Models for Curricular Integration of Higher Education Makerspaces

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INTRODUCTION

Higher education makerspaces have great potential to provide transformative learning experiences for students on campuses around the world [1]. A number of spaces are student-founded or exclusively student-run [2], exist to support optional, extracurricular clubs and activities, or are otherwise adjacent to the student academic experience. While this approach has demonstrated the capacity for impact on those students who choose to engage with making in those spaces, integration of makerspaces and their resources into the broader curriculum has the potential to reach and positively impact a larger segment of the student population [3] [5].

In addition to the potential to reach more students, integration of making and makerspace resources into the curriculum can strengthen the academic experience by exposing students to experiential, inquiry-driven learning experiences and building skills that may not be emphasized in more traditional coursework like collaboration, design synthesis, and iterative problem-solving [5].

The goal of this paper is to share a variety of models for considering and implementing integration of makerspace resources with the academic curriculum at each of the seven institutions represented here. A brief description of the makerspace resources at each institution is followed by a representative sample of different approaches to integrating with the curriculum. Where possible, a set of lessons learned and future initiatives and directions are provided.

CASE WESTERN RESERVE UNIVERSITY: SEARS THINK[BOX]

Sears think[box] - An Innovation and Entrepreneurship Ecosystem: Sears think[box] is a world-class innovation and entrepreneurship ecosystem that encompasses a makerspace for prototyping and fabrication as well as a full spectrum of resources for entrepreneurs. Located in a dedicated 7-story, 50,000 square-foot facility its physical presence on our university campus enhances all aspects of university life, serving as an integral resource for students, staff, faculty, and alumni. Uniquely, this space is free and open to our corporate partners and the general public. A mission of Sears think[box] is to encourage students, faculty, alumni, and members of the community to tinker and creatively invent in their coursework, research, entrepreneurial pursuits, and personal projects.

Each of the 7 floors, (1 - 7), has a dedicated focus and supports Community, Collaboration, Prototyping, Fabrication, Projects, Entrepreneurship, and Incubation respectively. Collectively they contribute to the center's ecosystem and definition of think[box]-ing. Sears think[box] attracts over 5,000 visits per month and in 2017 had over 70,000 user visits to the space of which 5,000 were unique users. Through a strong partnership between multiple schools and university offices, Sears think[box] focuses the efforts of Case Western Reserve University - an R1 research institution - into a complete menu of services, resources, and facilities to guide and support the creation and commercialization of intellectual property.

Currently, Sears think[box] is engaged in Phase 3 of construction which focuses on the build-out of floors 6 and 7, the entrepreneurship and incubator floors respectively. Phase 3 is slated to be completed and the floors operational by Mid-September 2018. It is this backdrop that provides the motivation for the think[box] planning team to define a wide range of operating strategies and policies to ensure think[box] provides our entrepreneurs with the services and support systems necessary for venture creation.

Sears think[box] is managed by an executive director and small senior management team assisted by a multidisciplinary Steering Committee with representatives from all of the Case Western Reserve University colleges and schools. Think[box] is managed on a daily basis by eleven full-time staff, a team of paid undergraduate student workers, and is fiscally managed by the Case School of Engineering.

CWRU's curricular connections and learning experiences: Sears think[box] exists to provide both the university and community-at-large with opportunities to engage in supportive entrepreneurship, creative innovation, and detailed making. To this end, think[box] offers a range of 'How-to-think[box]' classes each semester that focus on these three areas and are open to all. For the 2017-2018 academic year, think[box] offered over 40 classes and had over 200 registrants. Some examples of classes include Laser-Cutting, Arduino for Beginners, Podcasting, Introduction to SolidWorks, Start with Your Value Proposition, Group Dynamics, and more. Think[box] also provides regular training sessions for the wood and metal shop, which provides the user with an ability badge indicating their skill level with each piece of equipment. For the 2017-2018 academic year, think[box] provided over 700 trainings. The learning outcome for attendees of these classes and training sessions is that a strong level of comfort is established with think[box] so that users are compelled to regularly utilize its equipment and services for business and project ideas.

Sears think[box] also serves as a venue for both internal and external groups to gather and engage in the areas of entrepreneurship, innovation, and making. For the 2017-2018 academic year, think[box] hosted over 45 events and programs, with over 1,773 attendees. These events and programs included design competitions, student showcases, workshops, book launches, business pitch competitions, and more. One specific example is the Morgenthaler-Pavey Startup Competition, held in conjunction with Weatherhead School of Management, which enabled six startups to pitch their business ideas for a chance to win up to $25,000 in prize money.

Sears think[box] has also held Maker Camps for K-12 schools, which has provided the students with foundational knowledge in design and prototyping, as well as hands-on experience with equipment. One example is the Magnet Maker Camp, which was held for two private local high schools. Twelve students spent the afternoons at think[box] learning how to use CorelDraw, laser cutters, 3-D printers, vinyl cutters, and a waterjet cutter for pre-determined projects. Students were also given time during the week to create something on their own. The camp's average rating was 4.75 out of 5 for overall experience and students emphasized the laser cutter as their favorite piece of equipment.

Competition teams benefit from shared think[box] space and facilities*:* The 5th floor of Sears think[box] is open 24/7 and focused on providing space and resources for users to work on their projects, this includes dedicated, lockable 'caged' areas for student competition teams like 'Mini-Baja', 'Design, Build, Fly', 'Rocket' team, and 'Robotics' team. In total these teams have about 2,400 square feet of dedicated space to call their own and work on their respective projects. The result of these creative students working in close proximity to one another sharing the 5th floor and being given extended access hours to the design studio (5th floor), prototyping equipment (3rd floor) and fabrication equipment and processes (4th floor) has been remarkable. The 'Mini-Baja', 'Design, Build, Fly', and 'Robotics' teams had their most successful competition seasons ever and they attribute their successes to strong collaboration between the teams coupled with easy, immediate access to all the design, prototyping, and manufacturing resources offered by think[box].

