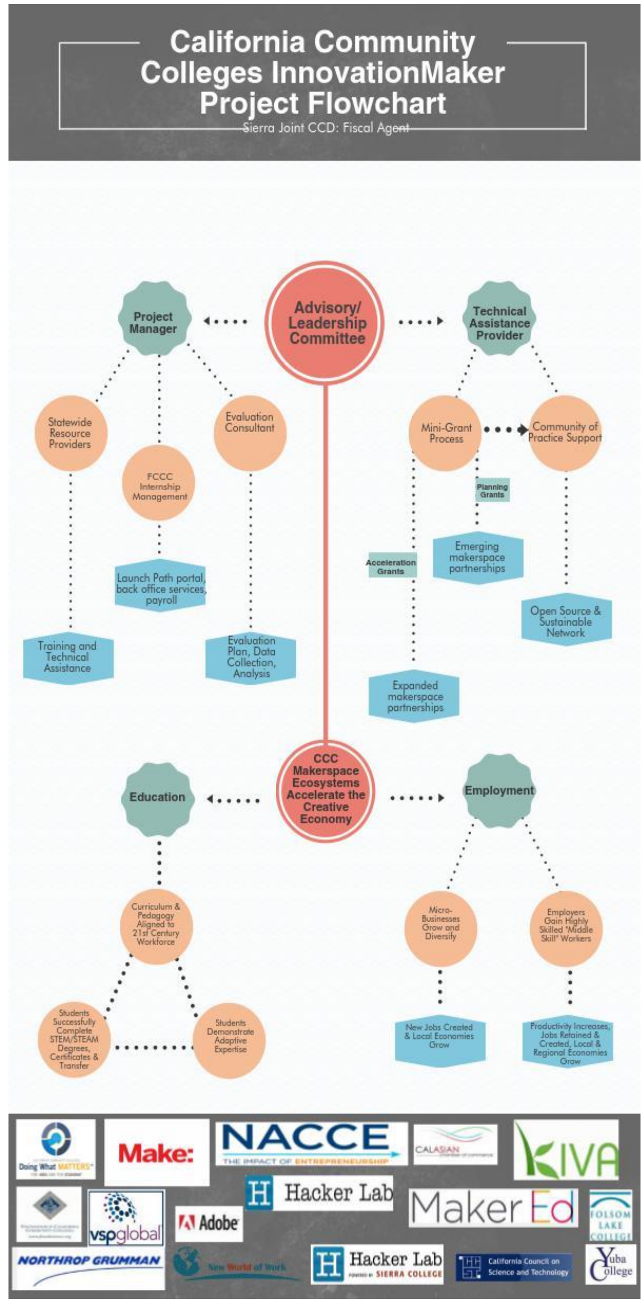

Fig.1: Structure and Projected Outcomes of CCC Maker

4. There is support for community college-based makerspaces in the business community. There are a number of clear benefits for local business involvement in the education process as well as moving part of the educational experience into the local business environment. We feel we are being encouraged to tailor each site to the needs of the local community (industry or agriculture for example), which adds value to the local business economy.

EXAMPLES OF CHALLENGES WE ARE FACING

1. Some community colleges have a broad and deep understanding of makerspace and education integration; others have no experience at all. Our initiative needs to be able to accommodate this spectrum of starting points.
2. What are the CCC Maker core features that should be found in all sites and what are the features that can be unique to the individual setting? We feel that finding this balance can only be "learned by doing" as the mini-grant sites begin in 2017.
3. Un-written rules of wide and willing collaboration, unsuccessful outcome discussions, sharing resources, and trying new ideas at the edges of traditional learning models are important and challenging cultural features we seek. We intend to deliberately create and model a positive common culture.
4. Communication structures (website, Facebook, Twitter) need to empower colleges as they experiment and iterate. Similar to using You Tube to learn how to do or fix something, the CCC Maker community needs to build a peer network for makerspace support and learning.
5. What are the most effective metrics to describe our progress? Do we use a combination of retrospective measures? For example, should we use utilization data (number of sites), student participation, degrees and certificates completed, or derive the number of jobs that have been created?

CONTEMPLATING THE INTENDED OUTCOMES

Imagine the implications of a successful CCC Maker initiative. What does success look like? What are the stories that will be told?

Integration of the maker movement and an entrepreneurial mindset will deeply affect how education is delivered, and how students are prepared for future careers. [Table 1].

These possible future outcomes can be divided into five distinct categories that include student success, educator leadership in pedagogic platforms, the value of community college-local community linkages, repeatable models of CCC Maker sites guided by the CCCCO, and successful inclusion of non-traditional student populations into this education system.

A. STUDENT SUCCESS IS THE DRIVING FORCE BEHIND THE CCC MAKER MOVEMENT. COMMUNITY COLLEGES REFINE THEIR EDUCATIONAL PORTFOLIO WITH ADAPTABLE LEARNING PLATFORMS THAT CHANGE AS THE DEFINITION OF STUDENT SUCCESS CHANGES.

1. Students create customized curriculum tracks based on their personal interests. They combine traditional academic courses with exploration and skill building from the makerspace labs. New combinations of curriculum tracks are common; electronics could go with art, app design might be combined with accounting, social programs could go with math. All combinations are possible.
2. There is a measurable increase in STEM/STEAM careers because of the interesting, interactive, and relevant content taught at the community college.
3. 21st Century workforce skills are an integral part of the curriculum.
4. Students are recruited into careers because of their participation in the CCC Maker programs. Some go on to become entrepreneurs. Others are employed in technical careers based on their makerspace-led training. A portion of the students are artistically inspired by their instructors, their peers, and their access to art-making equipment found in the makerspaces.
5. Student support services including counseling, career planning, and personal growth, shows measureable results in path-finding, self-confidence, and social skills

Table 1: Projected Outcomes of CCC Maker

California Community College Makerspace Ecosystems Accelerate the Creative Economy	
Education	Employment
Curriculum and Pedagogy Aligned to 21st Century Workforce	Micro-businesses Grow and Diversify Employers Gain Highly Skilled Middle Skill Workers
Students Successfully Complete STEM/STEAM Degrees and Certificates, and/or Transfer to University Students Demonstrate Adaptive Expertise	New Jobs Created and Local Economies Grow Productivity Increases, Jobs Retained and Created, Local and Regional Economies Grow

B. EDUCATORS ARE LEADING THE CCC MAKER PROGRAM AND CURRICULUM DESIGN.

6. Student success is due in large part to the competencies, academic support, and educational experiences that faculty have designed.
7. Educators have incorporated self-paced instruction, peer learning, digital programs, and makerspace lab team learning into a cogent model that is effective and inspiring [6][7]. Students have been challenged to learn new skills in teamwork, accountability, and empathy for the world around them.
8. The makerspace environment is a component of faculty professional development and currency. It includes curriculum design support, community business interaction, and continued learning encouragement. Program design and outcomes are evaluated for effectiveness.

C. THE COMMUNITY COLLEGE ENHANCES ITS ROLE IN THE COMMUNITY AS PARTNERSHIPS WITH BUSINESSES AND OTHER COMMUNITY ORGANIZATIONS LEAD TO STRONG INTERDEPENDENT RELATIONSHIPS.

9. Businesses take on new community college roles as mentors, coaches, and curriculum contributors.
10. Community colleges adapt instruction to the needs of the region and employers that drive the local economy.
11. Community partnerships give students the opportunity to see inside the world of commerce. Student and instructor internships add value to the student, instructor, and business.

D. THE CALIFORNIA COMMUNITY COLLEGE CHANCELOR'S OFFICE BUILDS A GROWING NETWORK OF CCC MAKER SITES THAT INCORPORATE PROGRAMMATIC STANDARDS AND SYSTEMATIZED METRICS.

12. The CCC Maker program evolves as campus experiences help refine and shape the successful initiative. The initiative is always evolving.
13. Programmatic standards and metrics are used to show the effectiveness of each key program area.
14. A key contributor to the success is the overarching communication network that ties students, instructors, and campuses together with meaningful interaction.
15. Key findings and insights are shared at the state, national, and international levels creating a super-network sharing infrastructure.

E. THE CCC MAKER INITIATIVE IS A CIVIC MODEL OF SUCCESS BECAUSE OF ITS POSITION AS A THOUGHT-LEADER AND DEMONSTRATED COMMITMENT TO INCLUSION OF NON-TRADITIONAL POPULATIONS OF STUDENTS, INSTRUCTORS, AND SUPPORT STAFF [8].

16. Non-traditional students are valued and encouraged to participate in community college makerspaces at all levels. Deliberate efforts to engage non-traditional students and instructors create makerspaces that are reflective of campus and community diversity.
17. College makerspaces become an effective platform for reforming social-economic problems through dialog and demonstrated outcomes.

CONCLUSION

This paper is an overview of the California Community College Chancellor's Office CCC Maker statewide initiative, designed to grow a network of STEM/STEAM focused makerspaces on a significant scale. Through the Doing What MATTERS framework and the recommendations of the Strong Workforce Taskforce, the CCC Maker initiative is a three-year strategy with a goal to create relevant career pathways and stackable credentials, promote student success, and get Californians into open jobs.

A nationally recognized leadership/advisory group guides the project and provides a voice to educate and influence. A Project Manager oversees administrative operations and guides training opportunities and resources. A Technical Assistance Provider is developing a mini-grant award process to community colleges and will facilitate training and resources to grantees to support the planning and implementation of makerspaces and affiliated ecosystem partnerships, and build a community of practice that is open to all.

Anticipated outcomes include adaptable learning platforms that support student success; new delivery models designed and delivered by faculty; strong partnerships with business and industry that support student transitions to employment; metrics and evaluative models that communicate the value of makerspaces integrated into the educational environment; and the democratization of 'Making' and STEM/STEAM career paths and occupations by engaging special populations reflective of community college demographics: women, racial and ethnic minorities, veterans, students with disabilities, economically disadvantaged, and English-language learners.

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The Value of Campus Collaboration for Higher Education Makerspaces

ISAM 2016 Paper No.: 48

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INTRODUCTION

The concepts of community and collaboration are essential characteristics of makerspaces. The value of collaboration has been highlighted as an idea accelerator by a number of authors including Jon Gertner's history of Bell Labs and its reliance on innovation as the fuel for discovery. Gertner described the "Black Box" lab as an innovation hub that relied on forced interactions to mesh "many interlocking small parts grouped physically near enough to one another" to create a powerful and purposeful machine [1]. The value of collaboration in the maker-movement was presented by Chris Anderson as critical to establish "open-innovation communities" where participants voluntarily join and contribute to common causes [2]. According to Anderson, the value of the work draws talented participants, and the openness of the activities in makerspaces serves as an invite for people to contribute to projects.

The importance of innovation within academic settings leads to "innovative learning," a term established by Tony Wagner in his book on mechanisms that promote innovation and creativity [3]. He argues that the "culture of schools and classrooms must be transformed" to create modern learning environments centered on purpose-driven creation by multidisciplinary teams. More recently Dale Dougherty emphasized the role of collaboration within school-based makerspaces as a mechanism to promote learning and discovery [4]. Dougherty emphasizes culture and community are both needed to create environments where "students feel inspired to make and where caring and knowledgeable mentors provide support.

For higher education, in addition to the concepts of community and collaboration within each makerspace itself, the makerspaces also serve an important role in promoting collaboration across campuses. As spaces that can be viewed as being agnostic with respect to programs, departments, and schools, higher education makerspaces have the potential to promote multidisciplinary interactions that may not otherwise exist.

This paper examines the role of higher education makerspaces in promoting campus collaboration at seven unique institutions. For each university and institute, an overview of the local maker community is presented, followed by a review of how that community advances collaboration at each institution.

CARNEGIE MELLON UNIVERSITY: INTEGRATIVE DESIGN, ARTS & TECHNOLOGY NETWORK (IDeATe)

CMU IDeATe Overview: At Carnegie Mellon University, innovation through efficient technical practices is supported through the Integrative Design, Arts & Technology (IDeATe) Network [5]. IDeATe serves as a campus-wide resource for the maker community, providing interdisciplinary courses, spaces, and resources that encourage collaboration between programs, faculty, students and staff. IDeATe facilities reside in Hunt Library and consist of five types of defined areas:

- Hybrid lecture, collaboration, and project spaces
- Studio lecture and collaboration spaces
- Dedicated collaboration spaces
- Dedicated equipment spaces
- Lending and administrative spaces

All activities and the associated work areas span across three floors, providing about 10,000 square feet of dedicated space. Other than the equipment, lending, and storage spaces; the majority of IDeATe is tailored for flexibility, modularity, and reconfiguration. Wheeled tables and chairs, dry-erase table-tops, and mounting grids hanging from the ceiling are some of the universal elements that allow for easy reconfiguration of the spaces. The hybrid lecture, collaboration, and project spaces act as a meeting space for courses, but primarily serve as collaborative work areas for the community. Supporting embedded computation, integrative media and fabrication processes, each area is located within 10-feet of one another, making it easy to access separate technologies without leaving the community. In defining these areas by similar processes and technologies, the community begins to understand where they can find assistance, information or advice on progressing projects.

The IDeATe Network also provides interdisciplinary courses, without prerequisites and open to all students. Here students engage and innovate through collaborative assignments with support from a network of participating faculty. Currently, undergraduate degrees affiliated with IDeATe are available and graduate programs are under development. After participating in an IDeATe course, students retain access to the facilities or equipment on which they've received training for the remainder of their tenure at Carnegie Mellon University. As a result of being located in the library, the IDeATe facilities are accessible 24/7. In addition, the constant flow of students visiting the library generates interest with the external campus community.

Approximately 1,800 members of the Carnegie Mellon community are members of IDeATe, with the distribution being 90% undergraduate, graduate, and Ph.D. students, and the remaining percentage faculty and staff. The student community includes 38% science, engineering, and math majors, 12% social studies, humanities and business majors, 27% fine arts and design majors, and 23% undeclared majors. 59% of all members are male, while 41% are female.

While IDeATe's spatial programming and design are important factors in supporting collaboration, proactive participation from the entire community promotes innovative and effective practices. This leads to a culture accustomed to eliminating boundaries between communities for the sake of efficient and rewarding experiences. In creating platforms for members within the IDeATe community to become more actively involved in the development of the space, community, and culture, administrative stakeholders encourage the fundamental aspects and beliefs on which IDeATe was founded. From these positive experiences, the IDeATe community reaches out and engages the external campus community, further promoting the collaborative cultural standard. The IDeATe administrative team provides guidance for this process and implements systems that encourage positive experiences and promote best practices in collaboration.

CMU IDeATe Administrative Structure: IDeATe began as a campus-wide initiative under the Provost's Department in 2015 before transitioning to the University Libraries. The transition was made to support campus-wide collaboration and establish the network in a space that already encouraged a collaborative culture. The IDeATe Network receives support from the President and Provost, as they continue to meet with IDeATe leadership, faculty and students on a frequent basis. The IDeATe administrative and technical team coordinate collaborative efforts and build relationships throughout the university while managing the facility, equipment and course-related concerns. This staffing includes the library's Dean, Associate Dean, Project Coordinator, Project Manager, Technical Director, Systems Developer, Facilities Manager, Facilities Assistant, two Library Liaisons, three Student Leads, and ten Student Employees.

Students staff the Lending Booth between 10 AM and 10 PM to provide the IDeATe community with equipment to borrow and material to purchase. These students manage the lending equipment inventory database and deliver equipment to IDeATe Classrooms for courses. The IDeATe floating senior staff consists of students who dedicate at least six hours per week to the IDeATe community, facilities, and culture where they assist students, maintain equipment, and make improvements to facility-based systems. Students who excel in their original duties are promoted to the senior staff where they take on a broader role promoting the IDeATe culture, by engaging and assisting the external and internal community. They also develop improvements and create solution for facility and equipment related issues. In every aspect of the student staffing evolution, they are speaking, meeting, and solving problems as a group. As a result, members of the IDeATe community are continuously exposed to these student staff examples of efficient and effective collaborative practices.

CMU IDeATe Campus Collaboration Activities: Collaboration within IDeATe is a cultural characteristic that is promoted through every day practice. A number of examples illustrate this collaboration: faculty co-teach courses, group projects are regularly assigned, the network is large and diverse, and the facilities were built to facilitate collaboration. Each element of IDeATe's structure is aimed at building relationships, networking, and engaging the existing and external campus communities.

IDeATe courses act as the primary resource for collaborative engagement as they are open to all students, co-taught with faculty from different backgrounds, and have no prerequisites. Semester-long courses provide extensive information on elaborate topics, with several team based project assignments throughout the semester. Half-semester courses deliver essential information at a faster pace, while maintaining interdisciplinary interactions through group exercises. Micro-courses are both popular and effective. Typical topics include laser cutting, soft fabrication, or learning Arduino. These courses have two to three-hour meeting times and occur on weekends. Two to three sessions are required for each topic. Usually, group projects are not assigned during micro-courses but collaboration tends to occur naturally, as the fast pace and longer lab times encourage the students to ask each other for help. Most notably, five seats are always reserved for faculty or staff in each micro-course. This course-format, provides a quick method for getting training, during non-work/non-study hours. While primarily provided as a resource for the student community, faculty and staff have found this extremely valuable, as they are able to fully participate in a course that does not interfere with their work schedules.

Senior student staff also offer open-hours to assist the entire campus community on weekdays with technical projects or ideas. Open-hours assistance allows any member of the campus community, access to IDeATe technologies, equipment, and materials. Most importantly, those seeking assistance are exposed to the IDeATe culture. This experience generates interest from the external community, while eliminating boundaries and increasing the network's accessibility.

