

Designing the Yale Center for Engineering Innovation and Design

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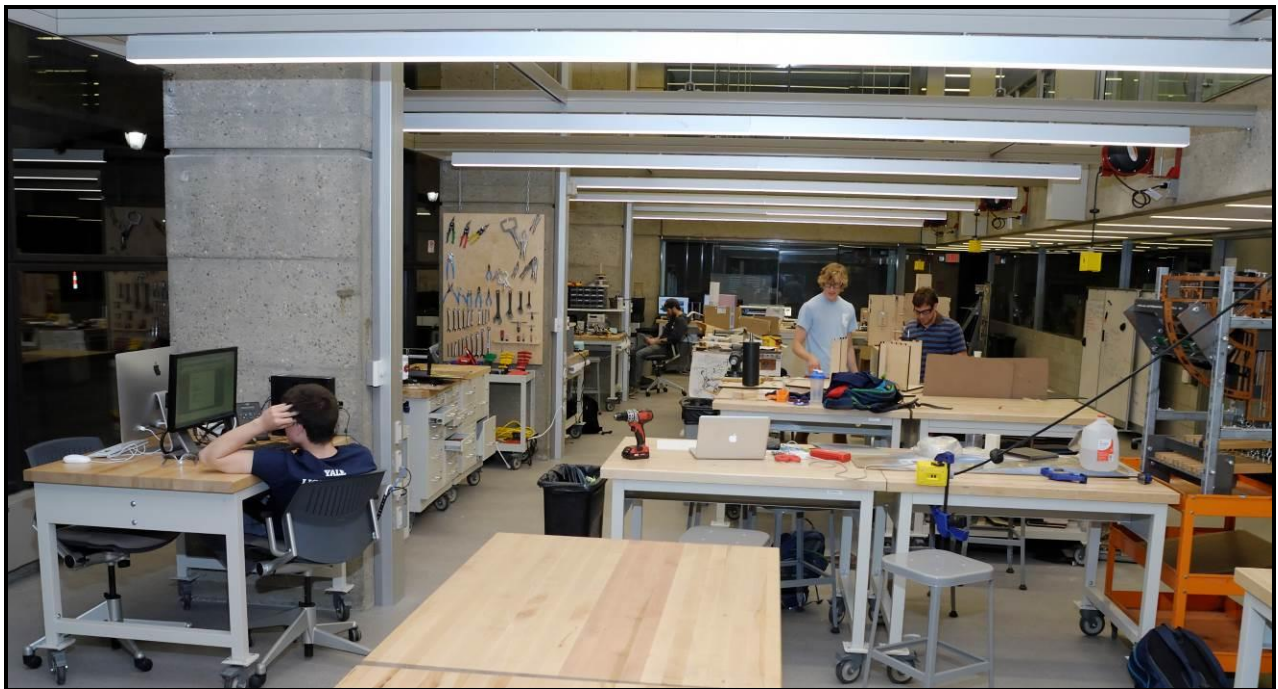
Abstract

In 2009, the faculty of the Yale School of Engineering & Applied Science created a strategic plan for advancing the school, with one of the three goals of the plan being to advance the culture of engineering on the Yale campus. Central to this goal was the creation of the Yale Center for Engineering Innovation and Design, a new 8,500 square foot space for instruction, fabrication and assembly to support curricular and extracurricular design activities. This paper details the concept for the Center, its design and outfitting, and the success of the first year of operation in 2012-13. The paper discusses the principles that guided the design of the Center, the collaboration of colleagues at and beyond Yale to plan the Center, the creation of a community of design enthusiasts who actively use the Center, and the Center's advancing the culture of engineering at Yale.

Introduction

The Yale Center for Engineering Innovation and Design (CEID), which opened in August of 2012, is much more than its 8,500 square feet of meeting, design, fabrication and assembly space. More significantly, the Center catalyzed the Yale design and innovation community to come together, learn from each other, and nurture a culture for creating that had previously not existed on Yale's campus. Since opening, the CEID developed into an "Academic Maker Space" that has energized the engineering culture at Yale.

The story of transforming an engineering library into a well equipped and fully staffed center for design and innovation demonstrates the culture changing potential of a properly designed space for creating physical objects. In Yale's case, a decision was made to relocate its engineering books into another of Yale's many libraries and convert the former engineering library into a space that supported new ways of learning – learning by design, learning by innovating, and learning by fabricating objects. Yale responded to the growing Maker/DIY interests and abilities of today's students by creating a home to associate, design, innovate and create.