The future of curricular integration at think[box]: Currently think[box] faculty and staff are engaged in a number of curricular-based initiatives. Briefly these are:

- Early stage of researching and developing a sequence of courses (possibly 2, or 3 - TBOX 101, TBOX 201) that could be taken as electives by students following a range (still to be determined) of degree programs. It is our hope that TBOX 101 could be taken by students following non-engineering or science-based programs.
- Sears think[box] has a close relationship with the Cleveland Institute of Art and currently offers a joint course on Design Thinking. We plan on developing that collaboration further to explore studio-based design/make/validate courses that would be cross-listed between the two institutes. Our initial focus is likely to be aimed at courses for students following Mechanical Engineering (CWRU) and Industrial Design (CIA) degree programs at the respective institutes.
- Think[box] is in the early stages of developing customized programs for corporate partners which in the future could lead to think[box] offering a focused innovation/design-thinking certificate program.

GEORGIA INSTITUTE OF TECHNOLOGY: INVENTION STUDIO

The Invention Studio is a free-to-use, 5000 sq. ft. makerspace and culture at the Georgia Institute of Technology. Though initially founded specifically for the Capstone Design course, the Invention Studio has taken on a life and culture of its own, far beyond just a capstone design prototyping lab. There, 2000 student users per month hangout, create things (using $1M of capital equipment), meet, and mentor each other for at least 40 courses as well as independent projects. The Invention Studio is centrally managed and maintained by an all-volunteer 100 person student group with support from the university staff and courses. Each volunteer donates 3 hours per week to staff the shop for student users in exchange for 24-hour access.

Georgia Tech's curricular connections and learning experiences: Over 40 courses have voluntarily embraced the Invention Studio for prototyping facilities and support. Here we give a few examples:

ME 1770: ME 1770 is an introductory mechanical engineering design course. The course is organized to introduce students to design, engineering and to provide prototyping experience. Students learn CAD, free-hand sketching critical for visual-spatial reasoning, communication, modeling, and perspective sketching. Software tools include Mechanix, a sketch-based AI tutoring sketch developed to provide expert feedback on student sketching skills within large classrooms typical of engineering. To provide more time for interaction with teams and instructors, a flipped classroom model has been implemented. Creativity and intrinsic motivation are engaged through the addition of a 3D printer project in the Invention Studio that exercises students' CAD skills while also providing the opportunity for creative design and a deeper understanding of manufacturing tolerances. Industry continues to stress the criticality of students understanding manufacturing tolerances, dimensioning, and related issues. An open-ended team project provides greater opportunity for creativity, which has been shown to increase retention. Students who learn the perspective sketching express that the sketching improves their ability to communicate, increases their creativity, and they feel it is a good use of their time and will serve them later in engineering.

ME 2110: Creative Decisions and Design (ME 2110) is the required second-year design-build experience for undergraduate students. In this course, students learn that it is important to conceptualize and draw an idea on paper. However, it is a totally different experience to implement the design such that it functions in an efficient, robust, and reliable manner. The students also learn the basics of fabrication, as well as mechatronics and real-time programming. ME2110 holds the unique distinction of being overwhelmingly identified in undergraduate exit surveys as the most difficult course in the ME undergraduate curriculum, and also, by far, the students' favorite experience.

The course uses basic mechatronic concepts and projects as a vehicle for mechanical design and technical communication instruction. It provides many students with their first machining and fabrication experiences, as well as providing experience in collaborative design environments and with technical communication. The continued evolution of this course has led to a curriculum that is both challenging and rewarding. Significant industrial support has provided excellent resources and indicates the value that industry places on the concepts taught in the course. The final course project and contest provides many students with the highlight of their undergraduate educational experience.

The inclusion of mechatronic projects benefits students, who are able to practice the design concepts that they have been taught while forming a strong foundation in mechatronics principles. The projects are also rewarding, as they often afford the students their first opportunity to design and build a computer-controlled machine. However, the integration of mechatronics projects into the course poses significant challenges for the faculty. For example, the basic mechatronic concepts, such as electric motor operation and control system programming, must be taught in addition to the mechanical design material. Such a course also provides an opportunity to integrate oral and written technical communication with a two-fold benefit for the students. First, the students practice the basic tasks of describing and presenting designs. Second, in presenting the design tools used to develop their designs, the students display their understanding of the course material, allowing instructors to revisit those topics that the students have not mastered. Large mechatronics projects provide experience with documenting a complete design process, including discussion of the traditional design and concept evaluation tools. These projects provide an excellent vehicle for benefits listed above for two reasons. One reason is that much of the project cannot be seen, such as computer code, making clear and concise description a necessity. The second reason is that such projects can become complex, necessitating thorough presentations and reports. The project complexity also provides the opportunity to require interim reports and presentations, giving the students additional technical communication experience. Providing the tools necessary to include a large-scale mechatronics project into a required undergraduate course that typically has 150–200 students per term is a large expense. To offset this, corporate sponsorship is crucial. Partnerships with industry for such courses are beneficial to the school, students, and the industry sponsors. Students are exposed to key industry companies, while receiving experience that is valued by employers. Much of the student prototyping for this course occurs in the Invention Studio.

Workshops: Student volunteers have become well-engaged in the Studio, taking initiatives to improve equipment capabilities and to host workshops for their peers in specialized design and manufacturing topics. For example, they regularly run evening workshops on topics such as microcontroller programming, motorized scooter design, stained glass window making, book-binding, knitting, and others. Multiple workshops are held in evening hours every semester, are free or low-cost, and are open to all Georgia Tech students, faculty members, and staff.

Georgia Tech's lessons learned from curricular integration: Georgia Tech relies on the Invention Studio as the central campus facility for "create-innovate-design-build" curricular experiences for dozens of curricular experiences, for example from the freshman level (ME 1770), through the sophomore (ME 2110), and junior-level (ME 3210), and culminating in a capstone design course (ME 4182/GT4823), interwoven with extracurricular opportunities (Invention Studio, Inventure Prize, CREATE-X).