CMU IDeATe Campus Collaboration Example: In 2015, Student Housing began a five-year project to update, upgrade and improve campus housing. This group was looking for fresh ideas on improving the space. Student Housing contacted IDeATe to discuss ideas related to makerspace technologies. Following the first meeting, a plan was formulated to design, create, and deploy a makerspace within the first renovation project, Morewood Gardens Dormitory.

The layout of the space was jointly coordinated by IDeATe and the CMU Office of Campus Design and Construction.

During the project's planning phase, students participated a process to determine the equipment that would be available in the space. Soldering tools, clamps, audio recording devices, cameras, hand tools, power supplies, and oscilloscopes were only some of the items requested and purchased for the new facility. IDeATe students helped purchase equipment and developed an inventory check-out system for the new equipment. A laser cutter was also purchased and installed by IDeATe technical staff. Normally such equipment is not allowed in student housing facilities, but by collaborating with CMU's Environmental Health and Safety Department, the space and equipment installation was approved and implemented.

As another example of collaboration, an IDeATe collaborative solution was installed in one of the spaces. The ModWall consists of several computer numerical control (CNC) routed panels that can be mounted to and removed from a wall using thumbscrews. Each panel can be flipped to reveal either a birch plywood face for aesthetic value, a dry-erase panel for sketching, or a cork face for attaching displays. The user can modify the wall into any configuration. Users can also remove panels and take them to a desk to sketch, ideate, or use as a work surface. This project was developed and constructed by the IDeATe students for all students. This partnership continues to produce results with the latest development being laser cutting micro-courses taught in the Morewood Gardens' makerspace. The space continues to evolve and is managed, maintained, and modified by the student community.

CASE WESTERN RESERVE UNIVERSITY: SEARS think[box]

Case Western Reserve University's Sears think[box] Overview: Sears think[box] began in 2008 from the question "How can the university create a physical and mental space that encourages cross-disciplinary collaboration, innovative thinking, making and building, and, if appropriate, product development and company creation?" Answering that question, a 3,000 square-foot maker-centric lab opened in 2012 on the main campus of Case Western Reserve University (CWRU). In 2015, the project moved into a seven story, 50,000 square-foot center for innovation that contains everything needed to design and create physical prototypes of new products [6].

The center's mission includes providing access to the entire student body as well as the general community to foster and support collaboration, innovation, and making. The facility supports ideation, team building, and very rapid prototyping (using Play-Doh, straws, popsicle sticks, and toothpicks to generate ideas). These ideas are brought to life using 3-D printers, circuit board routers, laser cutters, a digital sewing machine, a small metal shop, a wood shop with a CNC table router, and other prototyping and fabrication equipment. All of these resources are available to students, staff, and faculty, as well as members of the public, at no cost. Because of this open access policy, think[box] has exploded in popularity since its 2012 opening and now receives over 5,000 visits a month. The center is the third most popular facility on campus (after the gymnasium and the library) and the second most cited "core facility" by campus researchers. Visitors arrive from every school and department at CWRU. Twenty percent of the visits are from the local community which includes a nearby art institute and other surrounding universities, area high schools, local entrepreneurship offices, and industry. Collaboration between users is evident by the multitude of interdisciplinary projects developed using think[box] resources.

Some projects created in think[box] move beyond the original physical object and develop into business ideas. These teams work with on-campus entrepreneurial programs and Cleveland community resources focused on business development. Sears think[box] and other innovation and entrepreneurship initiatives at Case Western Reserve have been instrumental in building the university's brand, reputation, and outreach as a leader in the field. This has been achieved by leveraging the assets of the university and region into a single comprehensive facility that is distinctive in its scope, scale, and access. At a university where over 75% of students arrive from outside Ohio, this entrepreneurship center is contributing to the region's "brain gain."

Case Western Reserve University's Sears think[box] Administrative Structure: Sears think[box] is administered by the Case School of Engineering, but is operated as an open campus and community center. This access is reflected in the collected metrics that show that 20% of think[box] users are from the surrounding community (defined as non-CWRU users). As an indication of broad impact, during the 2015-2016 academic year, Sears think[box] was visited 66,235 times by 4,150 unique users.

Sears think[box] is managed by a faculty member who is the Executive Director, an Outreach Director, a Manager, four full-time technical staff, and a Department Administrator. To support users on a day-to-day basis, think[box] also employs approximately 35 undergraduate students from CWRU and the neighboring Cleveland Institute of Art. Student employees are responsible for staffing the welcome desk and training users in operating laser cutters, 3D printers, and other machines. They are also responsible for maintenance of equipment, giving tours, operating higher-end 3D printers on behalf of users, and assisting with developing tutorials required for efficiently operating of the facility. At least three student employees are always present when the center is open (currently 63 hours per week on M, W & F 9:00 AM to 6:00 PM; T & TH 9:00 AM to 10:00 PM; Sat 10:00 AM to 4:00 PM; Sun 12:00 PM to 4:00 PM). Administration of the center is supported by a number of several software systems including YouCanBook Me, Trello, Slack, Google Drive, and Event-Board.

Case Western Reserve University's Sears think[box] Collaboration Activities: Collaboration is an important element of the center's DNA. This collaboration is apparent in the users' diverse projects and in the multitude of interactions and partnerships across campus and within the local community. Collaboration is even a design feature in the facility. The second floor of Sears think[box] is dedicated to collaboration with moveable furniture, whiteboards, multi-media collaboration workstations, hotel offices, and a conference room. This floor allows students to engage in team building exercises, run brainstorming sessions, develop pitch presentations, make rapid prototype visualizations of their ideas using craft materials, and collaborate remotely using tele-conferencing equipment. This space is also used for collaborative events including Hack-a-Thons, business pitch sessions, workshops, and networking receptions. CWRU hosts a chapter of Design for America (DFA) which is an extra-curricular design studio experience where students form interdisciplinary teams and work with local community partners to tackle pressing, real-world challenges. Teams work throughout the school year on projects that last anywhere between eight weeks to a year. Many of these projects involve interaction with think[box] at some level. DFA members collaborate with think[box] staff and students to manage the Collaboration Floor and currently are developing and teaching a range of design-related pop-up-classes open to the think[box] community.

Case Western Reserve University's Sears think[box] Collaboration Example: Sears think[box] recently obtained funding from the Fenn Educational Fund of the Cleveland Foundation to pilot an interdisciplinary ten week-long, full-time summer program for a small group of undergraduate students to work on industry-sponsored projects. Eight students covering the disciplines of Biomedical Engineering, Mechanical Engineering, and Electrical Engineering and Computer Science formed cross-disciplinary teams and worked on projects from six companies. Students were assigned to project groups based on their interest and experience. Contributing companies and the supported projects included:

- American Greetings: prototype a new product line for a global company
- Moen: develop the next generation showerhead
- Lincoln Electric: monitor temperatures close to the weld pool
- Lubrizol: design internet-of-things wearables
- METRO Health: create a pediatric chest tube insertion simulator
- Cuyahoga County: enhancing local community communication

Each project required students to iterate their design, produce prototypes, and validate their ideas using the full range of think[box] resources. During the program's ten weeks, the teams were mentored by DFA students who developed and ran short workshops to cover particular steps in the design/make process. This Sears think[box] pilot enabled students to collaborate on many levels, develop team building skills, practice project and time management, and use the full range of think[box] resources. This pilot project also helped think[box] management develop future initiatives involving a larger number of students.

Another example of cross-campus collaboration prompted by this academic makerspace is a partnership between Sears think[box] and CWRU LaunchNet, the university's support office for student startups. CWRU LaunchNet helps students turn their ideas into products and services. Students who engage with LaunchNet are encouraged to explore entrepreneurship as a complementary or alternative activity to traditional career paths. Sears think[box] provides the resources that allows these early entrepreneurs to develop prototypes to assess and validate their product ideas. A common phrase among these students is "think[box] makes – LaunchNet sells." To date over 50 student start-ups and commercialized research projects have benefitted from this close collaboration between these two organizations. These start-ups have raised over $5.7M from various funding sources.

Georgia Institute of Technology: Invention Studio

Georgia Institute of Technology Invention Studio Overview: In 2009, the Georgia Institute of Technology (Georgia Tech) recruited its first student volunteers to manage what would become the Invention Studio: a continually expanding, "student-run design-build-play space" open to all students [7]. Currently the Georgia Tech Invention Studio is a 6,000 square-foot state-of-the-art prototype fabrication facility used by 2,000 different students per month, with approximately 400 student entries each day. Each semester, 25 classes utilize the facility, and students may also use the space for personal projects. The facility is managed and maintained by an 80-member undergraduate student organization. Equipment valued at $1M includes 3D printers, laser cutters, waterjet cutter, injection molding, thermoforming, milling, and others, along with a lounge, meeting, assembly, and testing space. Over 30 companies have donated to build and support the facility through the Invention Studio's connection to the Capstone Design Course.

The Studio is free-to-use and is accessible 24/7. It is a multidisciplinary endeavor, staffed and utilized by students from the colleges of engineering, sciences, and architecture. The Invention Studio seeks to (1) provide students with free access to hands-on, state-of-the-art prototyping technologies; (2) serve as a cultural hub and meeting ground; (3) bolster design within curricula and as an extra-curricular activity; (4) encourage collaboration between diverse teams of students from all years and majors; (5) welcome all types of projects, personal and professional; (6) excite students for careers involving creativity, design, innovation, and invention; (7) enable students to tackle open-ended, real world challenges; and (8) to serve as an exhibit and tour space to enhance the university's ability to recruit top students and showcase student work through local, national, and international news outlets [8].

As a physical, intellectual and practice space, the Invention Studio engenders all aspects of a community of practice. As such, it has the potential to support situated learning through participation in the life and activities of the maker community. In this way, the Invention Studio serves as a significant conduit for learning.

The most unique aspects of the Invention Studio as compared to similar university and community maker spaces are as follows: primarily student-run and "owned"; accessible 24/7 for students who run it, daytime hours for all users; lacking restrictions on the types of projects (for example, personal art projects are as welcome as course requirements); free-to-use (with a few caveats for research); state-of-the-art and comprehensively equipped; intimately linked to the curriculum; and centrally located on campus.

Georgia Tech Invention Studio Administrative Structure: A student club, historically called the Makers Club, "owns" and runs the space. The club has approximately 80 volunteer members, comprised of undergraduates from a diverse set of majors and years. Students in the Makers Club agree to staff the Invention Studio for three hours per week in exchange for 24-hour keycard access to the space. During this "shift" the Makers Club member on duty is called a Prototyping Instructor (PI) and wears an identifiable arm band. While on duty, PI's help their peers learn equipment, supervise safety, maintain equipment and the lab space, learn and advise about a wide variety of design and manufacturing tools, build their resumes with skills, and gain leadership experience. Around the clock access is a valued reward for these students and leads to weekend-long hacking sessions involving everything from pumpkin carving to Battlebot building.

The Makers Club has spending authority on social activities, tooling repair and maintenance, and expansion of the equipment and space layout. In consultation with faculty and staff advisors, their needs are considered in major proposals and plans.

The club is led by a President, Vice President, Secretary, and Director of Programs elected annually each spring. In addition, "Masters" for each major class of equipment are elected. These are PI's tasked with becoming domain experts on a particular class of Invention Studio equipment (e.g., laser cutter, waterjet, or CNC mill). They are ultimately responsible for upkeep and training other students on their respective machines. While the officers meet each week to manage day to day concerns, there is only one mandatory PI meeting per month. The Studio is staffed 10 AM to 6 PM during the week and there are approximately five PI's on duty at any time. Staffing accountability is ensured by identification card scanning to enter and exit the space. While machine specific training occurs on-demand by on-duty staff, there is an additional weekly event known as Makers Mondays to introduce new students to the Invention Studio and maker community. These meetings generally begin with an introduction to the Invention Studio and might also include project presentations, guest speakers, or specialized training on the machines.

The students are peripherally supported, but not managed or overseen, in their mission by several paid university staff. These personnel and the percentage of their time dedicated to supporting the Invention Studio is as follows: technician who performs complex machine tool repair (50% time) and assists research faculty with cost-reimbursable jobs in support of the university's research mission (50% time); machine shop professional who runs an adjacent professional university shop assists with training on the most complex machine tools (20% time); academic professional who interfaces between the Makers Club and university staff regarding major initiatives such as equipment moving, electrical and pneumatic supply installation, and budgeting (10% time), in cooperation with the facilities, marketing, communications functions of the university; administrative assistant who purchases materials requested by the Makers Club, supports the communications and marketing staff, and coordinates large event logistics (20% time); faculty advisor who assists the Makers Club with its vision and fundraising (3% time).

Georgia Tech Invention Studio Campus Collaboration Activities: The success of the Invention Studio has led to its involvement in various campus outreach activities such as freshmen orientation (where all incoming freshmen in this orientation program visit the Invention Studio) and daily guided tours (for parents and prospective students, industry representatives, alumni and their families, groups of grammar school students, high school science clubs, summer science camps, "parents day" visitors, visiting professors, and other students) ranging in size from 1-50 persons.

As another example of impact, the Invention Studio's vital role to provide campus-wide support was leveraged as part of a funded $7.3M NSF-funded Math and Science Partnership grant at Georgia Tech entitled Advanced Manufacturing and Prototyping Integrated to Unlock Potential (AMP-IT-UP). AMP-IT-UP is led by the Georgia Tech School of Mechanical Engineering, in close collaboration with Georgia Tech's Center for Education Integrating Science Mathematics and Computing (CEISMC). While AMP-IT-UP is primarily aimed at developing hands-on engineering curricula for middle and high school classrooms, the grant includes an annual "Makers Summer Camp" at Georgia Tech as well as the implementation of junior Makers Clubs at partnering middle and high schools.

In 2013, the first Makers Camp was held in the Georgia Tech Invention Studio. In its first implementation, 24 high school students (rising 10^{th}-12^{th} graders) were hosted for a week. Members of the Makers Club developed the curriculum for the camp, which included laser-cut nametags, quad-copters, and racquetball launchers. Makers Club members also staffed the camp, providing on-the-spot training and safety supervision.

Georgia Tech Invention Studio Campus Collaboration Example: The students' ownership of the space has led to unexpected, wonderful cultural roots, and spontaneous initiatives. For example, students regularly run evening workshops on topics such as microcontroller programming, motorized scooter design, welding, stained glass window making, book binding, knitting, and other technology-associated areas. The students write the curriculum and operate the courses for free or for a minimal fee to cover material costs. The workshops are one example of the Makers Club wide impact across Georgia Tech.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY: MAKERLODGE FRESHMAN TRAINING PROGRAM AND PEER MENTOR MAKERSPACE

MIT MakerLodge Overview: MIT has a large number of academic makerspaces in addition to traditional machine shops and research labs. One of the MIT makerspaces is the subject of this paper. The MIT MakerLodge, shown in Figure 1, is a student peer mentoring and training makerspace [9].

The MakerLodge was created to support annual training of the 1,100 MIT freshmen that want to learn about maker tools, techniques, and safety. At MIT, students do not declare a major until they become sophomores, and so the MakerLodge does not serve a department or school and is a campus-wide makerspace. The MakerLodge consists of two rooms, which sum to a total of 850 square-feet. One contains fabrication tools while the other contains a space for textile and vinyl work as well as a collaboration and lounge space for the volunteer student mentors who deliver the training.

MIT MakerLodge Administrative Structure: To help coordinate maker-related activities at MIT, an organization known as Project Manus was created by the Provost. MakerLodge is one of the programs developed by that team. The MakerLodge is administered via a collaborative relationship between Project Manus staff (Prof. Martin Culpepper, Mr. Jonathan Hunt, and Mr. Ike Feitler) and nearly forty student volunteer mentors [10]. During the space's design and creation process, the staff and volunteer mentors came together to create policies and a culture for the space that was amenable to both sides. The students are empowered to purchase, schedule trainings, hold social events, make improvements to the space, and conduct the training of the freshmen. The staff conduct the final testing and certification of the freshmen and record their credentials in Mobius, an institute-wide information management system that helps members of the MIT community navigate the vast array of making resources available on campus. Student mentors volunteer 3-5 hours per week to train their peers in exchange for their own social space, funded social events, access to other facilities on campus, and 24/7 access to the MakerLodge for their personal making.

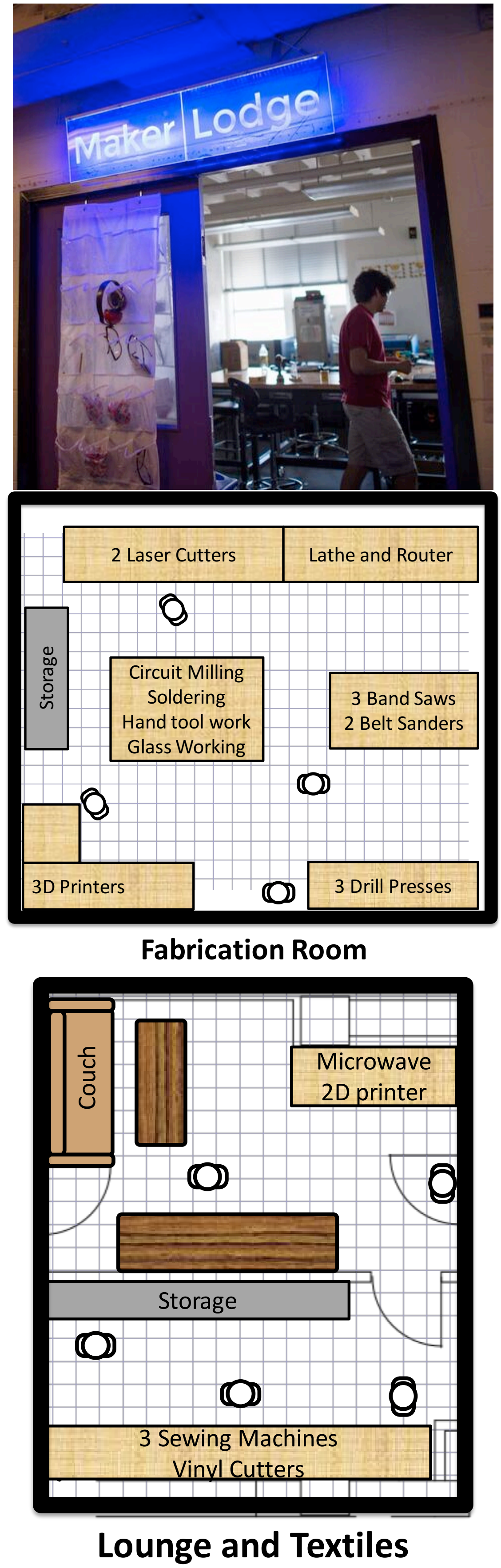

Figure 1. MIT Freshman Training Facility.