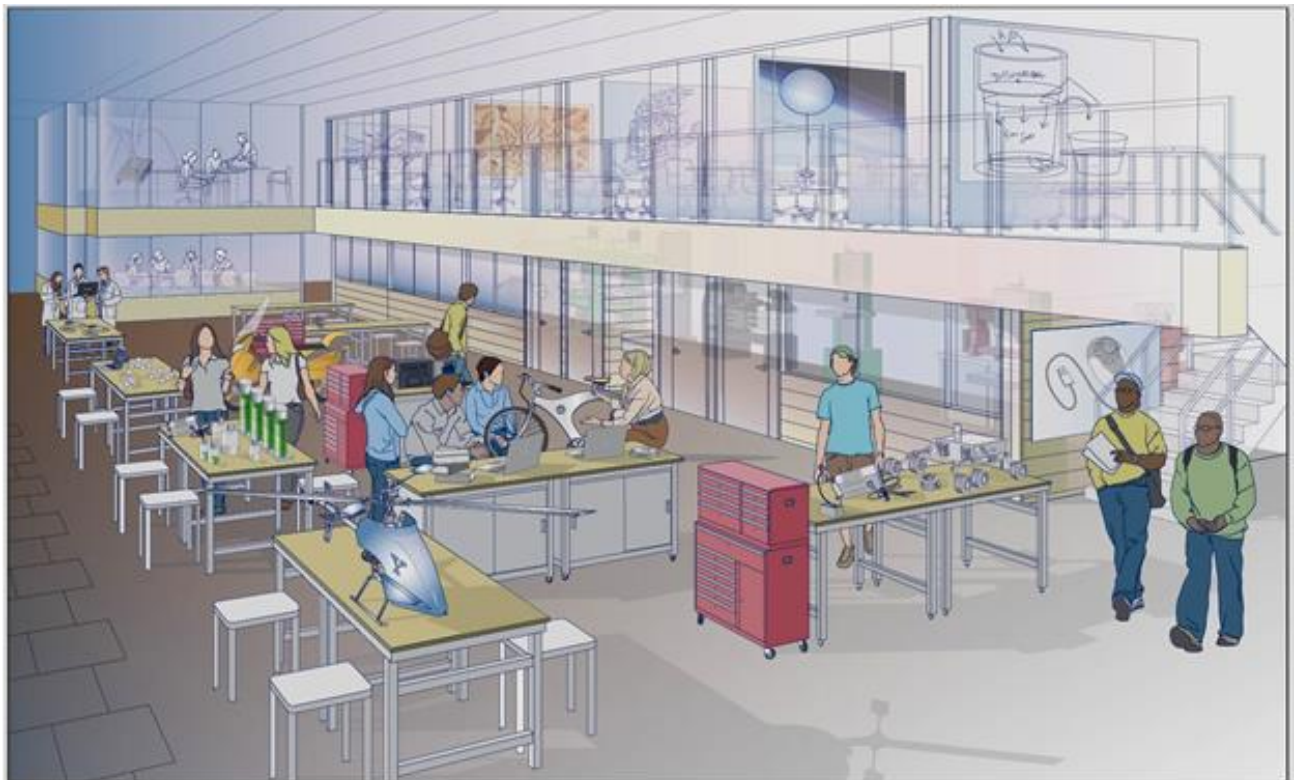


The Yale Center for Engineering Innovation and Design has had a dramatic effect in increasing the visibility of engineering and sparking creativity at Yale. Located on the ground floor, outfitted with 20 foot tall windows that look out to a walkway and street, and aided its visual openness, the Center serves as a beacon that urges all to be creative. The Center hosts student design teams, design-based courses and information workshops, and is equipped with modern tools/machines to support these programs. The Center is open to all members of the Yale community that have an interest in design and innovation, with its membership ranging from

theater majors that fabricate stage props to forestry students who construct scientific equipment for field work in Tanzania.

The Need for an Academic Maker Space at Yale

This decision to create the Yale Center for Engineering Innovation and Design was prompted by a number of factors. The primary factor was the increased importance of design in engineering education. Today's engineering students must not only understand engineering fundamentals, they must be able to use that knowledge to solve problems. Most often these problems involve the design, construction, testing and use of engineered systems. While spaces to accomplish these tasks were previously available at Yale, they were scattered in location and purpose. In addition, the need for increased levels of design skills was growing within Yale Engineering's research labs, with a greater number of researchers seeking students who could design and fabricate devices that are needed to investigate engineering questions.



The creation of the Center was also prompted by a thriving extracurricular activity culture at Yale. Despite their large number and significant success, prior to the Center's existence there was no common location for student engineering organizations to meet, design and build in. For example, three students that won the U.S. Patent and Trademark Office Collegiate Inventors Competition worked in their dorm rooms to design and construct a hand held dermatology device. As another example, a team that designed, constructed and installed a gravity-fed water distribution system for a Cameroon village did so in a mixture of classrooms and seminar rooms. While Yale Engineering supported these teams using existing machine shops located in the basement of an academic building, the work was hidden and not noticed. The Center for Engineering Innovation and Design was envisioned as a better method to address these student team needs.