New courses requiring occasional use by a few dozen students can be integrated without significant planning, whereas courses that will inject hundreds of students on a structured path (e.g., design and 3d print) require resources to support and staff. Maintaining active communication with course instructors and Invention Studio staff is therefore critical

These curricular opportunities significantly enhance the quality of our graduates as they enter the workforce. The unifying theme in these initiatives is the high level of trust that been invested in our students. The students have responded with enthusiasm, dedication, and commitment because we have trusted and enabled them to "*create and make*."

MASSACHUSETTS INSTITUTE OF TECHNOLOGY: MAKERLODGE AND MARTIN TRUST CENTER FOR ENTREPRENEURSHIP PROTOWORKS

Small spaces making a big impact: MIT has over 45 design and build spaces that are available to students. The MakerLodge and Martin Trust Center ProtoWorks are two makerspaces that exist outside of departments, and are therefore available to students across all majors. These spaces provide key entry points for students to get into making by supporting maker-specific project-based classes (Introduction to Making) and enabling students to have non-class experiences that provide a solid foundation for future making in classes, research, entrepreneurship and personal endeavors.

(a) (b)

Fig.1 MIT's Makerlodge (a) and Martin Trust Center for Entrepreneurship ProtoWorks (b) facilities

The MIT MakerLodge [7] is an 800 sq. ft. makerspace created to enable MIT freshman to obtain training in basic maker tools, including laser cutters, 3D printers, drill presses, bandsaws and hand tools. The training in MakerLodge is developed in coordination with a broader makerspace community, but is in large part student-designed and student-delivered. One staff technician oversees the MakerLodge program in addition to other duties.

The Martin Trust Center for Entrepreneurship's ProtoWorks is a 340 sq. ft. makerspace which is open to all MIT students working on an entrepreneurial idea. It is staffed primarily by highly-qualified student makers with oversight provided by a staff facilitator as part of his several responsibilities in the Martin Trust Center.

MIT's curricular connections and learning experiences: *MakerLodge* - Most MIT freshmen take advantage of faculty led, interest-based freshman advising seminars. The topics of these seminars range from *Geek Book Club* to *Photography*, to *Solving Climate Change and Environmental Challenge* [8]. The *Mens et Manus* seminar, *The Joy of MIT* [9], enables freshmen to explore their interests with hands-on projects. At the beginning of the fall, the freshmen in the seminar go through the MakerLodge program and are trained on four 3D printer models, two laser cutter models and other tools. With this basis for making, the students are able to take on more ambitious projects early in the freshman year. Over 1,000 freshmen have participated in MakerLodge over the two years of operation.

Introduction to Making - *Introduction to Making* is taught jointly between the School of Business and the School of Engineering. ProtoWorks supports the course by providing a space that the students can come to learn how to use the tools and build their projects throughout the semester. The course's undergraduate TAs work with the shop facilitator to establish a balance between course access and keeping the space available for the general student audience it serves. The TAs host lab hours in ProtoWorks and run the students through the basic training at times when the shop would otherwise be closed. The average class size is 35 students and has been taught for four semesters.

MIT's lessons learned from curricular integration: MakerLodge has been in operation for 2 years. In that time, we have learned that less can be more when training emergent makers. An MIT freshman's time is so packed that trainings had to be time-optimized (less than 5 hours total) to maximize the value to them. There is a significant drop off in interest if the training lasts more than 5 hours. Optimizing the trainings by reducing the time students spend waiting, e.g. reducing the vector path length of the laser cutting for the project, etc. is necessary or students will not participate. We have found that the once our freshmen have had a taste and develop confidence with a few tools they have the desire to seek out opportunities to learn more on their own. These results are shown in Fig. 2.

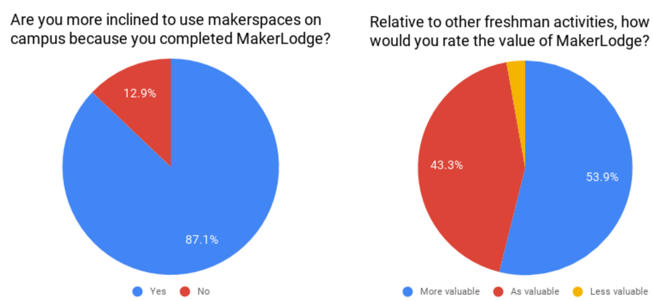

Fig. 2: Data from a MakerLodge student satisfaction survey

Introduction to Making - We have known that once a class starts utilizing a particular student run makerspace, it can quickly take over. Even with this knowledge we experienced the situation where near the end of the term, as final projects were due, the students from Intro to Making and their projects took over the ProtoWorks and made the space less inviting to the intended entrepreneurial audience. A key problem is the students desire to 'bite off more than they can chew' and pursue 'super cool' projects. Although they completed projects and did them well, they were unnecessarily complicated for the learning goals of the class. Following this realization, we have adjusted the project scope for Intro to Making and put a size limit on the final projects. We also increased our effort to form a joint community between the TAs and the student mentors that run the space so when issues start to arise, they can be quickly resolved. We have not experienced similar problems since making the changes in the class.

The future of curricular integration at MIT: There are more students craving maker education than just freshmen. As the MakerLodge Program and Introduction to Making course have grown, we have continued to hear from students from across all departments the desire to develop deeper levels of understanding and skill with various maker equipment and design principles. We are currently building out a new makerspace that has the mission to conduct Research and Development on training - to run experiments that determine how to maximize the bang (student satisfaction, retention, etc.) for the buck (resources, time, etc.) in training ranging from introductory to advanced. We will continue to build on the student-run model for training and spaces in preparation for the new large community space destined for the planned 20,000 sq. ft. makerspaces in the MIT Metropolitan Storage Warehouse.