MIT MakerLodge Campus Collaboration Activities: MIT created the Mobius Maker App via a collaboration between students, the administration, alumni, the Office of Environmental Health and Safety, facility managers, and other stake holders at MIT [11]. The app, shown in Figure 2, was created to address several barriers that dampened the speed of student access to maker tools and facilities. Specifically, the app enables students to search and find machines anywhere on campus, navigate the 40+ spaces where equipment is accessible, understand their entry requirements for each space, store their training credentials so that they have a trusted means of demonstrating their competency, and make payments for any use or material using their student maker account (MIT Makerbucks) or with a credit card. The app also enables facility managers to manage their machines, financial accounts, and have more information about students. The latter enables managers to make better and faster decisions such as how much training and oversight is needed for unfamiliar students, and this reduces time for both student and facility managers.

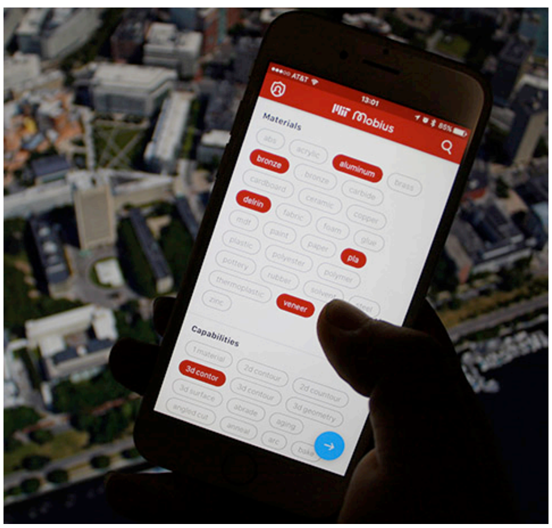

Figure 2. Mobius App for MIT's makers and makersystem management.

The features of Mobius, and the database it runs on, enable different campus stake holders to have access to information they may use to make individual and joint decisions. It also provides a database that is trusted by all users, thereby fostering information-based decision making and fact-based decisions.

MIT MakerLodge Campus Collaboration Example: Prior to the creation of MakerLodge, freshmen were finding it increasingly difficult to get access to maker facilities at MIT, primarily because: (i) MIT's training facilities are unable to train hundreds of freshmen each year due to growing training demands from other populations and increasing enrollment, and (ii) many design/build/makerspaces at MIT reside within academic departments and are prioritized for use by students in those majors. Because freshmen do not belong to any major, their access to training and spaces was becoming a significant barrier to the MIT's 'mens et manus' or 'mind and hand' learning experience. MIT's Project Manus was tasked with leading the effort to solve this issue.

The first step was to gather data that enabled all parties to understand the scope of the problem and define constraints on the problem. Training all MIT freshmen in general maker technology (3D printers, laser cutter, lathe, mill, band saw, drill press, and sewing machine) was estimated at requiring 11.3 person years. If all 40+ MIT design/build spaces were closed and only used for training all day long, it would take more than a semester to train all the freshmen. This led to a cost/benefits analysis (evaluating the 'bang for the buck') with respect to maker-tools. Based on this analysis, it was discovered that over 600 freshmen could be trained in the first semester if that training focused on four types of 3D printers and two types of laser cutters that are found in most of MIT's design/build spaces. Project Manus managed a collaboration process between the stakeholders in Figure 3 to implement all aspects of this training, qualification, and certification system. Stake holders were recruited by emphasizing the benefits to the students first and subsequently the benefits to the stake holders themselves.

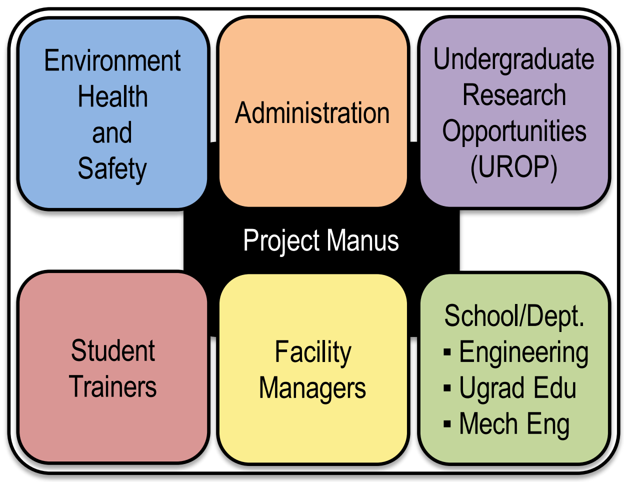

Figure 3. Stakeholders brought together to draft and support the MakerLodge Program.

The resulting training, competency testing and certification process administered through the Makerlodge, students receive the following:

- Tool box ($7/student) and set of tools ($18/student for wrenches, screw drivers, hammer, and other hand tools)
- Arduino micro-controller ($13/per student)
- $100 value awarded in Makerbucks (to spend via Mobius on materials and machine time)
- Mobius-recorded training credentials to show to facility managers to verify student machine competency and gain entry to a design/build space
- Ability to access 12 MIT maker facilities (Figure 4)
- Ability to join a freshman maker community that provides social events, maker events, general life and class support at one of the 12 MIT maker facilities [12]

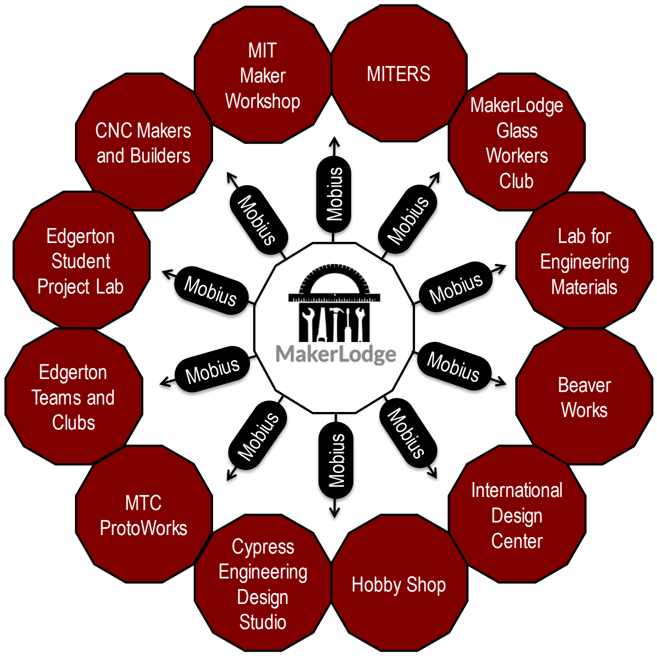

Figure 4. Collaborative network of facilities that accept freshmen graduates of the MakerLodge Training Program and Mobius' role in facilitating student 'flow' between these facilities.

The MakerLodge Program, including the training, qualification, and certification components benefits many groups at MIT. From the School and Department perspectives, students are better trained and more fully capable in participating in early (freshman and sophomore level) hands-on education activities. This increases the programs' abilities to offer more advanced courses that focus on real world problems. The student mentors benefit from the skills they refine while teaching their peers, as well as 24/7 access to the space in return for their volunteer instruction. The resulting system has great value for MIT's administration as it addresses students' expectations of the 'mens et manus' experience they came to campus for.

The training workload for the facility managers has decreased with the centralized process, enabling more time to teach and assist students with more advanced needs. The verifiable training credential system reduces concerns associated with new users and helps customize additional oversight and training. Lab-based research programs have also benefitted from the initiative as students are better prepared to design and build experiments and equipment within these labs. Also, the MIT Office of Environmental Health and Safety (EHS) now has a standardized training program that enables a greater number of students to receive general safety training. As MakerLodge is in its first semester, data is currently being collected to measure the program's impact on many facets of the educational experience, and to document the benefits to the stakeholders.

This project required significant levels of collaboration from a large number of individuals and organizations to frame the program, raise the money ($550,000), obtain space (850 square-feet), obtain buy in from facility managers, gain approval from EHS, and recruit the student mentors. These steps were accomplished in a total of four days. This success demonstrates the power of using analysis, gathering stake holders, and utilizing trusted platforms and relationships to create new systems. The role of a maker advocate (Project Manus) was also key to managing this collaboration. The MakerLodge was constructed, staffed, and prepared during the summer of 2016 and is currently running its first year of training for MIT freshmen at a rate of 50 students/week. In the spring, students will be trained at a similar rate on the other technologies (including, for example, glass working, CNC routing, band saw, drill press, and other machine tools) indicated in Figure 1.

STANFORD UNIVERSITY: PRODUCT REALIZATION LAB (PRL)

Stanford PRL Overview: The Stanford Product Realization Lab (PRL) is the largest teaching lab and academic makerspace at Stanford University, and has been a part of the university since its founding 125 years ago [13, 14]. During the past 40 years, under the leadership of Professor David Beach, the Lab has evolved from its role as the Mechanical Engineering Student Shops, serving 100 Mechanical Engineering students a year, to the Product Realization Lab, a collaborative community focused on learning through making, with over 1,100 active student members per year. The PRL is open to all Stanford students, who may use PRL resources to support coursework, research, and personal projects. Faculty and staff may also use the lab for work that supports the teaching mission of the university. PRL members come from all parts of campus: currently, 50% are undergraduates, 47% are graduate students, and 3% are faculty and staff. 25% of the Lab's members come from non-engineering fields such as Art or Biology, 45% are students in the core Mechanical Engineering/Product Design majors, and the remaining 30% are engineers from other fields, such as Computer Science or Civil Engineering. Approximately 60% of students are male and 40% are female, which aligns with the ratio of undergraduate and graduate students at Stanford. After completing a brief safety orientation, students pay a small fee ($100 per year) for a lab membership pass. This small fee encourages a sense of ownership and belonging, and covers many of the consumable materials and tools that the lab supplies.

The PRL spans approximately 9,000 square-feet with six distinct lab areas: machining, woodworking, foundry, welding, plastics, and rapid prototyping. Professional and industrial-scale and quality equipment supports student work. Open collaborative work space is found in Room 36, the rapid prototyping lab, where wheeled furniture and equipment can be reorganized as needed. A skilled and trained staff of 18-20 graduate-level Teaching Assistants (TAs) support and mentor students during open work sessions in each of the PRL lab areas. Faculty from across the university collaborate with the PRL to develop appropriate curriculum for their students. Students in courses that do not traditionally have a physical design or engineering focus, such as Archaeology, Civil Engineering, and Writing, can have powerful hands-on experiences enabled by the Product Realization Lab which magnify the learning impact of their coursework.

Stanford PRL Administrative Structure: The PRL operates under the auspices of the Mechanical Engineering Department in the School of Engineering, yet welcomes students from all disciplines and levels across the campus. The Lab currently has two co-directors (a Teaching Professor and a Senior Lecturer) and an associate director (Lecturer), who teach design and manufacturing courses, develop new curriculum, and direct PRL activities and staff. A Program Administrator and an Outreach Strategist provide support for and promote the lab's activities. Most significantly, the PRL is staffed by a team of 18-20 graduate student TAs who mentor PRL students and provide a structured, safe working environment. Applications for these highly sought-after positions (there are typically about 40 applicants for the 10 open positions each year) come from graduate students in several disciples, typically Mechanical Engineering and Product Design, with some from Civil Engineering and the Graduate School of Business.

Each of the TAs has extensive prototyping, design, and manufacturing experience in the PRL or a similar environment. Prior to the start of the academic year, the TAs engage in two weeks of training which prepare them to teach and mentor students. This large team of welcoming and encouraging Teaching Assistants is crucial to promoting the vibrant, collaborative learning environment and culture of the Product Realization Lab. The TAs teach the safe and effective use of equipment and provide design mentorship in each of the PRL's six areas in four-hour sessions (8:30 AM to 12:30 PM, 1:30 to 5:30 PM, and 7:00 to 11:00 PM) Monday through Saturday. A required, in-person, hour-long safety orientation begins the process of building the awareness and skill set needed to work in a new and challenging environment. The safety orientation and TA staffing model minimizes barriers to entry and ensures that the PRL is accessible to all Stanford students.

Stanford PRL Campus Collaboration Activities: Although the Product Realization Lab is primarily a teaching lab supporting coursework, exploration and personal work are highly encouraged. The PRL team is passionate about engaging new students, and sharing the joy that develops through physical learning. When a faculty member approaches the PRL team with an idea about how to incorporate some form of physical making into their course, PRL faculty help to develop content that will be the most relevant to those students and their work. Flexibility of workshop content and structure is critical to engaging the interest of new students in disciplines that might not typically find themselves in the PRL. By offering instructional, hands-on workshops with a specific teaching goal in mind, the PRL team reaches new groups of students and helps to support their learning. Workshops range from brief, low resolution prototyping exercises with simple tools and materials to more structured, design and process-oriented learning opportunities, such as how to design for and use a laser cutter to build the small-scale wheeled robotics platforms that are a common element in several engineering courses.

Product Realization Lab faculty reach beyond the walls of the PRL to collaborate with other instructors and organizations. Professor Beach has been a core member of the teaching team for "Design for Extreme Affordability," a course that is a partnership between the Stanford d. school and the Graduate School of Business. Students in the class work with international organizations to develop products and services that improve the lives of under-resourced populations around the world. Prototypes of products such as the Embrace infant warmer, the Miraclefeet clubfoot brace, and d.light solar lighting were developed in the PRL with the support and coaching of Professor Beach and the PRL TAs. Additionally, Professor Beach participates in the Stanford Summer Engineering Academy (SSEA), a program of the School of Engineering Diversity Affairs group that engages under-represented minorities in the summer before their freshman year. While these students have not yet declared majors, the program aims to help them build confidence in their ability to pursue an engineering major. PRL faculty also collaborate with colleagues from the within the Mechanical Engineering Design Group to host annual executive education courses that teach the Stanford approach to applying design thinking and creativity to business innovation.

Stanford PRL Campus Collaboration Examples: Professor Hideo Mabuchi, chair of the Applied Physics Department, was interested in creating an experimental ceramics firing system that would allow for flexible fuel and ash modulation. He wanted to develop new courses that would allow students to explore the integration of ceramics craft with the study of clay and glaze chemistry and physics, evaluated with modern tools such as electron microscopy. Professor Mabuchi and PRL Co-Director Craig Milroy developed and built the firing equipment, which made possible new Applied Physics and Art courses and provided new students with a novel experience. Professor Mabuchi also hosted ceramics workshops for other students at the PRL using the equipment, giving engineering students the opportunity to explore craft and aesthetic traditions.

Dr. Gabrielle Moyer, a lecturer in Stanford's undergraduate Program in Writing and Rhetoric (PWR), teaches a course, "Archi-texts: Building Rhetorically," which includes texts that feature space and environments. She wanted to augment the students' written work with a requirement to create physical representations of the metaphorical environments in their reading. Through a hands-on prototyping workshop in the PRL, the students learned to give physical form to their interpretation of ideas and concepts. Physically transforming materials transforms students and education.

Students in Professor Justin Leidwanger's Archaeology course "Engineering the Roman Empire" joined the PRL community to learn how to design and build examples of the

Roman engineering devices they were studying. The experience of building models of military devices and engineering feats like aqueducts engaged the students more deeply in their understanding of the scale and complexity of the Roman's work. Making something physical and real in the PRL transcends conceptual awareness.

The Product Realization Lab creates educational opportunities beyond purely theoretical learning and thinking. The openness of the PRL ensures that a broad community of students will converge and share knowledge and forge common experiences that endure beyond those students' time at Stanford. This interdisciplinary collaboration between faculty and students provides diverse perspectives and enriches learning. Every student can be an agent of change, and at the Stanford Product Realization Lab, they can explore new skills and ways of learning to find this self-confidence. Joel Dillon said of his experiences in the PRL: "A lightbulb came on. Not only did I see the world around me in a different way, but I also realized that I'm one of those people that can change the world."

University of California, Berkeley: Jacobs Institute for Design Innovation

UC Berkeley Jacobs Institute for Design Innovation Overview: Opened in fall 2015 and based in UC Berkeley's College of Engineering, Jacobs Hall (home of the Jacobs Institute for Design Innovation) is a 24,000-square-foot building that serves as an interdisciplinary hub for learning and making at the intersection of design and technology (see Figure 5). Integrating flexible, open studios with a wide range of workshops and equipment labs, the building functions as both an academic building and a community space. Three design studios (two with a capacity of 45, and one with a capacity of 130) provide teaching space, as well as space for a range of learning formats and programs. On the building's first floor, an "all-purpose makerspace" serves as a point of entry for users, with drop-in workspace as well as accessible tools like consumer-grade 3D printers, laser-cutters, and basic hand tools (see Figure 6). More specialized labs, nestled throughout the other three floors of the building, complement this space and collectively unite a variety of making practices under one roof: these labs include a CAD/CAM computer lab, wood shop, metal fabrication shop, electronics lab, AV production lab, and advanced prototyping lab. As a whole, the range of equipment in the building reflects the institute's view of the "21st-century workshop" as integrating digital fabrication tools, programmable electronics, and powerful design software [15].

