The Value of Campus Collaboration for Higher Education Makerspaces

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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 EventBoard.

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.

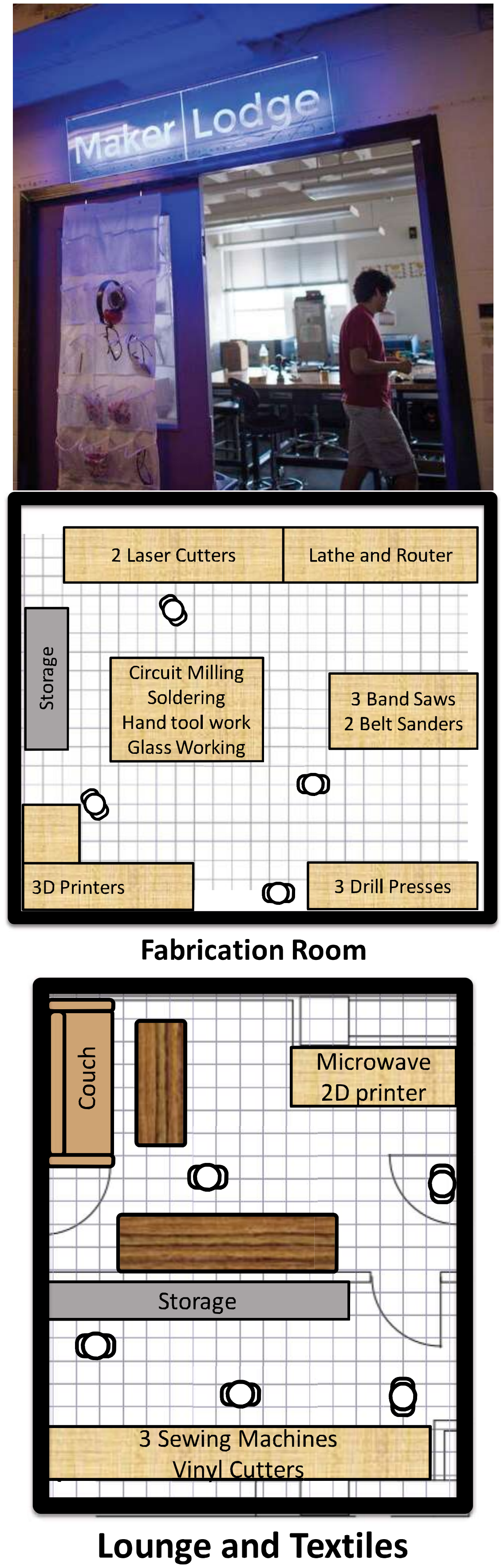

Figure 1. MIT Freshman Training Facility.

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.

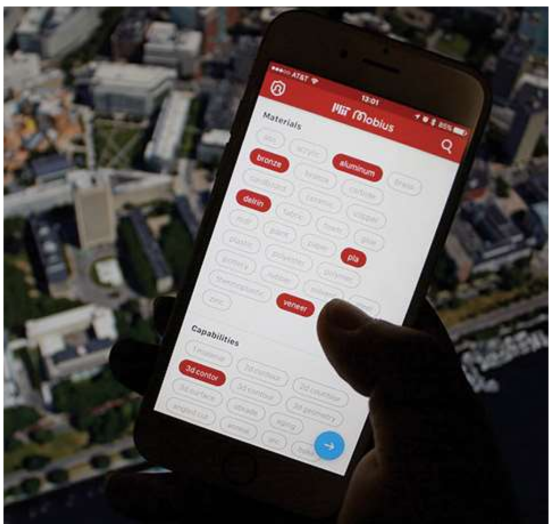

Figure 2. Mobius App for MIT's makers and makersystem management.

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.

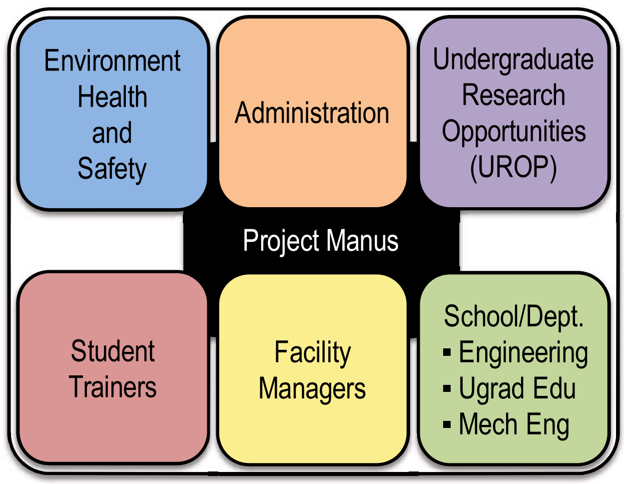

Figure 3. Stakeholders brought together to draft and support the MakerLodge Program.