OLIN COLLEGE OF ENGINEERING: THE SHOP

The Shop at Olin College of Engineering is an assemblage of spaces (totaling approximately 4500 sq. ft.), equipment resources, and people with the primary goal of supporting the college's heavily project-based, hands-on, experiential curriculum. Because Olin College does not have departments, The Shop is not hosted or funded by a department, and instead serves all students, faculty, and staff regardless of affiliation. The Shop was opened at the same time Olin admitted its first class of students in 2002, and it currently supports the entire Olin student body (approximately 350 students). It is staffed by a combination of one full-time faculty director, 3 full-time staff members, and a team of approximately 18 student workers affectionately called NINJAs (an acronym that stands for "Need Information Now, Just Ask").

Olin's curricular connections and learning experiences: The Shop is integrated with Olin's curriculum through four primary avenues: 1) providing introductory training on fabrication equipment and techniques to support early design experiences 2) directly supporting courses with an emphasis on making a physical product or project, 3) supporting courses that use making as a tool to study a particular topic (apart from design), 4) hosting and supporting co-curricular learning experiences.

1) Training to support foundational design experiences - ENGR 1200 - Design Nature is the introductory design course taken by all first-year students at Olin in their first semester. The course uses nature as a source for inspiration and understanding to enable students to develop bioinspired ideas into functional prototypes. Students complete two projects (one individual, and one team) in the course as they build experience in visualization, experimentation, estimation, prototyping, and fabrication in the context of design. To support the courses learning objectives, The Shop provides introductory training to all first-year students in the early weeks of the semester on Olin's first safety tier ("green") machines - the bandsaw, drill press, and belt sander. After completing "green" machine training, students are free to use The Shop any time and pursue more advanced training.

2) Directly supporting courses with a making emphasis - A number of courses at Olin include learning experiences or projects where students are expected to make a physical artifact. One such course is ENGR 2110 - Principles of Engineering, a required second-year course for all students in which multidisciplinary teams of students collaborate on an eight-week project that must integrate mechanical, electrical, and software/firmware elements in a mechatronic system. Projects are defined independently by the (approximately 20) teams, so the need for expertise and training on processes and equipment varies considerably. To support the course, a subset of Shop NINJAs coordinates with the course teaching team to schedule work hours that coincide with class times. NINJAs visit class to deliver demonstrations, offer ad hoc trainings, and generally support and consult with their peers on design and fabrication challenges they may be facing.

3) Making as a tool to study other topics - Recently, some courses at Olin have begun to integrate making not as the focus of a project or a skill to be learned as part of the design process, but as a tool for studying concepts encountered in more traditional engineering classes. One such example is a new experimental course, CIE2016A - Quantitative Engineering Analysis (QEA) [6]. The course is designed to teach advanced math and physics in the context of engineering problem solving. The first project challenges students to design and build a small-scale boat that floats and right itself within a single class period. After their first efforts inevitably fail, students are introduced to the math and physics that enable them to generate analytical solutions to the problem. During the last week of the first project, they build designs based on their analysis and demonstrate their boats' performance. In this type of curricular integration, the making skills or a prototyping mindset are not the focus of learning. Rather, in these experiences making is a tool for building and sustaining engagement and connecting and demonstrating theoretical concepts via a real-world problem.

4) Co-curricular learning experiences - At Olin, faculty and staff have the opportunity to offer "co-curricular" learning experiences - non-credit, limited-time learning experiences with an intellectual component. Many of these experiences make use of The Shop and its resources. For example, Professor Aaron Hoover teaches a bicycle frame design and fabrication course in which students learn about different aspects of frame design (geometry for riding style/terrain, materials selection, etc.), design their own steel frames from scratch, and fabricate them using oxy-acetylene brazing techniques. Professor Rebecca Christiansen has also run a co-curricular course called "Materials and Making" with a welding instructor. The co-curricular explored, in partnership with students, the creation of a materials science class that studies materials through the lens of machining processes like welding and milling. Potential course project designs were motivated by questions like "Why don't welded joints fail at the weld?" and "How is it possible to machine steel with steel itself?"

Olin's lessons learned from curricular integration:

1) Balancing dedicated support for courses with general use - Dedicated support for specific courses must be carefully balanced against maintaining an open and accessible space for all users. Without careful planning, a single course can "take over" a space, limiting its usefulness for the rest of the community. For example, the "green" machine training of approximately 90 first-year students requires closing The Shop for at least 10 hours over the course of several weeks. Minimal disruption to normal use patterns is achieved by scheduling these training batches early in the semester when demand for access to the space is low.

2) Integration with non-design courses requires teaching team collaboration - Using making as a pedagogical tool in a non-design course requires thoughtful and sustained collaboration between the makerspace faculty/staff and professor(s) running the course. Faculty without design expertise are often unaware of the possibilities afforded and constraints imposed by the makerspace resources. They may also need assistance appropriately scoping and framing projects to meet the learning objectives they have for students.

3) Staff and faculty involvement can propel integration - Directly reaching out to faculty and instructional staff to increase awareness of the capabilities of the space is critical to sparking new ideas for curricular integration. For example, at Olin, running dedicated "green" machine training sessions for any interested faculty and staff during intersession breaks has helped them to feel welcome in the space and invited them to connect their courses to activities and projects students are already pursuing in the space.

The future of curricular integration at Olin: Olin has a number of interesting initiatives to be developed in the curricular integration domain. Two are listed below:

1) Deepening learning experiences through making - The role of making in design courses is well-established by now. But, as we've seen with Quantitative Engineering Analysis and the Materials and Making co-curricular, making has the potential to deepen learning experiences in courses not explicitly devoted to the design process. Indeed, there is additional potential to deepen learning experiences in humanities and social sciences courses through the integration of making as well.

2) Connecting to partner institutions through a collaborative makerspace - Olin is part of a 3-college collaboration that includes Babson and Wellesley Colleges. Babson will complete construction of a new 10,000 square foot makerspace called the Weissman Foundry in the fall of 2018. A Weissman Faculty Fellow from each of the three colleges will teach and work in the space, and the space will also host a 3-college course titled "Affordable Design and Entrepreneurship." Collaborative course offerings as well as co-curricular programming is intended to foster greater collaboration between students and faculty on each of the three campuses.