Figure 5. Jacobs Hall at UC Berkeley opened in August 2015.

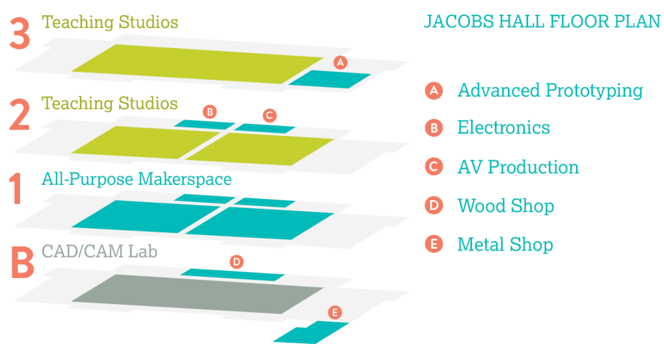

Figure 6. Jacobs Hall combines makerspaces and instructional studios in 24,000 square-feet. Some equipment is separated by function, which allows fine-grained access control.

A cross-campus hub, Jacobs Hall is open to all Berkeley students, staff, and faculty. The building supports multiple learning modes, including drop-in makerspace and lab access, academic courses, and a range of informal learning and community programs (see Figure 7). Through a pass, termed the Maker Pass and issued one semester at a time, any UC Berkeley student staff member, or faculty member can access Jacobs Hall's workspace, labs, and equipment on a drop-in basis (with payment of a small fee and completion of training); for the fall 2016 semester, for example, approximately 750 people hold an active Maker Pass. Roughly 20 academic courses take place in Jacobs Hall's teaching studios each semester, representing both interdisciplinary design courses developed by the Jacobs Institute (focused on core design skills and team-based projects, and open to students from all majors) and design-related curriculum offered by a range of departments (see Figure 8). Beyond the classroom, Jacobs Hall supports an active mix of learning formats and community programs, including student-led classes, regular meetings of student organizations, hands-on workshops, fellowship and student artist residency programs, talks from invited speakers, and other activities.

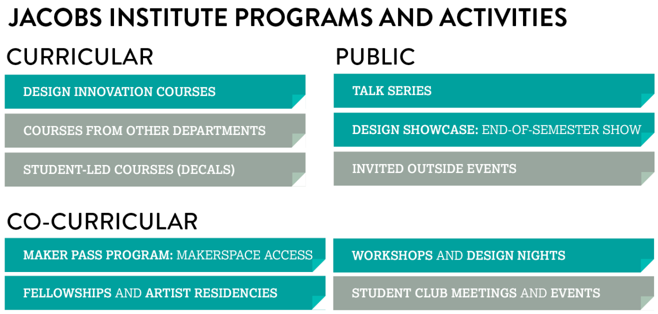

Figure 7. UC Berkeley's Jacobs Institute offers courses and other co-curricular and public events in addition to makerspace access.

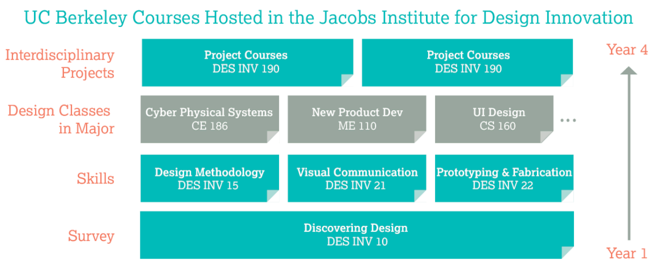

Figure 8. A variety of courses use the makerspaces in Jacobs Hall. DES INV courses shown here (Design Innovation) are offered by the institute; other courses are offered by departments across the university.

UC Berkeley Jacobs Institute for Design Innovation Administrative Structure: While the Jacobs Institute serves campus community members from all fields, it is administered by the College of Engineering, reporting to the Dean of the College. The institute works with members of departments both within and beyond the College of Engineering to infuse design into curricula and programs. Two faculty members from the College of Engineering currently lead the institute as faculty director and chief learning officer, respectively. Working closely with this faculty leadership, the institute's director of programs and operations leads a professional staff comprised of four program staff members (who work in areas such as academic affairs, student services, events, communications, and administration), and a technical team. For the technical team, a technical lab lead directs five design specialists (a mix of full-time and part-time employees). Collectively bringing both technical expertise and a diverse mix of creative backgrounds to Jacobs Hall, these design specialists develop and provide equipment trainings, support facility and program needs, and serve as in-house guides and mentors for the Jacobs Hall community. Finally, a team of undergraduate student supervisors support operations in Jacobs Hall and help manage access and safety during the building's evening hours (currently until 11 PM on weeknights).

The institute's leadership receives further input from key groups on and off campus. The faculty director's council is made up of tenure-track and tenured faculty with significant expertise in design education and meets monthly. They provide a sounding board for major initiatives and also help champion and lead individual projects. Complementing this faculty council, the institute's industrial advisory board brings external expertise to conversations with institute and College leadership, offering bi-annual input on strategies and opportunities. In addition, the institute has started to hold workshops with leaders of other design and innovation programs in higher education in the area.

UC Berkeley Jacobs Institute for Design Innovation Campus Collaboration Activities: From the planning stages of the Jacobs Institute, campus collaboration has been a priority. Jacobs Hall is open to users from across campus. The Maker Pass system is integrated with campus-wide systems like door access readers and Berkeley's learning management system for delivering safety training.

As Jacobs Hall was being designed and constructed, the institute's team met with lab managers and shop staff across the College of Engineering to identify opportunities for a larger "fabrication lab network" that would better connect the various shops and labs within the College of Engineering. As a first success of this planning, fall 2016 saw the introduction of a joint Maker Pass that opens access both to Jacobs Hall and to the neighboring CITRIS Invention Lab, a precursor to Jacobs Hall. In addition to better facilitating access, this joint pass also opens new opportunities for cross-pollination between Jacobs Hall's core undergraduate community and the researchers and startup teams who use the Invention Lab.

Campus collaboration has also been central to the Jacobs Institute's curricular efforts. The Jacobs Institute and the College of Engineering recently joined with three other Colleges (Environmental Design, Letters and Sciences, and Business) at UC Berkeley to create a campus-wide certificate in design innovation for undergraduates. The certificate will offer students a structured way to get introduced to design, gain several concrete design skills, and put them to practice in interdisciplinary project-based classes.

The Institute's own Design Innovation courses are open to students from all majors without disciplinary prerequisites. In its initial year, just over 50% of students in these courses came from outside the College of Engineering. In addition, the institute has worked to catalyze and support design-infused courses in a range of departments, for example through a course grant program.

UC Berkeley Jacobs Institute for Design Innovation Campus Collaboration Example: Each semester, the institute opens an application to hold courses in Jacobs Hall, welcoming faculty from all departments to propose courses to take place in the building's teaching studios. This initiative has led faculty in wide-ranging fields to develop new courses, or to reimagine syllabi, in response to the space and its resources for hands-on learning. Recent courses developed in concert with these efforts include Bio-Inspired Design, a lower-division integrative biology course; Sustainable Residential Design, a joint civil engineering/architecture course; and interdisciplinary project courses focuses on reimagining slums and reimagining the future of mobility. Seventeen new and updated courses were developed in advance of the building's opening, and other new courses continue to emerge. In the spirit of experimentation, the lineup of courses in the building evolves from term to term, allowing for broader faculty use and continuous learning. This has contributed to a richly interdisciplinary educational community at Jacobs Hall, bringing diverse voices into contact and more closely connecting Berkeley's cross-campus academic strengths with the processes and skills that help drive design innovation.

YALE UNIVERSITY: CENTER FOR ENGINEERING INNOVATION AND DESIGN (CEID)

Yale CEID Overview: The Yale Center for Engineering Innovation and Design (CEID) supports a spectrum of design and innovation activities for all components of Yale. The center consists of four types of defined areas: lecture and collaboration space, a design studio, workshops and a wet lab, and meeting rooms and offices. All activities and the associated work areas are contained within a contagious 9,000 square-foot footprint. Other than the largest pieces of equipment (CNC mills, lathes, and router), everything is on wheels to enable the space to be easily configured to best support projects and programs. There is a high degree of visual porosity between adjoining spaces – a design feature that facilitates collaboration and a sense of openness (in the overall design and as a CEID personality trait). For example, the separation between the lecture area and the design studio is a row of worktables (as opposed to a solid wall). The absence of physical boundaries invites the free and open exchange of knowledge, experience, and advice among users within the space [16, 17].

The Yale CEID is available to all students (undergraduate and graduate), faculty, and research staff at Yale. Individuals are provided with 24/7 access to the facility once they complete an on-line training module, pass a test on the presented material, and attend a facility orientation and safety presentation conducted within the CEID. Completion of these steps allows the trained person to become a "member" of the CEID, thereby providing access to the facility and its programs. Approximately 2,000 individuals at Yale are members of the CEID with the distribution being 40% undergraduate students, 25% faculty and staff, and 15% graduate students. The undergraduate membership includes 47% science, engineering, and math majors, 23% social studies and humanities majors, and 30% undeclared majors (typically freshmen and sophomores who have yet to specify their major). 56% of all members are male 44% are female.

The accessibility of the CEID to all individuals at Yale is an important factor that promotes campus collaboration within this higher education makerspace. With the space designed to promote interactions between users and an active campus-wide membership structure, the Yale CEID is structured to advance collaboration among its community of users. Members of the Yale CEID can use the facility for any purpose including work related to a course, research, entrepreneurial activity, student club, or a personal project. This openness in use, combined with the openness in access, help create a vibrant, multi-disciplinary, collaborative entity that reflects the diversity of interests and programs at Yale.

Yale CEID Administrative Structure: While the Yale CEID serves the entire campus at Yale, it is administered by the Yale School of Engineering & Applied Science. The center was created, in part, to promote collaboration between engineering and other programs on campus, as well as serve the design, fabrication and testing needs of Yale's engineering community. The center has a director, assistant director, and design mentor (all having an engineering or physics Ph.D.), as well as two design fellows. The design fellowships are two-year positions for recent college graduates where the fellows devote 80% of their work time to CIED operational items (such as equipment maintenance and training) and 20% of their work time to their own design interests.

Augmenting this work force are eight (undergraduate) student design aides who work part time in the CEID to provide peer-to-peer instruction and oversight (and other duties to keep the CEID functioning). Staff members are generally available Monday through Fridays 10 AM to 6 PM, with the student aides on duty from 6 PM to 9 PM, seven days of the week. Student aides are also assigned during the day on Saturday and Sunday. The staffing model is another important contributor to promote campus collaboration as the staff provides instruction, training, and guidance to all members of the Yale CEID community. This instruction is essential to engage users who do not have experience in design and fabrication but have a desire to design and fabricate projects related to their discipline and personal interests.

Yale CEID Campus Collaboration Activities: In addition to the CEID's space arrangement, membership model, and staffing support, a matrix of programs delivered within the CEID also contributes to the center's ability to engage a wide audience of users from across campus. The activities include specific programs in three domains (denoted as learn, make, and share) that span from informal sessions to formal meetings. As presented in Figure 9, the "learn" programs include informal workshops, documented training sessions, and formal courses that award college credit. Weekly evening workshops are hosted by CEID members (students, faculty, or staff) on a range of topics such as analog circuits, internal combustion engines, and chocolate-making, for example. The workshops introduce these technologies to members who have no background in the topic area. As such, the workshops serve as an entry point to new technologies for many of the participants. As evening activities, they are structured to be informal, content-heavy, hands-on, learning sessions.

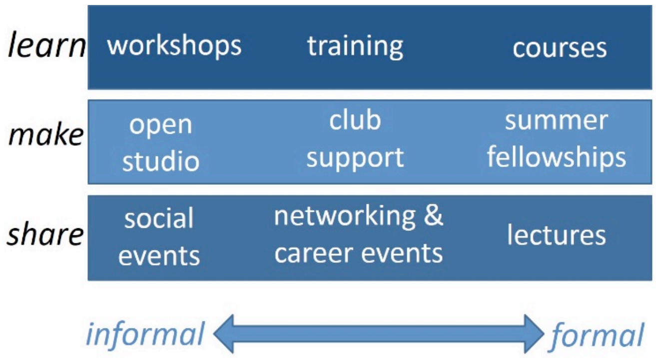

Figure 9. Programs offered within the Yale Center for Engineering Innovation and Design.

Equipment and machine tool training held within the Yale CEID is an example of a program offering between the informal workshops and formal courses. This training certifies members to use tools and equipment in the CEID, with the amount of training proportional to the skill and safety-awareness required by each machine tool and piece of equipment. The most formal "learn" program components are design courses that are held in the Yale CEID. Here, students enroll in semester-long design courses that focus on a specific topic such as sustainable design, introductory design, and medical device design [18]. Each course includes lecture, skills-training, and a topic-related design project.

Similar activities spanning the informal to formal spectrum are provided at the Yale CEID that align with "make" and "share" dimensions of this programmatic model. This matrix of activities provides a wide and varied coverage of topics and content, and has been intentionally designed as a tool to engage a wide and varied audience of participants from across Yale's campus.

Yale CEID Campus Collaboration Example: The Yale CEID course "Musical Acoustics and Instrument Design" resulted from, and now itself promotes, campus collaboration. The course was motivated by a workshop initially presented by a student member of the CEID where participants designed and fabricated their own flutes. The first segment of the workshop included a theoretical discussion on the physics of sound within a flute, followed by the fabrication component that was completed using a laser cutter.

Based on this workshop, a CEID design faculty member (Ph.D. in Physics) partnered with a faculty member in the Department of Music (Ph.D. in Music). This partnership between a physicist and a musician, composer, and programmer created a talented instructional team that presented the acoustical theory of wind, percussion, and string instruments, as well as electronic sound systems. Acoustics theory was augmented with hands-on skill development using manufacturing tools and equipment within the CEID where students constructed a form of each instrument presented in the course's lecture component.

The course culminated in a project where each student designed and constructed their own unique and original musical instrument. Examples of the constructed instruments include a horizontal guitar that required two musicians to simultaneously play, an electronic violin and cello (where motors and sensors generated signals that drove musical interface digital interface (MIDI) synthesizers), and a device that generated sound from fluid-level-tuned rotating wine glasses. The course brought together not only students majoring in engineering, physics, and music, but also students from a variety of other majors who were interested (and even talented) in engineering, physics, and music. As one example of the course's impact, the Department of Music faculty member now holds weekly "office hours" in the Yale CEID where his students and other members of the CEID community gather to explore musical projects involving technology and fabrication. Such interactions are individual threads in a diverse tapestry of participants and interests that have been created within the Yale Center for Engineering Innovation and Design.

VALUE OF CAMPUS COLLABORATION FOR HIGHER EDUCATION MAKERSPACES

The presented examples illustrate a number of benefits of campus-wide collaborations including developing new facilities and training methodologies to meet student making-needs. In the case studies from CMU and MIT, a number of offices from across the university and institute were linked together through makerspace activities. The connections were nearly instantaneous and the results nearly immediate, thanks in part to each groups' prior experience and application of analysis to make decisions. Figure 10 details some of the characteristics of the higher education makerspaces reported in this paper.

The value of campus collaboration related to higher education makerspaces with regards to curricular developments was illustrated in the case studies from UC Berkeley and Yale. For each of these institutions, the makerspace serves as a catalyst for partnerships between academic departments that may not have otherwise been established. The benefits of augmenting traditional lecture courses, in engineering and other disciplines, occurred in a number of instances at Stanford's Product Realization Lab. For these examples, the practice of physically transforming materials to augment learning transformed the education process across campus.

The value of collaboration for grant proposals was highlighted in the work detailed at Georgia Tech where a collection of departments and programs partnered to apply the lessons learned from the Invention Studio to K-12 programs. This example also illustrates an additional benefit of high-impact higher education makerspaces: serving as role models for similar spaces in middle and high schools. At Case Western Reserve University partnerships on a number of levels have been formed to facilitate entrepreneurial activates. These partnerships included working with other CWRU offices, philanthropic organizations, and corporations.

	Institutional Home	Size (sq-ft)	Membership	Type
CMU IDeATe	University Libraries	10,000	1,800	Community + Project/Courses
Case Western think[box]	School of Engineering	50,000	4,150	Community
Georgia Tech Invention Studio	Student-run Makers Club	6,000	2,000	Community + Project/Courses
MIT Maker Lodge	Project Manus and MIT Innovation Initiative	850	1,100	Community
Stanford PRL	Department of Mechanical Engineering	9,000	1,100	Community + Project/Courses
UC Berkeley Jacobs Institute	College of Engineering	24,000	2,600	Community + Project/Courses
Yale CEID	School of Engineering & Applied Science	9,000	2,000	Community + Project/Courses

	Staffing					Hours
	undergrad students	graduate students	academic	technician	administrative	
CMU IDeATe	13			10		24/7
Case Western think[box]	35		1	5	2	MWF 9am - 6pm, TR 9am - 10pm, Sa 10a - 4pm, Su 12pm-4pm
Georgia Tech Invention Studio	80			5		24/7
MIT Maker Lodge	40	1	1	1	2	24/7
Stanford PRL		18	4		2	M-F 8:30am - 11:00pm, Sat 8:30-5:30pm
UC Berkeley Jacobs Institute	11		2	11		M-F 8:00am - 11:00pm, Sat 12-6pm
Yale CEID	8		4.5			24/7 (staffed 10 am – 9 pm)

Figure 10. Institutional characteristics of higher education makerspaces.