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]

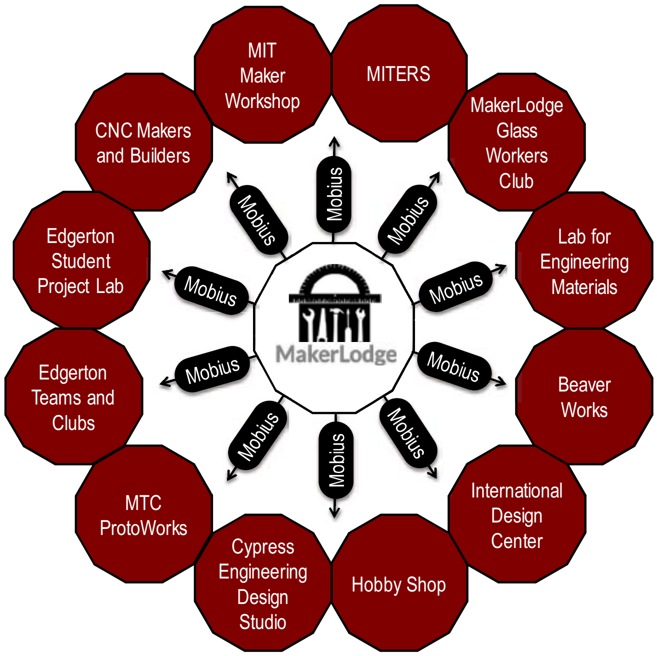

Figure 4. Collaborative network of facilities that accept freshmen graduates of the MakerLodge Training Program and Mobius' role in facilitating student 'flow' between these facilities.

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.

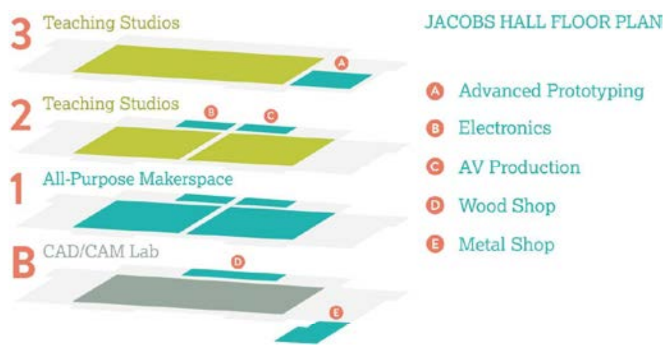

Figure 6. Jacobs Hall combines makerspaces and instructional studios in 24,000 square-feet. Some equipment is separated by function, which allows fine-grained access control.

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.

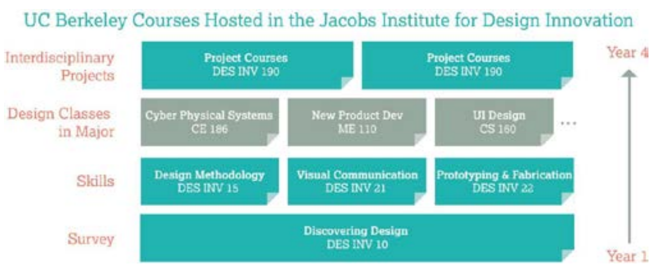

Figure 8. A variety of courses use the makerspaces in Jacobs Hall. DES INV courses shown here (Design Innovation) are offered by the institute; other courses are offered by departments across the university.

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.

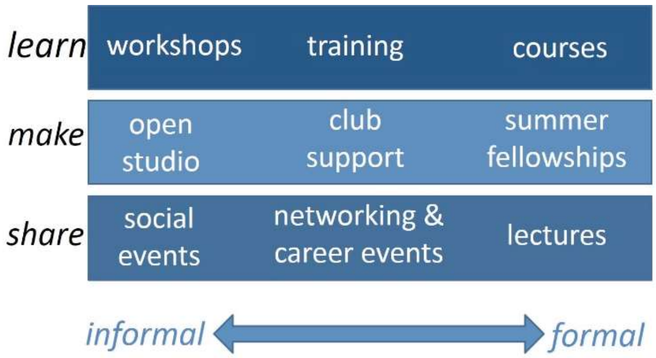

Figure 9. Programs offered within the Yale Center for Engineering Innovation and Design.

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.

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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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