STANFORD UNIVERSITY: THE PRODUCT REALIZATION LAB

The Stanford Product Realization Lab (PRL) is the largest teaching lab and academic makerspace at Stanford University; it spans approximately 9000 sq. ft. with six distinct lab areas: machining, woodworking, foundry, welding, plastics, and rapid prototyping. While the PRL operates under the auspices of the Mechanical Engineering Department in the School of Engineering, students from all disciplines and experience levels across campus are welcome. The Product Realization Lab is primarily a teaching lab supporting coursework in dozens of academic classes, but student research, personal work, and exploration are also encouraged.

Under the direction 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 of over 1000 students focused on learning through making. The PRL's two co-directors and two additional lecturers manage the labs and teach courses, while a group of about 20 graduate student Course Assistants mentor and coach students through open lab sessions, structured labs and workshops, and small group work.

Stanford's curricular connections and learning experiences: The PRL integrates with Stanford's curriculum through a few paths: 1) design courses taught by PRL faculty that center around significant hands-on work in the PRL, 2) engineering or design courses that include the design and making of something physical, 3) non-engineering/non-design courses that include elements of making to enhance other modes of learning

1) *Courses taught by PRL faculty* - There are currently 13 courses taught by PRL faculty that are based primarily in the PRL. These courses range from manufacturing process seminars to advanced design and manufacturing courses focused on specific processes such as silversmithing or injection molding. These 3-4 unit courses run for a standard academic quarter, and typically include hands-on structured lab activities in the PRL, along with design work and prototyping in the lab.

2) *Engineering or design courses that require making something physical* - Approximately 20 additional engineering or design courses include project work that is directly support-

ed by the PRL. When faculty communicate with PRL staff prior to large assignments, the lab is able to better meet the needs of the students. For example, a thermodynamics capstone course called ME140 Advanced Thermal Systems culminates in a rocket nozzle and fuel grain design, analysis, and testing competition. Each student team is required to machine several graphite nozzles and polyethylene fuel grains in the PRL. Many students in the course may be out of practice with the equipment required to make these parts, so special workshops are organized every year to reorient the students and get them set up with safe and efficient machining strategies to help them realize their designs. Another example of how curriculum can be supported is a course called ME112 Mechanical System Design. Typically this course culminates in a project where student teams design, analyze, and build a biomimetic mechanical device (such as a walking alligator or a swimming duck). Most projects lean heavily on the laser cutting resources in the PRL (many students would claim that they're "only there to use the laser cutter"), but the significant additional resources of the PRL Course Assistants, prototyping supplies, adhesives, fasteners, and small hand tools are also critical for their productive work. By discussing the specific project requirements with the course's teaching team, PRL staff are able to anticipate student needs.

3) *Enhancing learning in non-engineering/non-design courses* - As described in [7], the PRL often supports humanities courses from across campus. The PRL hosts focused workshops for students in courses such as Writing, History, and Classics to help students build the technical skills to physically realize the conceptual learning goals of their coursework. These collaborations have evolved organically as relationships are built between faculty and the PRL's management.

Stanford's lessons learned from curricular integration:

1) *Building a skills "tool belt" as needed* - It has long been the approach of the PRL leadership that students should not need to be trained on every tool prior to having a use for it. For example, if a student wants to work in the Woodworking Lab for a personal or course project, they do not have to be signed off on every piece of equipment first. With an on-duty Course Assistant in every open lab, students can seek out design and equipment guidance and instruction as needed. For more complex equipment or processes such as the manual mill or the sand casting foundry, structured labs or workshops are offered in the context of specific courses to give a larger group a consistent and relevant introduction to the tools.

2) *Lasting value comes from real work* - To truly integrate a learning experience in the PRL into their curriculum, an instructor should be willing to assign work that requires that the students really engage and create something in the lab. A one-hour visit to see a machine in action does not constitute a collaboration; to learn from the experience, it is critical that the students are faced with some struggle or conceptual friction as they make decisions about how they should address a given problem in a new way.

One example of this was seen recently in a multidisciplinary course called Design for Extreme Affordability. This course is made up of students from all across campus: the Schools of Medicine, Business, Law, Engineering, and Humanities are all represented. For the past several years that the course has been offered, all students in the course have been required to attend a PRL safety orientation and acquire a lab pass for the two quarters of the course, as there is a strong emphasis on prototyping and "getting physical" with project work. However, the students often provided feedback at the end of the course that they wished there had been more opportunities to learn in the PRL; while their passes give them access to the lab 12 hours a day, they did not put in the time to seek out learning on their own. In Winter 2018, the teaching team created a new assignment that required every student to visit the PRL early in the course and make a small personal object using three prototyping processes and three different materials. The energy and pride that was exhibited during the presentations of this assignment signified the value of this required work. The teaching team observed a strong bias towards prototyping throughout the course from non-engineering students such as medical and business students taking the roll of the primary "maker" on a team.

3) *Process-based design courses are one way to support a focused learning and design experience* - Students have been increasingly drawn to courses that emphasize a specific topic. For example, students often take ME318 - Computer-Aided Product Creation, because it makes extensive use of CNC machines, which the students think is cool and exciting. However, the real goal of the class is to teach students the importance of Lateral Thinking and the CNC tools are instrumental to support that topic. Typically less than 1% of former ME318 students use CNC machines after graduation, but the use of that particular tool has been a way to further their design process more broadly.

The future of curricular integration at Stanford:

1) *Further collaborations with non-engineering/non-design faculty* - As mentioned previously, the relationships that have led to Humanities courses engaging with the PRL have generally evolved organically; for example, a Course Assistant was teaching at a summer high school program where a Stanford instructor was also teaching. Their conversations generated excitement about trying to incorporate workshops and an assignment into an undergraduate writing course. New and interesting collaborations may need more of a catalyst and intentional effort to cultivate, and additional effort could be spent on outreach.