The speed, scope, and overall impact of the resulting campus collaborations associated with higher education makerspaces reflects common characteristics of makerspace communities. Makerspaces promote focused problem solving using a variety of resources. For any particular problem, if the resources are not immediately available, they are obtained or alternatives are selected to keep the project moving forward. Innovation is another common characteristic among makerspace members, and the presented collaboration examples illustrate how those innovative skills can be applied to a wide array of problems. Collectively these examples illustrate how higher education makerspaces have been able to make immediate and important contributions to establish a culture of collaboration within each institution.

Acknowledgement: Laura Mitchell, Communications and Program Office for the Jacobs Institute for Design Innovation assisted with that section of this paper.

Disclaimer: The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any institution or organization.

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High School Makers: What They Mean for Colleges

ISAM 2016 Paper No.: 49

Invited

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INTRODUCTION

High school students are becoming increasingly exposed to making. Their exposure and experience go beyond the traditional "making" definition of mere physical production, though, and expand to any manifestation of turning an idea into reality. Where previous making was typically limited to engineering professionals and their associated machinery, high school students who are intrigued by problem solving and the skills and mindset needed for making are torn across a variety of academic and career pursuits.

High school student exposure to maker resources and capabilities increases their expectations for their college and university maker experience. While the exposure that students may have in high school varies drastically, every high school student expects that their college experience will surpass that of their high school exposure. This lends a particular challenge to universities for bridging the experience levels of the varied high school makers while providing apt opportunities for all to grow, requiring the proper facilities and community.

Throughout this paper, I will refer to students from the MIT Launch program [1], a residential entrepreneurship summer program for high school students held at MIT. This is a competitive program [2] where students from across the US and world [3] come to MIT for four weeks to start real companies [4]. These high school students characterize the top makers applying to universities in recent and coming years [5].

THE DEFINITION OF "MAKING"

The phrase "making" has very different connotations to high school makers versus in university academic settings.

"Making" for high school students is generic – creating something from nothing. When asking high school students what "making" means to them, responses include, "Turning thought into action," [6] "*doing* instead of thinking," [7] and "innovating for the future," [8] where less than 10% of the responses referred to the creation of something tangible [9]. These indicate a vague representation of making that includes all of design, strategy, problem solving, building, coding, and business development of all types of ideas – products, services, or applications. These students consider making to be a general skillset and mindset instead of niche academic and career path.

Universities tend to identify makers narrowly as engineers. They tend to provide access to their resources primarily to their engineering students and err on the side of making as the production of something physical. While many schools are adjusting their perspective of what making means, the mindset, goals, and experiences of these students are often still misaligned with what the schools provide.

A. TYPES OF MAKERS

High school students that identify themselves as makers fall within a variety of types. Among the MIT Launch entrepreneurs who self-identify as makers [10], not all identify as engineers, and in fact, they identify cross-functionally across a range of skills, as seen in Table 1 below.

Table 1 MIT Launch high school students who self-identify as makers identify their skills across a range of disciplines

Innovator	90%
Inventor	59%
Engineer	59%
Designer	54%
Software Developer	49%
Technologist	49%
Scientist	36%
Artist	31%

Making, then, is not limited purely to engineers from their perspective. High school makers consider a wider range of machinery within the realm of making.

B. MACHINERY

High school students today are coming to universities with anywhere from vast making experience to none, depending on their resourcefulness and the opportunities presented to them in their community. Meanwhile, most universities are not yet equipped to handle either extreme of student, with a level of intensity of equipment that only allows their committed engineering students to fabricate in the latter years of their schooling.

<u>i. High School Access</u>

The advent of inexpensive rapid prototyping machinery has allowed increased access to making across demographics beyond the previous limitations [11]. This making takes the form of both electronics (Arduino and Raspberry Pi) and mechanical methods (3D printing and laser cutting). The prevalence of making at the high school level can be noted through instances of keywords on the MIT Launch 2016 application [12], shown in Table 2 below.

Table 2 Instances of "maker" keywords in applications of high school students to the MIT Launch entrepreneurship program

Electronics	
Arduino	56
Raspberry Pi	21
Electronics sensor	9
Mechanics	
3D print	72
Laser cut	9
Tools	107

The prevalence of these words indicates how accessible these items are to students in high school, to the extent that they use them in an activity listed on their resume. Some of these activities include having built their own 3D printer, published applications on the Apple Store, and developed an Arduino sensor-based invention.

ii. University Machine Shops

Traditionally, schools only provide access of machinery to students at the highest level of their degree programs, which means that at universities there are machine shops that only certain engineering degree programs may use, typically mechanical engineering students [13].

Some schools have developed more accessible maker spaces. 40 have been identified at 35 colleges and universities in the United States [14], though the equipment would primarily underwhelm top high school makers.

3D printing tends to be a cornerstone of most maker spaces, though <3/4 of the 40 mentioned had a 3D printer. The most common 3D printer was a MakerBot, the brand that popularized the desktop 3D printer, though rising freshman may scoff at it as a choice in a university maker space. High school students manning the "maker corner" at one of the nation's largest hackathons [15] advised against the MakerBot and towards different desktop 3D printers, such as the Ultimaker [16], claiming the MakerBot performed worse than the 3D printers that they had made themselves for the hackathon.

Both more standard maker equipment such as electronics and bench tools, plus more advanced equipment such as a laser cutter, were found in less than half of the maker spaces of the 40 identified. Table 3 outlines the prevalence of key prototyping equipment in the maker space study.

Table 3 Portion of 40 university maker spaces with prototyping equipment

3D printing	29 / 40	72.5%
Laser cutting	15 / 40	37.5%
Metal shop	15 / 40	37.5%
Wood shop	11 / 40	27.5%
Electronics shop	22 / 40	55.0%

Given the extensive maker experience of some students prior to university, these resources would prove underwhelming for them to continue putting their ideas into action, regardless of their potential career pursuits.

C. CAREER AND ACADEMIC PURSUITS

Since these high school makers define their skills and mindset capabilities more generally than traditional engineering paths, the students typically find themselves torn across a variety of academic and career pursuits.

When asked about their career interests, over half of the high school student applicants to the MIT Launch summer program expressed interest in multiple distinctly different academic paths [17], where over half of these paths are what we would categorize as "makers" [18].

Students feel ill-equipped to make such an important decision without having been given the proper resources to explore what the academic and career paths will actually mean for them. A common question I have from the students of MIT Launch throughout the program is what path will best set them towards becoming an entrepreneur. They ask about whether they should major in business or engineering. They have a clear interest in making – creating something from nothing – and yet are uncertain about the best path within the current university setting that will enable them to pursue their passions. Universities that allow students to explore their maker tendencies earlier in their careers provide a higher chance of their students finding alignment with the portion of their making abilities that will fuel their impact in their workforce.

MIT has made huge strides towards supporting makers to find their path: allowing them to apply with maker portfolios [19], minor in entrepreneurship [20], and having a series of initiatives within Project Manus that catalogues maker spaces with varying focuses aligned to different student needs plus allowing all freshman to be trained in making [21].

MAKER EXPECTATIONS OF COLLEGE

It is the responsibility of a university to cultivate and grow their students, while preparing them for real world success. Universities must transition students from high school and allow them to surpass the experiences and skills development of their high school experience.

First, the transition to college underwhelms many students. Nearly 34% of students drop out in their first year, where they are overly optimistic in their expectations and confident in their abilities of college [22]. The experience of these incoming students is varied, though the expectations of students with vast maker experiences are set very high, which could leave them feeling that they could learn more by putting their ideas into action outside of the university setting.

Meanwhile, many students come to university without any maker experience, and schools must walk a fine line in how they cater to the maker experiences of students to not alienate these aspiring, yet inexperienced, new makers.

A. TOP HIGH SCHOOL MAKER RESOURCES

The top high school makers have had a plethora of resources at their disposal, both through their high schools and through being resourceful about external opportunities. These include:

- School maker spaces [23] - while sometimes limited, some schools are significantly funded and offer advanced prototyping machinery beyond just desktop tools.
- Classes – there is an increasing trend towards project-based learning in the classroom, including the use of Makey Makey [24], Little Bits kits [25], and more.
- Clubs – some “maker” extracurricular clubs include FIRST Robotics [26] where students build competitive robots and the MIT Launch Clubs [27] where students launch startups and prototype for their companies.
- Hackathons [28] – 24-60 hour events where students create solutions to a range of problems through coding and making.
- Competitions – Lemelson InvenTeams [29] where teams receive up to $10k to invent technological solutions to real world problems, Verizon Innovation Challenge [30], and more
- Summer Programs - Make School [31], MIT Launch [32], iDTech [33], etc.

In addition to having such a significant number of opportunities to learn to make from peers, mentors, and online resources, students are even given leadership opportunities to start and run clubs and spaces associated with making. All of these experiences give these top high school makers the expectation that they will be able to jump into similar experiences at the university setting.

C. MAKING UNIVERSITY MAKING ACCESSIBILE

The primary challenge of a university maker space is not only allowing these top incoming high school makers a setting to further explore their skills, but also to make that setting accessible to aspiring, new makers without being intimidating. Bridging this gap comes down to creating the proper culture, including onboarding and training processes that build community.

Maker spaces must be setup with the proper culture that allows both new and experienced makers to flourish. This includes having adequate equipment for advanced makers to use their skills, while having an orientation that does not intimidate the new users. The culture must build community and support among the other makers. More experienced makers must be given a sense of accountability to uphold the ideals of the safety and mentorship of the space, ideally through overseeing newer makers and even holding workshops to share their projects and teach new makers how to use the space. Further, top makers can be empowered to setup the infrastructure of the extracurricular resources.

One of the challenging parts of running a maker space once it is set up is getting new makers over the hurdle of starting to make. Many people are intrigued by making, but aren’t sure where to begin. This can be alleviated through having example template projects, workshops, and resources [34].

CONCLUSIONS

Universities must learn to adapt to a new age of high school makers. These makers have a more general definition of making beyond that of just an engineer, requiring maker spaces to allow students access to rapid prototyping machinery even early in their college careers. Further, these makers are driven by general creating and problem solving, which does not necessarily align itself with a more niche traditional major, limiting their propensity to declare a major early in their college career. Colleges may consider providing opportunities such as entrepreneurship minors to allow students to explore their maker propensities within their academic plans.

High school makers also have varied incoming experiences, with top high school makers having made use of a plethora of previous making resources that set high expectations of the increase in availability of maker resources that will be available at college. This means that universities must cater to openness and machinery expectations of these top students, plus provide extracurricular programming to support them, while paying special attention to not alienate aspiring new makers by leveraging the experience of these top students to build community.

REFERENCES / FOOTNOTES

Some of these resources and foot notes contain unpublished documents, these documents are available upon request via email to the author.

[1] MIT Launch – https://mitlaunch.com
[2] Admissions rate of 10-20% and yield on offers >90%
[3] 2016 students came from 23 states and 23 countries across 2 sessions of 70 students each
[4] ~50% of companies are still running one year after the program
[5] MIT Launch alumni matriculation primarily to top universities, submissions to MIT maker portfolio primarily rank in top 5% of submissions

[6] Kaili Wang, 10/31/16, MIT Launch alum
[7] Kelvin Zhang, 10/31/16, MIT Launch alum
[8] Trisha Kagalavadi, 10/31/16, MIT Launch alum
[9] 23 high school students polled with only 2 citing the need to develop a tangible product
[10] Qualtrics survey 3/9/16 to MIT Launch alumni resulting in 187 responses, 59 of which self-identified as "makers"
[11] http://www.bcg.com/expertise/capabilities/technology-digital/rise-3d-printing.aspx
[12] 947 high school student applications to the MIT Launch summer program 2016 via launch.fluidreview.com
[13] Google search of "university machine shop access" reveals primarily results with "engineering" in the title and suggests multiple searches with "engineering" and "mechanical engineering" in the title
[14] file:///C:/Users/istach/Downloads/A_Review_of_University_Maker_Spaces.pdf
[15] HackBCA II - https://hackbca2015.devpost.com/
[16] https://ultimaker.com/en/products
[17] Applicants to MIT Launch were asked about their Academic Plans and Career Interests, where over half of the over 2000 responses included at least two responses within the "Career Interests" text box
[18] "Maker" types include entrepreneur, engineer, designer, marketer, inventor, fashion, writer
[19] http://mitadmissions.org/apply/freshman/supplements
[20] https://innovation.mit.edu/education-practice/eiminor/
[21] https://project-manus.mit.edu/
[22] http://www.huffingtonpost.com/brian-harke/high-school-to-college-tr_b_620043.html
[23] Referenced 31 times in MIT Launch applications
[24] http://makeymakey.com/
[25] http://littlebits.cc/
[26] http://www.firstinspires.org/ includes hundreds of thousands of high school makers, including an entrepreneurship competition
[27] https://mitlaunch.com/clubs/ already at over 150 schools in its 3rd year
[28] MIT Launch has sponsored 35 hackathons and applicants have referenced the word "hackathon" 93 times
[29] http://lemelson.mit.edu/inventeams
[30] https://appchallenge.tsaweb.org/
[31] https://www.makeschool.com/
[32] https://mitlaunch.com/
[33] https://www.idtech.com/
[34] A website should be complete with helpful lists of needed softwares, file repositories such as Thingiverse and GrabCAD, the process for use, and potential projects.

A Brief Introduction of China's Maker Movement and Makerspaces

ISAM 2016 Paper No.: 50

Invited

Helen Tan
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In this presentation we provide a brief overview of the historical and current status of "maker movement" and makerspaces in China, highlighting a few noticeable examples and trends.

2015 is the watershed year for China's maker movement, marked by Chinese Premier Li Keqiang's visit to Chaihuo Makerspace in Shenzhen at the beginning of the year. Before the visit, "maker" was a niche concept little known to the general public. Seeed Studio is a typical example of a handful of active players in the maker community.

After 2015, with top-down government encouragement, thousands of "makerspaces"/ "incubators" of different natures sprung up in China and the "maker" concept became mainstream. Despite the obvious bubbles, we'll present a few highlights worth noticing:

(1) Shenzhen with its unique hardware supply chain resources and being a young and entrepreneurial city, has emerged as the center of all maker related activities. It also plays an increasingly significant role in the supply chain for global hardware startups and makers.

(2) Chinese universities are putting much more resources to promote maker culture and entrepreneurship. We'll show the case of Tsinghua University's iCenter makerspace, as an example of how Chinese universities are consolidating their school resources, incl. leveraging the Mao era university-factory heritages, to build makerspaces as a hub for promoting entrepreneurship.

(3) The significant growth in international collaborations and exchanges, with the significant expansion in scale of Maker Faire in major Chinese cities as an example. We'll also showcase the expatriate maker/engineer community in Shenzhen.

Finally, we'll also briefly introduce what we at Higgs Hub have been working on.

Making is Thinking – How doing transforms our thinking centric paradigm of innovation and education

ISAM 2016 Paper No.: 51

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Making is thinking[1]. This is a much more radical claim than it might seem at first glance. It is not that making is simply critical to thinking (which is true), for to phrase it in this manner is to see making and thinking as two *separate* activities. The claim *Making is Thinking* argues for something more fundamental—that *the very act of making is a form of thinking*.

The claim "making is a form of thinking" is one that has been around for quite some time. The traditions of American Pragmatism (especially John Dewey[2]), Process Philosophy, and Phenomenology all make this claim central to their larger projects[3]. Over the last twenty years this question has become a critical research topic in the field of mind and brain studies—cognition, and the realization of the truth of this claim at a physiological level has given rise to a revolution in the field of cognition in which a brain centered/brain only model of cognition as given way to an embodied and embedded concept of cognition. This new mode of studying thought is termed Enactive Cognition[4].

Enactive Cognition advances a new framework in which thinking cannot be reduced to a discreet activity that happens in the brain. Where classical forms of cognition make the claim that thinking is the internal processing of representations derived from informational content supplied by the senses, enactive cognition shows that thinking is a distributed activity that makes a *non-decomposable* loop between a body in action and an environment. Hence the term "enaction"—to come into being via activity. The enactive framework understands thinking to involve four E's: embodied, embedded, enactive and extended (4E).

Enactive Cognition distinguishes two very broad forms of thinking: "know how" and "know what"[5]. Most often when we refer to thinking in everyday speech we are talking about the "know what" form of thinking. This is the form of thinking that involves clear concepts, representations and information. Know what, enactive cognition demonstrates, is a small part of what we do and who we are[6]. In our daily lives, we are mostly in a state of active "know how". "Know how" is much less understood or even recognized. Distinct from conceptual thought and prior to it is where skilled know-how operates. Know how is what we deploy when we navigate the stairs, ride a bike or make an exceptional move in a game of soccer. It is what we do when we form a bowl in clay, hand plan a piece of wood, or lay a course of bricks. It is what we do when we nurse a baby, sit down in a chair or stand at the appropriate distance from someone to converse. It is a form of *a-conceptual* or pre-conceptual thought. It does not involve the generation of mental ideas or representations (much of it is happening in a type of flow state). This state is the state we mean when we say "making is thinking". In the state of know-how we are involved in a practice that Evan Thompson calls a "laying down the path in walking." *The action is self creative*. It is a state in which we co-emerge with what we do (properly speaking *what the event does*).