2) *More diverse entry points require new ways of thinking and teaching* - An increasing number of students seek out structured learning experiences in the PRL before their academic coursework requires them to do so. In some ways,

thinking about ways of supporting these students' work is a step away from curricular integration, towards a more generally open learning environment. The current operating schedule and structure of the PRL, coupled with the desire to balance open lab time with course-specific lab work, would require consideration to add an element of more significant learning opportunities outside of the structure of courses.

UNIVERSITY OF CALIFORNIA, BERKELEY: JACOBS INSTITUTE FOR DESIGN INNOVATION

The Jacobs Institute for Design Innovation has its home in a dedicated 24,000 sq. ft. building, Jacobs Hall, which opened its doors in 2015. The Institute is a project of the College of Engineering, but explicitly open to students and faculty across the entire campus. The first floor of Jacobs Hall is dedicated to the university's most active makerspace, with more than 1100 registered users in a recent semester. The two floors above the makerspace are largely dedicated to three teaching studios, two for classes with up to 45 students, and one for classes up to 120 students in size. The basement has additional workshop resources as well as a CAD/CAM classroom. Together, the classrooms host 20-24 classes per semester, with a combined enrollment of about 1200 students per semester. About half of the students who get a "Maker Pass" to use the makerspace also enroll in a class in Jacobs Hall during the same semester; many other students use the makerspace for classes not held in Jacobs Hall; student club activities; or personal projects. A detailed picture of usage statistics is available in Schoop et al.'s MakerLens paper [11].

Berkeley's curricular connections and learning experiences: Teaching and making are tightly interwoven at several levels: through existing departmental courses; new courses launched by the Institute; student-led courses; and additional teaching modules and informal programs.

Departmental Courses - Jacobs Hall hosts many courses dedicated to human-centered design and emerging technologies from departments across the university. Examples include New Product Development (ME110); Designing for the Human Body (ME 178/BIOE 137); Critical Making (CS 294-85); Product Management (IEOR 186); Bio-Inspired Design (IB 32) and Flexible Hybrid Structures (ARCH 259). Faculty can elect whether they require their students to also get a Maker Pass to access the makerspace. A number of these departmental courses were first identified through a small course grant program in 2015 in which faculty applied with existing courses that could benefit from the making resources and studio classrooms or with new courses they envisioned. Many of the original applicants have become regular teachers in Jacobs Hall. In addition, a semesterly application process invites faculty to apply to teach design courses in Jacobs Hall by asking two questions: 1) How would your course benefit from the teaching resources and makerspace in Jacobs Hall? 2) How does your course contribute to the mission of the institute?

New Design Innovation Courses - In addition to departmental courses in existing majors, the Institute's leadership also identified a set of core conceptual topics and practical design skills that were not yet well-served. In response, we created a new campus-wide course designation to teach these topics - DES INV for design innovation - and a process for proposing and reviewing courses in this new designation. Each semester, four to six DES INV courses are now taught in Jacobs Hall. Our initial work focused on building a comprehensive lower division curriculum for first- and second-year students, so students can later take their skills into project-based classes in their major. In contrast to existing disciplinary design courses, DES INV courses were explicitly designed to be open and accessible to students from any major on campus. The DES INV suite[1] of courses comprises:

- **DES INV 10** - Discovering Design: A broad introduction to the world of design, covering design careers, design fields, histories of design, and ethics in design.
- **DES INV 15** - Design Methodology: Exposure to the mindset, skillset, and toolset associated with design: approaches to noticing and observing, framing and reframing, imagining, experimenting and testing.
- **DES INV 21** - Visual Communication and Sketching: Great communicators today should never hesitate to reach for a pen and draw. This course gives participants practice and confidence in their ability to communicate through sketching.
- **DES INV 22** - Prototyping and Fabrication: This course teaches concepts, skills and methods required to design, prototype, and fabricate physical objects using 2D and 3D processes.
- **DES INV 23** - Creative Code and Electronics: This course teaches techniques to conceptualize, design and prototype interactive objects with and without screens; basic circuit design and construction for sensing and actuation; and debugging.
- **DES INV 24** - User Experience Design: Students work as individuals and in small teams to design mobile information systems and other interactive experiences.

As a research university, we are also interested in understanding the impact that DES INV courses have on our students. Initial results from survey research by Rosenbaum suggests that these design courses can increase self-efficacy and interdisciplinary awareness [8].

For students who have taken some foundational design courses, the Institute also offers upper division and masters-level courses where students can exercise their skills in particular design domains, working in teams that combine at least two different disciplines. Topics for these courses are expected to change over time, to respond to societal challenges and technology trends. Offered courses include:

[1] Course descriptions are available at http://jacobsinstitute.berkeley.edu/learn/courses/.

- **DES INV 190** - Re-Imagining Mobility: A collaboration with Ford to find design solutions to challenges introduced by changes in transportation technologies.
- **DES INV 190** - Designing Technologies to Counter Violent Extremism: A course that gets students to rethink how their technical preparation may contribute to counter radicalization and extremism.
- **DES INV 290** - Digital Fabrication Everywhere: A course that helps graduate students envision how digital fabrication can be of utility in their thesis or research projects.

In future semesters we will create additional courses focused on the design of VR/AR experiences and on design of prostheses.

Student-Led Courses and Clubs - A distinguishing characteristic of UC Berkeley is the existence of student-led DeCal ("Democratic Education at Cal") courses in many departments on campus. These courses are developed and taught by students, and enrolled students earn units towards graduation requirements. Syllabi are reviewed and approved by faculty, but students are in charge. In the evenings, most design studios in Jacobs Hall are taken over by these DeCals. Examples include: Assistive Technology Design; Web Design; Graphic Design Principles; 3D Printing and Design; Solar Decathlon. Recent enrollment in DeCals hosted in Jacobs Hall has been 350-400 students per semester. These courses are often created by student clubs. Many of these clubs also meet in Jacobs Hall in the evenings.