One could make an argument that this is all well and good but is this a-conceptual thinking really thinking? And if it is how does a form of a-conceptual thought lead to a conceptual one? The work of Mark Johnson[7] and others has shown how basic embodied states such as "frontness" give rise to our general conceptual schemata for time (we move forward, we leave the past behind). Here we can see a clear example of how our everyday embodied forms of action which are in themselves a-conceptual give rise to rich conceptual logics. Johnson demonstrates that these active embodied states give rise to all of our basic conceptual logics. Thinking begins in doing and thinking begins in being a-conceptual[8].

Now why does it matter to focus on the fact that "making is thinking" in relation to Makerspaces and Innovation Centers? It matters because if it is true that know-how (making-thinking) *precedes* conceptual thinking (know-what) then three key things follow: 1. our definitions of creativity are wrong, 2. how we teach creativity is also wrong, and 3. Makerspaces in the broadest sense of the term are critical to *all* intellectual pursuits[9].

This is a serious claim that requires some unpacking. First we need to come to grips with what is implicit in how we frame creativity-. Creativity is imagined to be the space of *thinking* par excellence. We tell stories of innovation in terms of ideation, brain-storming, moments of deep meditative reverie, and sudden profound insight (those eureka moments)—all forms of thinking separate from making. Our dictionary definitions of creativity revolve around "The use of imagination or original ideas to create something" (Oxford)[10]. Again purely thinking centric, with making coming after the ideas are established. And it is from this logic of creativity=ideation that we have come to the point where we are now trying to define creativity as a unique brain property[11], or we speak of how "creatives" have different ways of thinking than the rest of us and so on[12].

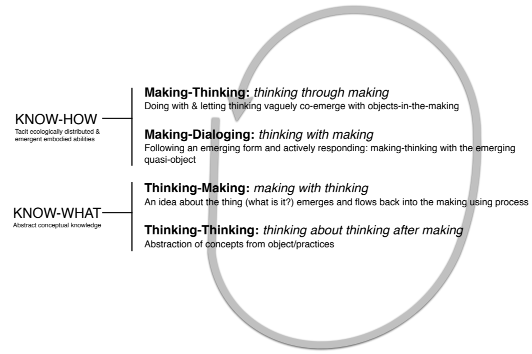
From this set of assumptions we teach creativity and innovation in terms of brain exercise and a process of developing ideas first and only when they are somewhat conceptually worked out do we move on to making them and refining them. This is true of classical forms of Design Pedagogy[13] and it is true of newer practices such as Design Thinking[14].

In all of these thinking comes first, and it is the most important activity—making is secondary, and comes much later in the process. And nowhere is there an acknowledgement that making is thinking. Clearly there is a serious problem.

From the perspective of Enactive Cognition (making is thinking) there are three major problems with this model of "creativity = ideas": 1. Conceptual thinking as a practice relies on existing conceptual logics, such that if you begin in conceptual thought you can only conceptualize things that are known well enough to put into concepts. But the new, in being something truly novel, is at the very least partially if not wholly *a-conceptual*. You cannot get to the a-conceptual from the conceptual. Therefore the practice of beginning in conceptual thinking is of a fundamentally limited value in the early phases of creativity 2. Making (enaction) is not what comes *after* conceptual thinking but rather what *precedes* it. Our engaged actions lead to our most basic conceptual schemata[15]. This is all the more true of innovation—novel concepts co-emerge within an experimental practice of making. Novel concepts emerge from a-conceptual practices. Thus *innovation and creativity is necessarily linked to making.* 3. Creativity is ultimately *not a thing* (that could be found in a brain). Creativity is an embodied, embedded, enactive, extended dynamic *process. W*e should not be focusing on how to make people more creative *but on teaching 4E innovation processes. Thus,* a better definition of creativity would be: It is the process by which something novel emerges[16].

Once we realize that the entire framework of the "ideas first"—*I think therefore I am*—model of creativity is wrong we need to look critically at what we are teaching as ways to be creative[17]. What should the process(es) be? Let us begin by reviewing the process of "where novel ideas come from" from within the enactive framework. As enactive cognition has demonstrated the body and the environment fundamentally shape the mind — "it might even be possible to say that bodily movement, transformed onto the level of action, is the very thing that constitutes the self.[18]" Given this: the answer to the question "where do ideas come from?" must be that Ideas come from situated embodied action—ideas emerge from deeply engaged forms of primarily non-cognitive doing. Not "I think therefore I am" but "We do therefore I become." This form of "absorbed" doing is *not* what happens in brainstorming or ideas storming. It is never so explicit, or removed from action—how could it be? Rather it is a type of tacit knowledge (know how) where *doing exceeds knowing*. It is a type of "thinking through"—a doing-with and letting things/ideas vaguely and tentatively co-emerge with stuff in action. This early phase of making-thinking is one with no clear and distinct ideas or concepts, but more of a "following-in-doing-with". From this phase one begins to "think with" the emerging of a situation or object still very much in becoming. It is only after this that one begins to "think about" what is emerging in any concrete and conceptual manner. Here is where ideas begin to emerge. (see diagram below).

If we are serious about innovation and creativity then (1) we have to put enactive making at the center of the learning



THE (ENACTIVE) CREATIVE PROCESS

process, *(2)* we have to revise our fundamental framework of what it means to be human: we are not "thinking beings" or "rational animals" we are "skillful makers" — *homo faber* and not *homo sapien, and (3)* we need to see things not merely as bearers of our intentions or placeholders for our meaning but as themselves active agents in the process that are always already conceptualizing actors[19].

To be able to put this framework into action we need to pause and ask: why and at what cost is it that we in the west have had this "ideas first" model of creativity for so long? Just beginning with the history of the word creativity: the very word "Creativity" is of very recent origin. It only dates back to the 1920's. Why? For the longest time the western tradition had no place for such a concept. What we might call today "creativity" was understood for the longest time as "recovery" or "discovery" of what was there all along (the deities/demiurge's intentions, plans, laws, etc.). From Greek Philosophy to Christian Metaphysics creativity existed outside of, and prior to, human action. Only God could create. Humans could only follow—well or poorly. All of the terms we still use in relation to creativity reveal this deep historical process: "inspiration," "vision," "insight," "revelation," "discovery," etc. These are all idea centric terms that relate *back* to what already exists. To have insight or discover is to see or uncover what has always been there. Now this is fine in a closed universe of fixed possibilities, but as we now know we live in an open, dynamic universe full of chaotically emerging novelty. All of our scientific understanding points towards a world of emerging novelty, a world where the old models of making as recovery simply do not fit. We bring up this history not as a criticism of the western tradition or as an interest in stepping into the terrain of theology but to alert us to the fact that we have unconsciously absorbed these practices into our current reality as worldly makers and innovators. We need to ask ourselves: are we simply putting new wine into old bottles?

To finish our brief history of the word: the term "creativity" was coined by Alfred North Whitehead to define the most basic process underlying all reality. Reality, for Whitehead, is a *creative movement into novelty*—and this is true from the big bang to hip-hop. Whitehead went on to develop the most comprehensive model of creativity as *a process of emergent novelty coming into concrete being* during his tenure at

Harvard in the 1930's and 40's. But, while his word stuck, his ideas did not. Creativity quickly reverted to the old model—becoming a thing -- a spark, a special sauce, a pattern of neurons, an idea[20]…

There are a number of important questions and trajectories that are raised by shifting our models of creativity, human cognition, the status of things, and the role of making in thinking. First and foremost, intellectual activities need to embrace making as foundational to thought. This can and should take many forms[21]. These are really beyond the scope of this essay, we would like to stay closer to our initial question of how the Makerspace revolution could be critical to the enactive creativity revolution and vice-versa.

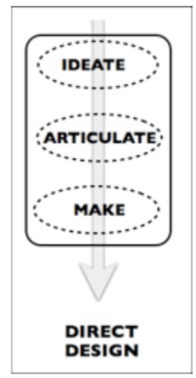
The Enactive framework has important consequences for Academic Makerspaces. In the model of creativity that we are proposing Makerspaces are not some marginal place or practice—nor is the term *academic* maker space an oxymoron. Makerspaces are *inherently* academic and are *necessarily* at the very core of thinking itself—and thus they *should be* at the very center of academic practices. If this is their proper place, the question is how should they operate? Currently most academic Makerspaces do not operate from within this framework. They operate within an essentially service framework as second class intellectual citizens relegated to the margins of academic environments as bridges with communities, quasi-extracurricular spaces, and resources to be drawn upon as needed. Now clearly these are necessary activities, but Academic Makerspaces can be much more than this.

How? This involves embracing the enactive creativity paradigm. And on a concrete level we propose that it requires two large shifts in how Makerspaces operate: 1. their mission/logic, and 2. their pedagogy.

Let us begin by focusing on the mission: The mission of Makerspaces could embrace enactive creativity and innovation by putting making back at the core of creativity. In doing this Makerspaces can become the *place for academic research into creativity itself*. Given our history of two thousand years of misunderstanding creativity we are in serious need of rebooting the entire space of creativity research—academic Makerspaces are the most obvious location for such research from an enactive perspective. They are the ideal space for this in so many ways—not in the least because they are set up to be transdiciplinary workshops and any inquiry into creativity would be a highly collaborative undertaking. In this way Makerspaces can have a dual mission of 1. being a hub for creative making and 2. a lab to research creativity itself.

Now let us look at the question of pedagogy: To become this form of maker space not only is there a need for a shift in frameworks and mindsets, there is also a need for new forms of design pedagogy. Why not simply adopt current best practices of design pedagogy as most centers have done? Our current design pedagogies, for all of their great diversity (Bauhaus to Design Thinking), are most often processes of "ideas first" making. This should strike one as ironic, but sadly it is too often the case—making-thinking[22] is too often not at the heart of design (and certainly not at the beginning of the process) any more than it is at the center of any academic practice. Design, as a discipline has been taught as a deeply conceptual and "ideation first" practice. We need a new design pedagogy that puts *making-thinking* at the beginning of the design process and not ideation.

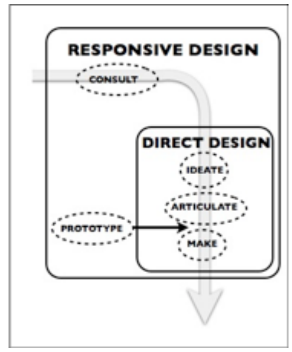
To get a sense of what this means we need to step back and do a cursory review of design methodologies: Design has been classically understood by the western tradition to be a process of *turning ideas into things*. You know the story: you have a vision—an idea—and you figure out a way to make it. Perhaps you make some drawings, work with fabricators, and other crafts people to realize your vision. And in the end, if everything worked out right, you have the materialization of your *original idea* and there is a pretty *direct correspondence* between idea, drawings, and finished product. This design process is what we call *Direct Design*.



Direct Design has not been without its critics in the world of design[23]. One key to the shift that spelled the end of conflating Direct Design with Design came about with the rise of various social, anthropological, philosophical, ecological, and systems models of understanding that gave us insight into reality as a complex interwoven, dynamic and evolving system(s). It became obvious that human making could not effectively happen separate from the world of users, practices, problems, needs, politics and so on. Direct Design with its reliance of working at a distance from the world was rightly criticized for being removed, closed, and quite simply not responsive to real world conditions. It became painfully obvious to many in world of design that Direct Design was incapable of effectively answering these criticisms without radically changing.

From an awareness of the power of engagement, a new and expanded form of design emerged: Responsive Design. Responsive Design is just that—it begins in a considered response to the world rather than springing from the "head" of a designer. Responsive Design at its best shifted the focus of design away from the narrow idea of designers and design as being focused on independently making (beautiful) things. Design now became about all the interactive processes needed to make anything come into being. Responsive Design came in many forms from Environmental Design to Human Centered Design[24].

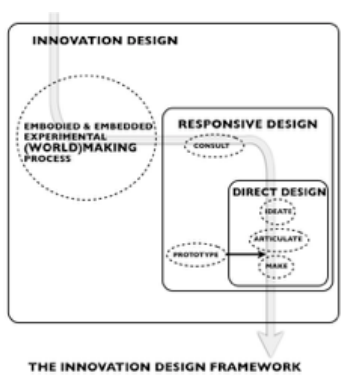
The simplest way to understand how Responsive Design transforms Direct Design is to see that it adds a new critical step prior to the beginning of Direct Design. This step is *Consultation*. Responsive Design does not replace Direct Design so much as it subsumes it.



But does consultation + ideation get us any closer to creativity? Let us quickly remind ourselves: Creativity treated as a process allows us to shift the focus from the mind (ideas) to *engagement with the world, things, and* *processes of making*. Making matters. Things matter. Our embodied states matter. When we do things, the things we use speak back to us and transform us. In light of creativity as a process the world becomes alive and in this engagement with the environmentally situated push and pull of active materials novelty emerges—novelty emerges *not* from our heads but from the middle of action. So while consultation is critical and ideas play a role in creativity, neither gets us closer to the core of creativity.

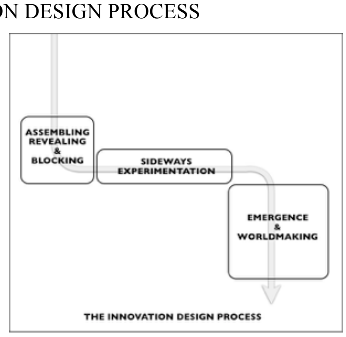
To get to the core of creativity we must again return to our question "where do *new* ideas come from?" with a clear answer: they do not come from other ideas but rather form a deeply embodied and embedded form of experimental making. Given this the answer to our real question "what comes *after* "ideas first" models of creativity?—is really a question about what comes *before* Ideation and Consultation. We need to add a series of embedded making processes prior to ideation to generate novel ideas.

We call these processes "Innovation Design." Innovation Design does not replace or contradict Responsive Design anymore than Responsive Design contradicts Direct Design—these are nested, interwoven, and complimentary design processes that together make up The Innovation Design Framework[25]. The goal of this framework is to act as an expansion and r*e-orientation* of our most common design tools to encompass novelty, creativity and innovation via embodied making. It gives us a way of moving from misunderstanding creativity as some impossibly mysterious "thing", to a difficult but accessible process of emergent engaged making for paradigmatic[26] novelty. With Innovation Design—in all of its variants—we in the Makerspace community can truly bring making-thinking and creativity back to the heart of our lives.

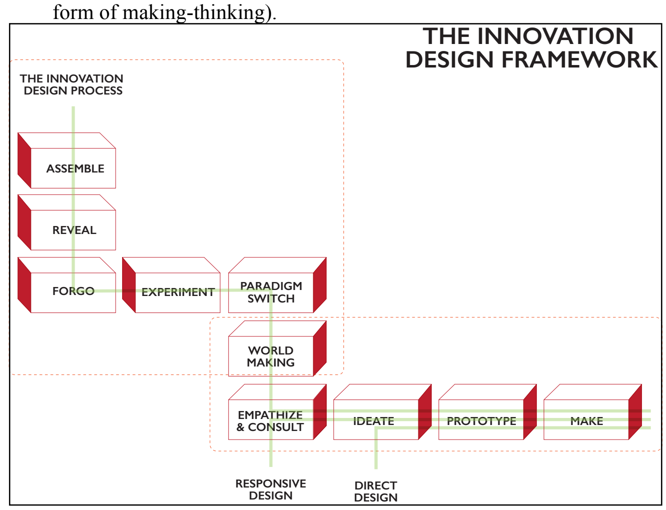


APPENDIX1: THE INNOVATION DESIGN PROCESS

Let's start simple: This creative procedure consists of four big moves: Assembling and Blocking, Sideways Experimentation, Emergence, and Paradigmatic Transformation. We can lay these out sequentially:



1. Assembling, Revealing and Blocking (Forgoing). Assembling is the coming together with a matter of concern and gaining a deep participatory understanding (we like to say of this phase: "become the problem"). Blockage is both a simple procedure and a quite complex one. Blockage is quite simply to do something different—it is to forgo repetition of what has already been done.
2. Next comes the phase of making-thinking. Here one becomes a follower and not a leader: what emerges in action with things in all of its truly ambiguous unknowable a-conceptual glory pulls one forward into the unknown (one is transformed as the problem is transformed—here a problem worth having begins to emerge—the problem never pre-exists this phase). This iterative process of *Sideways Experimentation* "leads" to the possible (nothing is guaranteed):
3. *Emergence* of new qualities, capacities, and affordances. At some point in this long and multi-branched experimental process one crosses a threshold into
4. A new quasi-*World (territory)*. Dwelling and experimenting from within this new paradigm is the true beginning of novelty (another form of making-thinking).



THE INNOVATION DESIGN PROCESS IN DETAIL

With this broad understanding of the big moves in the process let us look at the methodology in more detail. The process can be roughly divided into ten steps—note: this is somewhat arbitrary, and far too linear—creativity is always loopy (see above):

1-2. *Assemble & Reveal:* One begins a design process with a matter of interest/perplexity/curiosity (itself unformed) which asks for certain collaborators to *assemble* from diverse fields with the goal of *revealing* what is going on at all levels. Collaborators in this case go beyond human participants to tools, materials, processes, other species etc. (all of which don't share a common language, logic or outlook). Revealing is itself a more-than-conceptual practice.

3-4. *Forgo & Experiment:* From a position of rich embodied understanding the collective experimentally decides (move away from) what practices, and processes to *forgo* with the goal of developing a way of *experimenting* that leads the team out of the existing ways of engaging with the issue. This is a journeying into the unknowable.

5-6. *Paradigm Switching & World Making:* Experimentation is a form of sideways movement of following and co-evolving with the matter of interest. One is following across thresholds into ways that allow for a novel paradigm to emerge. This paradigmatic shift allows for a novel world to be sensed.

7-8. *Empathize & Consult:* This nascent world needs to be carefully brought into being via a process of deep empathy and consultation—what does it want?

9. Ideate & Prototype: With the emergence of a novel world one can draw upon ideation techniques that come from this world to develop prototypes that in turn reinforce the emerging world and ideation.

10. Make & Remake: Now the long process of developing an ecological roll-out of a "product."

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[4] From the seminal works of Manturana and Varela to Thompson, and Chemero. Key recent works: E. Thompson, *Mind in Life*, and Hutto & Myin *Radicalizing Enactivism*
[5] F. Varela *Ethical Know-How*. Stanford University Press. 1999
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[7] M. Johnson. *The Body in the Mind: The Bodily Basis for Meaning, Imagination & Reason*. University of Chicago Press. 2013.
[8] Enactive cognition takes this insight further to look at how making and the way things push back on us as we shape them to shape us. We make things, as Marshall McLuhan said, and then they turn around and shape us…
[9] It should be noted that this is not so far removed from how many disciples operate as deeply engaged research practices. But is certainly removed from their own self understanding of what they do and our more general models of what intellectual activity is. See B. Latour *We have Never Been Modern*, and I. Stengers *The Invention of Modern Science*.
[10] Let us pause before digging into this problem and quickly define what we mean by creativity: creativity is the process of making of something that is genuinely novel.
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[13] This is what we term "Direct Design". A concept that we will explain later in the paper. see: K. Aspuland, *The Design Process*. Fairchild books. New York. 2014.
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[16] It is critical to see that creativity is a property of reality but simply humans. Creativity is everywhere from the evolution of multicellular life to bird flight to the big-bang itself. It is all around us and ongoing.
[17] The assumption behind the "ideas first" model of design is a flawed understanding of how humans engage with the world around them and where ideas really come from. It assumes is that humans live in a representational world separate from reality, and that we are at our core "thinking beings" (that is beings who have and work with ideas). In this mind vs world model we are minds (our brains) with discreet input devices (our senses) housed in a moving platform (our bodies) generating ideas about an external world.
[18] S. Gallagher, *How the body shapes the mind*. Clarendon Press: London. 2006.
[19] This aspect of the argument that focuses on the agency of things is sadly a key part that there is no space to properly develop. But the enactive approach and the agency of things approach are properly joined practices. See: A. N. Whitehead. *Process & Reality*, B. Latour *Pandoras Hope*.
[20] The concern for understanding and utilizing *processes* that generate novelty was left to other fields far from the worlds of design (thus we need to turn to ecology, complexity, evolutionary biology, process philosophy (to name a few) to find serious engagement with *creativity as a process*).
[21] We certainly do not want to make an argument that this never happens, but it is certainly rare. For a powerful example of Making-Thinking in an academic environment see the Sense Lab (Montreal).
[22] It is important here to see the distinction between making in service of thinking (a process of know what), and the emergent logic of know-how in experimental making (what we term making-thinking) that we are proposing.
[23] Outside of Design the most powerful and far sighted critics might be G. Simondon and G. Deleuze. Simondon termed what we are calling direct design Hylomorphic Design. See G. Simondon. *The Genesis of the Individual*. But, again the issue is that it is more studied than put into practice.

[24] Design Thinking is simply a form of Human Centered Responsive Design. But with its wonderfully ambiguous and broad name "Design Thinking"—it can seem to many to be a methodology that encompasses all of design—thankfully this is far from the case. What is called by the overly broad and inaccurate term "Design Thinking" is simply a particularly popular forms of Responsive Design.

[25] That said, we are strongly critical of the ideation centric, and thing centric models of all practices of creativity and design which haunt many forms of Responsive Design (but are in no manner inherent to it).
[26] When the new becomes central to making then the classical "problem solving" ways of Design Thinking needs to be significantly rethought. Creativity and innovation do not solve problems, but rather they invent new problems and more importantly — *new worlds*, that, if anything, make the old ones moot. Innovation is the invention of new problems worth having for worlds worth making. What is needed today is a full reckoning of how novelty emerges via a tangible process of worldmaking.

Building a Makerspace To Nurture the Innovation Culture at the NYU Tandon School of Engineering

ISAM 2016
Paper No.:
52

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ABSTRACT

New York University Tandon School of Engineering has opened a makerspace on the Brooklyn, NY campus in September 2016. The space provides students with access to fabrication equipment and facilities for team design projects. The MakerSpace functions as the cultural hub for makers and the core of the innovation pipeline at NYU. It helps to coordinate project-based curriculum, entreprenuerial activities, incubator growth, and community engagement. Impacts of the space will be tracked through access, training, and surveys of users. This paper will discuss design principles and constraints for the startup of the space, lessons learned, and examples of how the space has been integrated into the school over the first two months.

Key Words: Makerspace, Culture, Community, Engagement, Programming, Impact, Innovation, Entrepreneurship

INTRODUCTION

In recent years, a push for project-based curriculum and the influence of the maker movement on engineering education has led to the multiplication of academic makerspaces on university campuses. The NYU Tandon School of Engineering has built a new 10,000 square feet Makerspace Lab on its campus in Brooklyn, NY. This collaborative lab space opened in September of 2016 and is referred to as the MakerSpace. It houses several prototyping areas in a large, open-concept floor plan across two floors.

The creation of the MakerSpace aimed to help nurture the culture of technical innovation the School of Engineering has been fostering in the last few years through the creation of several programs. Courses, extracurricular activities, research, and startup incubators support student ventures on campus and beyond. The MakerSpace allows students and design teams to fully develop prototypes in house as part of their engineering education experience and positions them at the cutting edge of the engineering and technology startup sector in NYC.

While successful case studies have been documented, little is known about the design process - from inception to opening and use - of such spaces. This paper provides such a case study as it presents the origins of NYU Tandon MakerSpace, the design principles that guided its creation and the first few months of use. An iterative and user-centered design approach was taken: the design process does not end the day construction starts or the space is open. It as an ongoing process that incorporates users' feedback and workarounds.

LITERATURE REVIEW

Making is being infused in engineering education because it teaches students a well-rounded understanding of engineering design. Making is commonly performed on teams, through hands-on tasks, with physical and practical constraints, and with user needs taken into consideration. Each of these aspects allows students to actively participate in the design process and interact with their physical prototype. These traits have been shown to increase engagement and motivation for students compared to traditional lecture based curriculum.

As a result, makerspaces are being constructed as quickly as the support for them allows. They are appearing in museums, libraries, and university campuses to reinforce STEM initiatives. The 2015 National Science Foundation and American Society for Engineering Education sponsored Maker Summit define makerspaces as a: 1) physical space for making projects, 2) community space with a focus on creativity and collaboration, and 3) multidisciplinary learning experience [1]. Thus, makerspaces are not conceived only as physical environments but also as socio-technical systems that support creativity, collaboration, and learning. Research on makerspaces has therefore highlighted three additional components to focus on (space and staffing, equipment and resources, and training and programming) to design successful spaces. It also highlights the importance of assessing the impact of makerspaces on students' learning and experience.

Hand-in-hand with the growth of makerspaces has been the incorporation of entrepreneurship in engineering education design. Substantial support from the National Science Foundation has developed Epicenter, a National Center for Engineering Pathways to Innovation. Epicenter, directed by Stanford University and VentureWell, is helping to transform undergraduate curriculum by incorporating innovation and entrepreneurship into coursework [2]. Critical outcomes for this program include interdisciplinary first-year and capstone design; certificates or minors in entrepreneurship; makerspace and incubator facilities; faculty and industry support; and a strategic plan and director [3]. This process of blending theory and practice, or as the Maker Summit referred to it – formal and informal learning, is infused throughout the curriculum and imbedded in the makerspace [4]. Integrating entrepreneurship from cornerstone (the first year engineering course) to capstone design in collaborative labs improves the sustainability of invention and entrepreneurship curriculum [5].

A. SPACE AND STAFFING

Space and location play a large role in the usage of a makerspace. In an attempt to position these spaces in a large, open, collaborative area, many have been built in libraries or spaces already designated as multidisciplinary centers [6]. An ethnographic study of makerspaces has found that the layout, entrance, flooring, and lighting can have an impact on how students access, view, and use the space [7]. Spaces that are inviting and limit boundaries to access are successful.

Staffing models in makerspaces include faculty, student, or staff operated, or a mix of the three [6]. A mix of these models have been successful, but the emphasis of the makerspace depends on the staffing model.

B. EQUIPMENT AND RESOURCES

3D printers, laser cutters, electrical workstations and prototyping tools, and wood and metal shop equipment are the most popular types in a makerspace. Some also include meeting or conference rooms and class rooms – named thinkerspaces. Additional spaces can be used to enhance the multidisciplinary aspect of a makerspace. Adding a wet lab, for example, can draw in bio-medical, bio-mechanical, and bio-molecular engineering students [8].

Student pricing for materials and use of equipment also varies. Some spaces charge a flat rate for filament and other materials, while some provide a free amount (similar to a paper printing allotment) and charge users once they exceed that amount [9].

C. TRAINING, ACCESS, AND PROGRAMMING

Most makerspaces create an orientation or safety training that users must pass to gain access to the space. Some spaces are open 24 hours, while others are open set times, usually based around student availability and class schedules.

Programming and events can encourage student ownership (especially important for staff led spaces) and can also encourage diversity of users by introducing new reasons for students to enter. “Pop-up” workshops and other informal training sessions can increase accessibility for new or untrained students [10]. Design competition and hackathons encourage design thinking and collaborative skills and are often housed or sponsored by the university makerspace [11].

D. ASSESSMENT

Academic makerspaces attempt to increase the technical and soft skills of modern engineering students, to encourage engineering design challenges, and to promote innovation and entrepreneurship. Assessment tools and best practices to decipher whether the spaces achieve those goals are still being developed. Most agree that student self-efficacy in design and confidence in prototyping skills are the goals of the space [10], [12].

HISTORY, DESIGN, AND SPACE

The NYU MakerSpace planning and construction spanned the past two years. Construction was completed at the end of August, 2016, and the space is now open for the fall semester. A committee of three faculty members and the manager of the space meet periodically to supervise the space and decide on policy decisions. The impetus for the MakerSpace came from a collaborative design space called the GreenHouse, which was created as a prototype of a future makerspace in January, 2013. It emerged from a student initiative and is supported by a faculty member, aiming to use design thinking and open innovation to collaboratively design spaces and services. This faculty member’s focus was in and around the Tandon campus with the goals of enacting the invention, innovation, and entrepreneurship (i^2e) motto of the school and increasing collaboration.

The previous space, which was centrally located, offered basic prototyping resources (cardboard, Play-Doh, Arduinos, etc.), small funding and connections to other prototyping resources available in the university (3D printing, laser cutting, etc.) as well as programming (skill shares, talks with entrepreneurs and innovators). The main aim of the GreenHouse was to give students opportunities to brainstorm ideas, experiment, and thus nurture their creative confidence. The space was run by students called GreenHouse Guardians, who, with the support of their faculty advisor, were in charge of managing the space, organizing the programming, and facilitating interactions in the space. The programming was supported by a VentureWell grant and had at its core the Prototyping Fund. The Prototyping Fund is a collaborative effort between the GreenHouse and NYU Entrepreneurial Institute and runs twice a year (in the Fall and the Spring). It offers grants of up to $500 to 10-12 student teams to build a prototype of an idea they are working on. These teams are ideally multidisciplinary and include at least 2 schools. The success of the GreenHouse space highlighted the need for more prototyping resources and led to the construction of the current MakerSpace, which now includes the GreenHouse area and programming. The fall project showcase for the prototyping fund will be held in the GreenHouse area of the MakerSpace on December 4th, 2016.

A. DESIGN PROCESS

The Planning Committee for the MakerSpace involved a group of faculty members (including the second author of this paper) and administrators working with the architectural team. The process followed an iterative design process (discover, analyze, synthesize, ideate, and develop) with a focus on users and practices. An important assumption shared by the architectural team and some of the members of the committee was that design would not end with construction and/or ribbon cutting. Students were also invited to a visioning session in order to incorporate their needs as well as learn from their involvement with similar spaces. Three main design principles for the space emerged from the original visioning sessions with faculty and administration:

(1) create a space where students could experiment - make and break things;
(2) create a space that will change the way engineering is taught in and out of the classroom;
(3) create a space that triggers collaboration and

cross-pollination of ideas.

While the committee focused on the design of the physical space, there was also a clear understanding that the space was a socio-technical system. The type of activities and programming that would take place in the MakerSpace were key in shaping some of the decisions about the design. A fourth design principle was included: (4) to design a space that was flexible in order to allow for multiple types of activities and programming as well as to support iteration due to new needs and evolving practices. When divergent views on an issue arose, the team regrouped around these principles. Several design constraints were set at the beginning: the budget as well as the location. There was some exploration on the latter but the team quickly realized that the current space on the ground floor of Rogers Hall was the best, possibly the only, option. A number of structural constraints also shaped some of the design decisions.

When construction started, another committee was created with a mix of faculty and administrators to discuss the governance structure, the staffing, and operational rules. The group reviewed other spaces within the university and the city (e.g. makerspaces in NYC) as well as in other universities to inform their decisions. The design principles also shaped the conversations and decisions during this phase. The GreenHouse experience was also influential during this phase. The decision was made to hire a space manager and an assistant space manager with the intention to engage students (individuals and organizations) to develop a sense of ownership from the main users of the space. The same design principle and inclusive governance philosophy have been informing the MakerSpace programming and organizing since its opening.

B. SPACE AND STAFFING

The location of the MakerSpace is within the NYU Tandon School of Engineering campus in downtown Brooklyn. It is a central feature of the engineering school as it is on the first floor of the main building. It is the first thing students see when entering the school and large windows and open doors provide an inviting and inclusive environment. Being in New York City, the dense urban area and limited room made space planning and layout a critical element of the design.

The main floor of the MakerSpace is designed to encourage interaction among users. Soft seating is mixed in with work tables and lab benches. Movable white boards are scattered throughout the space, and students are encouraged to re-arrange and reconfigure as they see fit.

The MakerSpace has two full-time support staff members: a manager (female, background in electrical engineering) and an assistant manager (male, background in mechanical engineering). In line with the MakerSpace inclusive governance policy, four graduate and 24 undergraduate students work in the space. Diversity of the staff was carefully considered during hiring to ensure a mix of gender, age, ethnicity, major, and background. The gender ratio of all graduate and undergraduate student workers is 39% female and 61% male, and their majors are displayed in Table 1.

Table 1 List of Student Worker Majors

Mechanical Engineering	10
Computer Engineering	6
Computer Science	5
Integrated Digital Media	2
Biomolecular Science	1
Chemical and Biomolecular Engineering	1
Civil Engineering	1
Industrial Engineering	1
Management of Technology	1
Total	**28**

C. EQUIPMENT AND RESOURCES

Support for student club projects and senior capstone design projects includes specialized training and mentorship from the staff. The goal of the space is to provide a collaborative work environment where student teams, staff, faculty, and specialists can build off one another's ideas. The equipment on the main floor and lower level makerspace room is shown in Table 2.

Table 2 MakerSpace Equipment

Type	*Machine Description*	*Quantity*
3D Printer	Ultimaker 2+	4
	Ultimaker 2+ Extended	4
	Stratasys Mojo	7
	Stratasys Dimension Elite	5
	Stratasys Fortus	1
	Stratasys Objet30 Pro	1
3D Scanner	Shapetools Next Engine	1
Laser Cutter	Epilog Mini 24	2
	Epilog M2 32	1
	Universal ILS 12.75	1
CNC	Othermill Pro	5
	Pensa Labs DIWire Bender	1
	Roland CAMM-1 Vinyl Cutter	1
	WARDJet E-0606	1
PCB	BotFactory Squink	2
	LPKF Protomat S63	1
	Manncorp Pick and Place	1
	Manncorp MC-301 Oven	1
Micro-CT Scanner	Bruker SkyScan 1172	1
Heating	Thermo Scientific Box Furnace	1
	Grieve Forced Convection Oven	1
Other	Morgan Plastic Injecting Machine	1
	Electrodynamic Shaker	1
	Noztek Filament Extruder	1
	Singer Industrial Sewing Machine	1
	Brother Embroidery Machine	1
	Super Dental Vacuum Former	1

Electrical workstations' equipment is not included in Table 2, but includes a soldering station, DC power supply, function generator, and oscilloscope at each bench. The space features unique machines including the micro-CT scanner, electro-dynamic shaker, and plastic injecting machine. These support specific curriculum and research within the school, but are also open to student use and testing in material science, product testing, and production methods.

D. TRAINING, ACCESS, AND PROGRAMMING

Hours for the space were decided by the design committee based on other makerspaces and student preference. The hours for the space are:

- Monday – Friday 9AM – 11PM
- Saturday – Sunday 11AM – 5PM

The MakerSpace main floor includes the GreenHouse ideation and collaborative work space, as well as work tables that are open to anyone in the school of engineering. So, during open hours, the doors are unlocked and open to all. Students, staff, and faculty who wish to use the equipment in the space must first attend a safety orientation and be registered as a user, shown in Fig. 1. Once this initial training is completed, the Ultimaker printers and the electrical benches are free and open to use.

Fig. 1 Safety Orientation and Printer Training

Depending on the knowledge, experience, and safety requirements for use, specialized training will be required for access to specific equipment. A tiered system is being developed for the corresponding difficulty of use.

The MakerSpace focuses on engaging students and the community. Orientation for the Fall Freshmen ended with a tour of the MakerSpace to highlight the central role of making in the student experience. The first-year engineering incorporated MakerSpace orientation into a mandatory laboratory exercise. Outreach will extend beyond the university for special events for the public. K-12 STEM education and pre-college courses will have access to the MakerSpace during the summer. NYU Tandon MakerSpace staff participated in the World Maker Faire at the NY Hall of Science on October 1-2, 2016.