Teaming Support - Project-centric courses involve teamwork, but few students or faculty are explicitly trained in how to create successful teams. To support students in effectively working in teams, Prof. Sara Beckman and collaborators have developed a series of assignments that teams undertake to be purposeful and reflective in their processes[2].

Berkeley's Lessons Learned from Curricular Integration: Reflecting on our curricular design activities over the past three years has led to some important themes: First, we are increasingly aware of the gap between short introductory safety trainings in the makerspace on one hand and semester-long design courses that use the makerspace on the other hand. In response, we are experimenting with different short workshop formats - some led by professional staff, and some by students. Initial lessons learned are described in Gottbrath and Rice, "Beyond General Workshop Safety" [7]. We are also starting to offer week-long introductions for transfer students from community colleges.

Second, after creating many new courses, it is important to give students pathways that help them navigate and sequence all these new offerings. Faculty across campus have recently launched the Berkeley Certificate in Design Innovation (https://bcdi.berkeley.edu/). Students can obtain a certificate by taking four different design courses across three different categories. Students can satisfy these requirements entirely with courses offered in the Jacobs Institute that utilize the makerspace; however, they are also encouraged to broaden their understanding of design through courses across campus, from architecture to theater scenography and musical instrument design. To date, about 100 students have enrolled in the certificate program and 33 have graduated, with only modest publicity. We expect these numbers to grow significantly.

Finally, some challenges of operating as an Institute without an associated degree program are coming into focus. Students that enroll in our courses have varying levels of involvement that may or may not correspond to the way curricular pathways have been designed. For example, students attempting to take advanced design courses may not have taken introductory courses; and some students in introductory courses already have extensive backgrounds. This diversity of preparation presents some challenges to teachers. These challenges are unlikely to disappear as the Institute strives to give a large number of students at least some exposure to design and making. However, we are also simultaneously planning to growing a cohort of students who wish to focus their future careers on design and making through a new masters degree program.

YALE UNIVERSITY: CENTER FOR ENGINEERING INNOVATION AND DESIGN

The Yale Center for Engineering Innovation and Design (CEID) is a 9,000 square foot facility open to the entire university. 2,500 members of the Yale community (including staff, faculty, graduate students, and undergraduate students) have 24/7 access to the space with this access granted following an initial orientation and safety training session. The space is comprised of a lecture area that adjoins the central studio, with no boundary between the presentation and work sites. Equipment requiring advanced training and active supervision, such as CNC mills, lathes and routers, is segregated from the studio in windowed workspaces. A BSL-1 wet lab is also in the makerspace. The CEID, now it its 6th year of operation, has a full-time staff of 2 design faculty and 2 design fellows. The non-tenure track design faculty have teaching responsibilities (one course/semester) as well as operational responsibilities within the academic makerspace. The design fellowships last two years and serve as a stepping stone between an undergraduate degree and graduate school or a position in industry. The CEID is administered and funded by the Yale School of Engineering & Applied Science.

Yale's curricular connections and learning experiences: Experience has shown that design-based courses held within academic makerspaces can serve as important mechanisms to cross academic boundaries. At the CEID, courses have been offered which provide design opportunities for undergraduate students from a collection of academic years and

[2] This material is available online at https://www.teamingxdesign.com/.

spanning departments and schools. As "discipline-agnostic" facilities, academic makerspaces promote experiential learning opportunities based on themes rather than disciplines. This approach mimics that of the real world where problem solving originates from needs that are not bounded by academic disciplines.

Two courses are profiled to illustrate this principle: an introductory course "Introduction to Engineering Innovation and Design" and an advanced course "Making Spaces." In each course, lecture components are combined with makerspace studio experiences to have students develop a theoretical understanding (of specific topics and the design process) and apply that knowledge/newly-acquired skills to open-ended problems. Clients (from the university and other academic institutions) present design challenges to small teams who work within each course to design, fabricate and document solutions to the proposed problems. Each course is open to all students, from all backgrounds, with individual students applying to participate in the course. The application process establishes a sense of belonging that helps create a unified mini-community among the course participants. The following course profiles illustrate how makerspaces can support client-based projects where students from multiple disciplines work together to solve problems.

"Introduction to Engineering Innovation and Design" is a course targeted at 25 first-year students. The course provides instruction in one topic in each of the School's majors in Biomedical, Chemical, Environmental, Electrical, and Mechanical Engineering, as well as Computer Science. Skills are developed in programming, CAD, fabrication, electronics, experimentation, and design through a series of weekly lab activities held in the makerspace studio. The lab experiences are all associated with that week's classroom lecture topic. The final 6 weeks of the course involve team-based problem solving for a university client. Before the semester begins, the course instructors search for external clients and then vet specific projects to find problems that can be solved using technology presented in the course within a limited time period. The clients, who originate from across the university, pitch their problems to the students who then work (in teams of 4) on a solution. Hour-long client meetings, overseen by the course instructors and teaching assistants, are held weekly where the team presents their progress and the client offers feedback. This guided relationship, that is the direct contact of the students and client and managed by the course instructors, is important to the course's success. The term ends with presentations of the solutions, many of which are taken from the makerspace and implemented in the field by the clients.

Two examples illustrate experiential learning in this course. In one application, curators from a Yale art museum were developing a new course entitled "Material Science of Art." The course, which included both lecture and lab components, planned to examine the underlying science and engineering associated with photography stability, pigment fading, paint viscosity, and material strength. These topics were then applied using historical artifacts to illustrate their relevance. Given this backdrop, a project was devised for the introductory design class where students developed a lab activity for the new course. Michelangelo's David served as the explored artifact to explore material strength and stress. The client/student team created a bench-top compression testing device that measured the applied force on student-created specimens cast into specific shapes. Using notched specimens, the effect of stress concentrations was explored. The use of different materials provided insight into specific material properties and their ability to accommodate the induced forces and resulting stresses. This knowledge was then applied using miniature versions of the David sculpture which were placed in the testing device and loaded to failure. In addition to design and planning, the project also applied course lessons in electronics, programming, CAD, machining, laser cutting, and force transmission.

In another application, a strength and conditioning coach from the Department of Athletics served as a course client. The project goal was to improve athletes' reaction time. Working from this problem statement, the team developed possible solutions and then prototyped to improve those design ideas. This process led to the creation of a 6x6 foot stimulus panel that energized 32 LEDs in a programmed sequence. The LEDs were embedded in a switch, with the athlete instructed to hit only LEDs displaying a specific color. The system was programmable with code written to address a coach's training protocol for specific reaction scenarios. In addition to the coach's involvement in the project, athletes from a variety of sports came to the CEID to evaluate the device. After the final presentation, the unit was relocated to the weight room in the university's gymnasium where it is used by coaches and athletes to improve performance.

This example illustrates how a course can draw in constituents (both students and clients) from various backgrounds. Makerspaces thrive based on the community that forms around them. In the case of this course, micro-communities with diverse team members led to innovative solutions. The students benefitted from developing discipline-related skills and witnessing their ability to apply fundamental knowledge to solve problems. The client-student partnerships developed in the course have frequently extended into research and student employment opportunities beyond the semester, further validating the value of uniting individuals and serving as a springboard for university-wide collaborations.

As a second course example, "Making Spaces" is a CEID-hosted course jointly offered by the School of Engineering and the School of Architecture at Yale. The course centers on a partnership with a client who needs assistance applying technology to solve a problem related to using space. During the course's initial offering in the Fall of 2017, the Director of the Smithsonian Institute's Arts and

Industries Building, located in Washington D.C., served as the client. The Arts and Industries Building was constructed in 1881 as the country's first National Museum, with the purpose of showcasing innovation. For over a century, the Arts and Industry Building did so with displays including Edison's light bulb, Lilienthal's glider, Bell's telephone, and Lindbergh's Spirit of St. Louis airplane. Since its 1881 origin, innovations have advanced but the building itself became stagnant before becoming dormant for the last decade. The course focused on innovation as a tool to engage and inspire future visitors while re-energizing this facility for the next chapter of its history.

The course applied practices from adaptive reuse and spatial design, coupled with design thinking methodologies, to research the existing facility and reimagine a new use. As the course client, the Director of the Arts and Industries Building hosted the students at the museum and worked with them (and the course instructor) to understand issues and explore viable solutions. As a collaborative effort, the course was comprised of equal part architecture and engineering students, with this combination established to address the challenges of implementing innovations within an iconic architectural structure. Project teams were formed around the central concepts of space representation/utilization, user experiences, and technology solutions. Lectures in these topic areas were combined with skills-development in making technologies to enable students to design and fabricate their solutions. The makerspace studio and its manufacturing equipment were used by both engineering and architecture students to explore ideas and build systems. Promising developments from the course included new ideas for integrating technology and architecture, and the creation of a device that simultaneously served as a navigational tool and display content trigger, providing each visitor with a unique museum experience.

Here too we see an example of the makerspace fulfilling its role uniting collaborators that otherwise might not associate with each other. There are no other Yale courses that openly solicit engineering and architecture students to work on a joint project. Similar to the first course, the success of the project rests with the careful vetting of proposals to ensure the desired results can be achieved within a short period of time. The full engagement of the client was also a factor in the program's success with a close partnership developing between the students, instructor and client over the semester. Regular, focused interactions were essential to keep the project aligned and meet the expectations of all participants. Documentation was also an important component of the interactions to record decisions, transmit information, and preserve the course's discoveries.

Yale's lessons learned from curricular integration: These two examples highlight the ability of courses within makerspaces to unite faculty, staff and students from across the university on technical problem-solving. The courses also illustrate the ability of academic makerspaces to serve as a clearinghouse to match University-wide needs with student-developed solutions created within an academic course. This model is an important one as it promotes interdisciplinary problem solving as well as experiential learning in a technical environment.

IMPORTANCE OF CURRICULAR INTEGRATION

The examples above demonstrate myriad possibilities for integrating makerspaces and their accompanying resources into the curriculum at a variety of institutions. MIT and Olin showed the impact of targeting students early in their first year on campus through dedicated curricular experiences intended to prepare students for more advanced design-build coursework or projects. Similarly, think[box] at Case Western provides curricular experiences to build students' baseline skills early and facilitates the practice of those skills through programs like design and startup competitions.

At Georgia Tech, the Invention Studio is critical to supporting early design experiences through the senior year capstone in Mechanical Engineering. Similarly, at Stanford's Product Realization Lab, core engineering and design courses are supported while PRL instructors also offer advanced courses on topics relevant to design and manufacturing.

Curricular integration at the PRL has also demonstrated how design and making can augment and deepen the student experience in seemingly unrelated courses like writing, history, or classics. Yale's examples also show the value of enabling multidisciplinary and cross-disciplinary collaboration among students who might not otherwise interact to deliver innovative solutions to design problems posed by real-world clients.

Berkeley's curricular integration of the Jacobs Institute is perhaps most extensive with the creation of a unique course designation for classes on topics in design and innovation, DES INV, and the development of a masters program for students focused on careers in design. Like the other schools mentioned above, the Jacobs Institute is explicitly open to all students and faculty on campus, increasing the accessibility of makerspace curricular experiences for the entire community.

Making space in any curriculum for new courses and learning experiences can be notoriously difficult. Academic departments are inherently resistant to change. The above examples represent institutional commitments to providing valuable learning experiences in design, innovation, entrepreneurship, and real-world problem-solving. Though these curricular integration efforts are not without their own headaches and friction, we are beginning to demonstrate the positive impacts these learning experiences can have on our students' (and occasionally faculty's) personal, academic, and professional growth.

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