E. ASSESSMENT

Assessing the impact of the MakerSpace will come from several sources. Surveys will be emailed in November, 2016 to all active users about their usage, experience, and personal gain from the space. The goals of the space include increasing student confidence in their design thinking skills from ideation to prototyping and prepare them for their engineering career. "Engineers solve problems" is a mantra that has grown out of the Maker movement and the NYU Tandon MakerSpace will equip students with the skills needed to tackle real world open-ended problems.

Students will be asked to state their opinion on how well the MakerSpace succeeds in the "Facility Achievements" described in [12]. So, how well does it:

- Serve as a cultural hub
- Enable students to tackle open-ended, real world challenges
- Serve as an exhibit and tour space
- Foster design in classwork and extracurricular activities
- Encourage collaboration and serve as a welcoming environment for all types of projects

In addition to surveys, assessment will include use of the space and equipment. There is a card swipe at the entrance for data logging. This will allow foot traffic calculation (overall visitors and single visits) and user profiles: faculty vs. student, gender, and school affiliation. During the first month of use, there were over 8,200 swipes, with over 1,700 unique visitors logged.

Users who wish to use machines that require training will be required to checkout at the front desk, which will be recorded. Materials being purchased from the front desk will provide a third data set to assess usage. Several student organizations are holding workshops in the space on topics including Design Thinking, Arduinos, Solder Skills, DIY Arduino, CAD Modeling, Costume Building, and Pop Up Prototyping. Effectiveness and attendance of the workshops is logged.

These data will be combined with qualitative observations (including in situ interviews) of the interactions in the space (individual work vs. team work vs. participation to a workshop; ideation vs. prototyping) which complements quantitative data and provides a richer story on the use of the space. Several faculty members will be incorporating MakerSpace work as a mandatory element of their courses in the spring 2016 semester. The MakerSpace manager will work with faculty to compare two similar classes - one which integrates the MakerSpace in the curriculum and one that does not. Comparison questions will include: for the class without MakerSpace requirement, what proportions of students went to the MakerSpace? Grades and the overall quality of projects for students who went to the MakerSpace and those who did not will also be compared.

DISCUSSION

Programming and events in the space have been identified as the key components for encouraging student interaction and diversity of users, which are key to the mission of NYU Tandon MakerSpace. In line with the design principles which have informed the design process since its start, the MakerSpace has been uniquely designed with an open, reconfigurable floor plan, an inclusive governance philosophy, and an iterative mindset. These allow them to support experimentation, collaboration, and cross-pollination: student and club led workshops, presentations, and competitions will focus on innovation and design, to encourage student growth in the NYU i^{2}e pipeline. The space is uniquely positioned within the building, within NYU, and within NYC to encourage such interaction and diversity.

What makes the MakerSpace unique is the combination of NYC tech culture and NYU curricular activities. It is poised to enrich a schoolwide expansion of project-based curriculum and entrepreneurship. This curriculum's connection to the MakerSpace is intended to be the backbone of the innovation network at NYU. A system of labs, programs, and people exist to support the school's i^{2}e mission. The MakerSpace is meant to be the hub for this pipeline as its goal is to invite students of all different backgrounds to produce their unique ideas in an open environment where support is available to guide them along a successful path, while respecting student's ownership of their accomplishments and contributions. The MakerSpace also aims to serve as a conduit for connecting the university with the New York City community.

A. CURRICULUM

Project-based curriculum begins at all engineering schools in the first-year engineering experience. At NYU, engineering students are required to enroll in an Introduction to Engineering & Design course. The learning objective for this course is to develop the foundation for innovation (informed by the Lean Launchpad methodology) that will be built upon in later project-based curriculum. With the creation of the MakerSpace, updates to this course include adding training on equipment central to the maker movement: Raspberry Pi, Arduino, 3D printers, robotics, and sensors. Students in the course are now required to attend MakerSpace orientation during one of their labs.

Several (current and future) collaborations with other programs at NYU Tandon aim to provide students opportunities to make full use of the MakerSpace's resources. Use of the equipment and space in established courses within the first-year engineering design course, the mechanical, civil, and electrical departments, and the integrated digital media degree will be the first incorporation of the MakerSpace into project-based applications. Integration with the curriculum will then grow to support pre-capstone and major specific design courses.

Moreover, the Vertically Integrated Projects program developed at Georgia Tech has been incorporated into the engineering curriculum. These courses are focused on interdisciplinary research project teams that must be taken over at least three semesters. Current projects at NYU include the Hyperloop, music experience design, human-computer interaction, and recycling plastic for 3D printing. Two of these projects use the MakerSpace for group meetings and prototyping. A new VIP course on Smart Cities Technology has been proposed for spring semester, 2017, and will make use of the space as well.

Another new project-based course is being deployed as part of the VentureWell program. This course is designed to be a pre-capstone course taken in the junior year. It will help to bridge the gap between the first-year engineering cornerstone course and the capstone design. Professors from different departments will provide instruction preparing students for a successful capstone project. The undergraduate and graduate curriculum will feed directly into the entrepreneurship pipeline available to students at NYU, seen in Fig. 2.

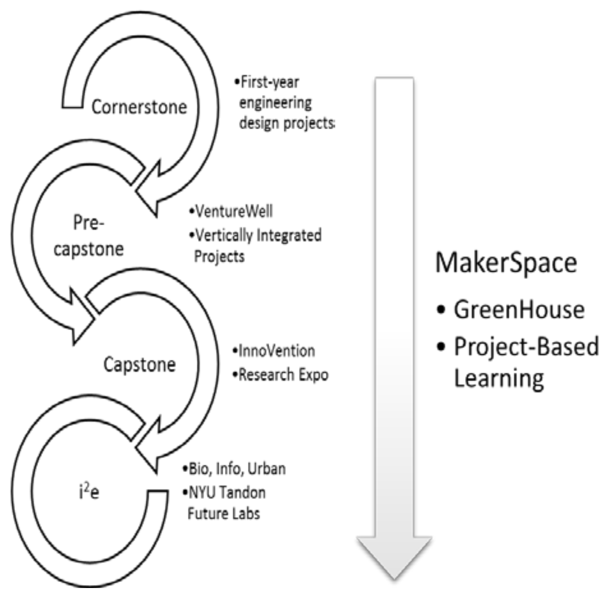

Fig. 2 Pipeline of Innovation at NYU

B. INNOVATION AND ENTREPRENEURSHIP ECOSYSTEM

In the NYU innovation and entrepreneurship ecosystem, the MakerSpace occupies a unique place both for ideation and prototyping. It serves the role to "greenhouse" students' ideas by allowing them to learn and hone skills, meet with students from different programs and schools and last, but not least, experiment, fail safely, and iterate. Once student teams have refined their ideas through iteration and prototyping, they are then ready to explore their business potential and to connect with other spaces and programs at NYU.

In addition to the innovation curriculum initiatives and project-based learning mentioned above, numerous opportunities and resources are already in place at NYU. One such space is the Leslie Entrepreneurs Lab (eLab) on the Manhattan campus and run by the NYU Entrepreneurial Institute. This 6,800 sq-ft facility serves as another type of collaborative work space, focusing on bridging the gap between prototyping to startup creation. The NYU Tandon Future Labs are business incubators that bridge the final gap in the innovation pipeline. These incubators accept companies who have already achieved seed funding and provide guidance and resources to grow. The three incubators and their supported initiatives are:

- The Data Future Lab: data, cyber security, financial tech, and IT

- The Urban Futures Lab: smart cities, smart grid, and clean energy
- The Digital Future Lab: hardware, digital media, and mobile

The MakerSpace is available to the incubator companies to utilize the advanced machining, PCB production, and imaging equipment. In return, companies are required to employ at least one graduate or undergraduate student and to offer workshops and advanced mentoring to NYU Tandon students interested in entrepreneurship. The first Future Labs workshop will be held on November 3rd, 2016.

C. NYC TECH CULTURE

NYU Tandon innovation culture and projects are driven by larger initiatives within the NYC science and technology arena. Smaller-scale manufacturing companies and startups are growing in the Brooklyn Navy Yards and Industry City (Brooklyn). The engineering campus itself is part of the Brooklyn Tech Triangle – the downtown Brooklyn, Dumbo, and Brooklyn Navy Yards which serve as a hub for entrepreneurs and tech activity.

Several other institutions in the New York area are working to push STEM initiatives and provide entrepreneurial support. NYC Media Lab, a consortium of NYC universities that partner with corporate members to generate "research and development, knowledge transfer, and talent development across all of the City's campuses." Several STEM non-profits, like Girls Who Code, support K-12 education and fundamental maker skills.

CONCLUSION AND RECOMMENDATIONS

This paper presents a unique case study of the creation and birth of a University MakerSpace. Indeed, while most papers focus on the official design process led by the architects, this paper takes a broader perspective. It describes the design process upstream (the first prototype of the space with the GreenHouse space) and downstream (the first few months of use of the space).

The MakerSpace aims to encourage multidisciplinary student interaction and collaboration while fostering the Engineering School's mission of invention, innovation, and entrepreneurship and supporting the full development of project-based curriculum at the school. The four design principles, combined with an inclusive governance philosophy and an iterative mindset, were crucial to the design of a space which has so far met its goals. Assessment of the effects of the space on the undergraduate and graduate engineering student population is currently being developed as it is crucial to the future development of the MakerSpace. It will also provide rich insight to current research on makerspaces in educational institutions, as very little is still known about the impact of these spaces on learning.

ACKNOWLEDGEMENTS

The author would like to acknowledge the efforts of the MakerSpace Committee who provided invaluable input, guidance, and support for this project. The author would specifically like to thank Katepalli Sreenivasan, Dennis Dintino, Kurt Becker, Anita Farrington, Peter Voltz, Michael Knox, Nikhil Gupta, Luke DuBois, and Brad Penuel.

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Opening Remarks: Dean Ian Waitz

Monday, November 14th

Ian Waitz
Dean, MIT School of Engineering
Professor of Aeronautics and Astronautics

Favorite making activities
Home DIY — wood, stone, metal, smart-home/electronics
Anything that is an excuse to buy a new tool
Working with a torch
Stained glass
Cooking
Making waves on my kite board

Ian A. Waitz is Dean of the School of Engineering and the Jerome C. Hunsaker Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology. As Dean, Waitz has focused on advancing the mission of the School of Engineering through the development of new programs and spaces for innovation and entrepreneurship, novel models and opportunities in residential education, expanded pathways for engagement with the Institute's alumni, friends, and industry partners, and programs and policies that further enable MIT's ability to provide an exceptional learning and research environment.

He is a member of the National Academy of Engineering, a Fellow of the American Institute of Aeronautics and Astronautics, and a member of the American Society of Mechanical Engineering and American Society of Engineering Education. He was honored with the 2002 MIT Class of 1960 Innovation in Education Award and an appointment as an MIT MacVicar Faculty Fellow in 2003. Waitz received his BS in 1986 from the Pennsylvania State University, his MS in 1988 from George Washington University and his PhD in 1991 from the California Institute of Technology.

Keynote Speaker: Dale Dougherty

Innovation at the Crossroads: The Expanding Role of Universities in the Maker Movement

Monday, November 14th

Dale Dougherty
Founder and Chief Executive Officer
Maker Media, Inc.

Favorite making activity
Cooking

Dale Dougherty is the founder and CEO of Maker Media, Inc. in Sebastopol, CA. Maker Media produces MAKE: Magazine, which launched in 2005, and the Maker Faire, which was first held in the San Francisco Bay Area in 2006. One-hundred Maker Faires all over the world drew 550,000 attendees in 2013. In the spring of 2014, the White House hosted its first Maker Faire. In 2011 Dougherty was honored at the White House as a "Champion of Change" through an initiative that honors Americans who are "doing extraordinary things in their communities to out-innovate, out-educate and out- build the rest of the world." At the 2014 White House Maker Faire he was introduced by President Obama as an American innovator making significant contributions to the fields of education and business.

Lunch Speaker: William Aulet

Import of Making to Entrepreneurship, and of Entrepreneurship to Making, in Education

Tuesday November 15th

William Aulet
Senior Lecturer, MIT Sloan School of Management
Managing Director, Martin Trust Center for MIT Entrepreneurship

Favorite making activity
Woodworking
Making Entrepreneurs

Bill Aulet is the Managing Director of the MIT Martin Trust Center for Entrepreneurship and a senior lecturer at the MIT Sloan School of Management. The center is responsible for entrepreneurship across all five schools at MIT in classroom education as well as student clubs, conferences, competitions, hackathons, and accelerators. During his tenure as the head of the Trust Center, he has conceived, designed, and overseen the implementation of new innovative programs including: Regional Entrepreneurship Acceleration Program (REAP), MIT Entrepreneurship Review, Founders Skills Accelerator, t=0 Entrepreneurship Festival, Corporate Innovators Sponsor Group, Applications of Advanced Entrepreneurial Techniques "GSD Ninjas," and Global Founders' Skills Accelerator.

Prior to MIT, Bill had a 25 year record of success in business wherein he raised more than $100 million in funding for his companies and led the creation of hundreds of millions of dollars in market value. Mr. Aulet holds a bachelor's degree in engineering from Harvard University and an SM from the MIT Sloan School of Management.

Dinner Speaker: Elaine Chen

From Making to Mass Production: Stories from the Field

Monday Nov. 14th

Elaine Chen
Curriculum Director & Instructor, MEMSI
Senior Lecturer, MIT Sloan School of Management
Founder and Managing Director, ConceptSpring

Favorite making activities
Metalworking (Powder metal, sheet metal, water jet, 5 axis CNC, turning, & sand casting)
Cooking on 2-burner propane stove & remote camping sites for 21 people (pictures to prove it)

Elaine is a startup veteran, product strategy and innovation consultant, and author who has brought numerous hardware and software products to market. As founder and managing director of ConceptSpring, Elaine works with leaders in established businesses to help them run new product innovation initiatives with the speed and agility of a startup. She is the author of the book *Bringing a Hardware Product to Market: Navigating the Wild Ride from Concept to Mass Production*. As the VP of engineering and product management at several startups, including Rethink Robotics, Zeo, Zeemote, and SensAble Technologies, Elaine has built, grown, and nurtured technical organizations from the ground up. She is a co-inventor on 22 patents. Her experience spans multiple industries, including consumer electronics, robotics, industrial automation, IoT, CAD/CAM, retail and supply chain software, and healthcare IT.

At MIT, Elaine designs, develops, and teaches courses and programs in entrepreneurship, coaches students on a one-on-one basis, and develops systems and processes to support entrepreneurial students. She holds a BS and an MS in mechanical engineering from MIT.

Morning Short Course

Makerspaces 100

An Introduction to Academic Makerspaces

9:00 am - 12:00pm
November 13th, 2016

MIT, Building 56 Room 154

Synopsis

Makerspaces 100 is an abbreviated version of the comprehensive 2 ½ day HEMI Course "Creating Safe and Effective Makerspaces that Matter to Students" that have been used to design, create/upgrade and sustain safe and productive academic makerspaces. We discuss proven methods to get students excited about using these spaces, forming peer-mentoring communities within these spaces and perpetuating a culture of safe, fun and responsible use. We'll also provide high-level synopses of fundamental principles of successful makerspaces:

- Understanding the general types and their pros/cons,
- The import of culture and community
- Assessing impact/justification
- Staffing and training models
- Optimizing access while minimizing boundaries
- Understanding safety and complimentary policy, insurance, legal and regulatory issues

Instructors

P. Zach Ali - Carnegie Mellon University
Malcolm Cooke - Case Western Reserve University
Martin Culpepper - MIT
Aaron Hoover - Olin College of Engineering
Vincent Wilczynski - Yale University

Schedule

09.00 Welcome, overview, and instructor introductions
09.05 Examples and types of makerspaces and makersystems
09.20 Culture and community, boundaries, and access (with Q&A and discussion)
10.20 Safety, legal and regulatory issues (with Q&A and discussion)
10.40 Space definition and layout (safety, community, programming, general do's and don'ts)
11.00 Navigating campus politics and poison pills
11.15 The import and proper use of metrics and data
11.30 Funding and Budgets

11.45 Q & A, Discussion
12.00 Finis

Afternoon Short Course

Basic Makerspace Equipment

An Introduction to Maker Tools

1:00 pm - 4:00pm
November 13th, 2016

MIT, Building 56 Room 154

Synopsis

An introduction to useful machines for makerspaces, with emphasis on utility/capability balanced with minimizing risks/hazards, cost and issues that pertain to safety and staffing. We will also discuss layout of these types of machines. A short lecture will describe the machines, do's and don'ts, safety issues, and other important issues. Then participants will work with MIT students and staff to use/observe the machines making parts. Participants will be able to choose a subset of (experience 3 of them) tools/technologies from the following pieces of equipment.

• 3D printing & Thermoforming
• CNC machining (circuit board milling, 3 axis milling)
• Vinyl cutting
• Sewing machine

Instructors

Martin Culpepper - MIT
Jonathan McIndoe Hunt - MIT
Saana McDaniel - MIT

Schedule

01.00 Welcome, overview and introductions
01.05 Basic makerspace equipment characteristics, safety and staffing
01.20 Session 1 with machines
01.55 Transition
02.00 Session 2 with machines
02.35 Transition
02.40 Session 3 with machines
03.15 Transition
03.20 Session 4 with machines
03.55 Wrap up and clean up
04.00 Finish

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1st International Symposium on Academic Makerspaces

ISAM was founded, and is run, by the

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