In addition to these programmatic needs, the Center for Engineering Innovation and Design was also created to address individual student needs. With the increased levels of technical skills among new students, thanks in part to a renaissance in hands-on learning and the accessibility of modern methods to design and fabricate, there was a growing need to accommodate students that entered Yale with these skills. Such individuals include budding entrepreneurs who want to develop a prototype and curious creators who want access to technology to design something they thought of. The Center was envisioned to address these factors in an accessible, visible and active space.

Physical Layout and Equipment

The Center was designed based on a survey of three design spaces: Stanford University's d-school, Northwestern University's Segal Design Institute and the Pappalardo Undergraduate Teaching Lab in the Department of Mechanical Engineering at MIT. Site visits and interactions with colleagues at these institutions provided insights into the ideal layout, equipment and functions in a design and innovation space. Concepts such as openness, modularity, re-configurability, and multiuse capabilities surfaced from these investigations. This survey also highlighted the value of a center being self-sufficient, as well as having a defined scope and purpose that was distinct from existing campus facilities. In addition, the reviews of other programs not only identified the key machinery/tools that should be located in a design center, but also illustrated the value of hosting a wide spectrum of activities to foster interest in design and innovation.



Based on this research, the Yale Center for Engineering Innovation and Design was designed with four functional areas: learning and meeting space, open studio space, controlled shop space, and office space. 5,000 square feet of the Center is on one floor, with 3,500 square feet

located on a mezzanine that is accessed using an open stairwell in the center of the main space. By design, the majority of the Center is open and reconfigurable with all of the tables and workbenches mounted on wheels. Most of the Center's walls are glass with air gaps between individual glass panels to audibly connect the space and facilitate safety monitoring. The use of glass includes the balcony balusters that allow the activities in the mezzanine workrooms to be viewed from the sidewalk outside the Center.



The learning and meeting space includes an instructional area for 50 students, with ample projection capabilities and white boards for team based problem solving. The standard configuration for the instructional area has the two sets of student tables oriented 90 degrees to each other, with the instruction station at the intersection of the configuration. This subtle difference from the traditional orientation of seats aligned in parallel rows is a pattern that promotes student to student dialog and serves as a visual clue that the Center's learning environment is different from most other classrooms. There are no physical boundaries that separate the end of the instructional area and the beginning of the studio area. This

connectedness facilitates the conveyance of information into the studio space, and eliminates boundaries between the various forms of learning whether they be instructor led, team based or individually focused.



Five glass-walled meeting rooms, each seating 8 persons, are located on the mezzanine where they look down on the studio. Collapsible white board walls separate each room to produce a space that is easily configurable for meetings as small as 8 and as large as 40 by collapsing the walls. LCD screens are mounted in each room and have the capability of displaying content from anywhere in the Center. Glass is used for the external walls in the meeting space to connect the activities inside each workroom to the rest of the Center.

An open studio encompasses the majority of the first floor of the Center where moveable shop tables provide the needed project work area. The studio includes hand tools that are accessible to users as well as basic electronics equipment for fabrication and testing. The studio also houses a

collection of 3-D printers that can be operated by members. Storage lockers were installed to store project materials since the operating philosophy of the Center is to always provide an open work area for those currently using the space. As such, if a member is not working in the space, they must store their materials in a locker rather than leaving those materials for an extended period of time on a lab bench.



Three shop spaces have restricted access. A BSL-1 lab houses chemical applications and microscopy tools. This space is unique to the Yale Center for Engineering Innovation and Design as most other design labs do not include a wet lab. Because of the need for a space for chemical based design, such as that associated with micro-fluidics and paper-based chemical tests, this lab extends the utility of the Center beyond the mechanical and electrical engineering disciplines to accommodate design needs in the biomedical, chemical and environmental engineering disciplines. Two restricted access workshops house mills, lathes, band-saws,

grinders, and other shop equipment. CNC control is used for a laser cutter and a router and is an option for the mills and lathes. A fume hood is provided in the workshop. Members may operate these tools, under the oversight of the Center staff once the members receive tool specific training.

Staffing and Membership

The Yale Center for Engineering Innovation and Design is directed by a tenured mechanical engineering faculty member who nominally devotes 25% of his effort to this endeavor. An assistant director and a teaching specialist are full time employees in the Center. Each of these employees has industry and university experience and has an engineering/physics PhD. The Center's support team also includes two design fellows – recent Yale graduates who have a design background, with one graduating with an art degree and the other a biomedical engineering degree. The Center is augmented with undergraduate student design assistants who are trained to provide instruction and oversight from a user perspective. This talented team keeps the Center productive and their wide range of experience and interests are a valuable resource for Center members. The staff established a pervasive tone of collaboration and community that propelled the Center into becoming a favorite space on campus for makers to meet and work.

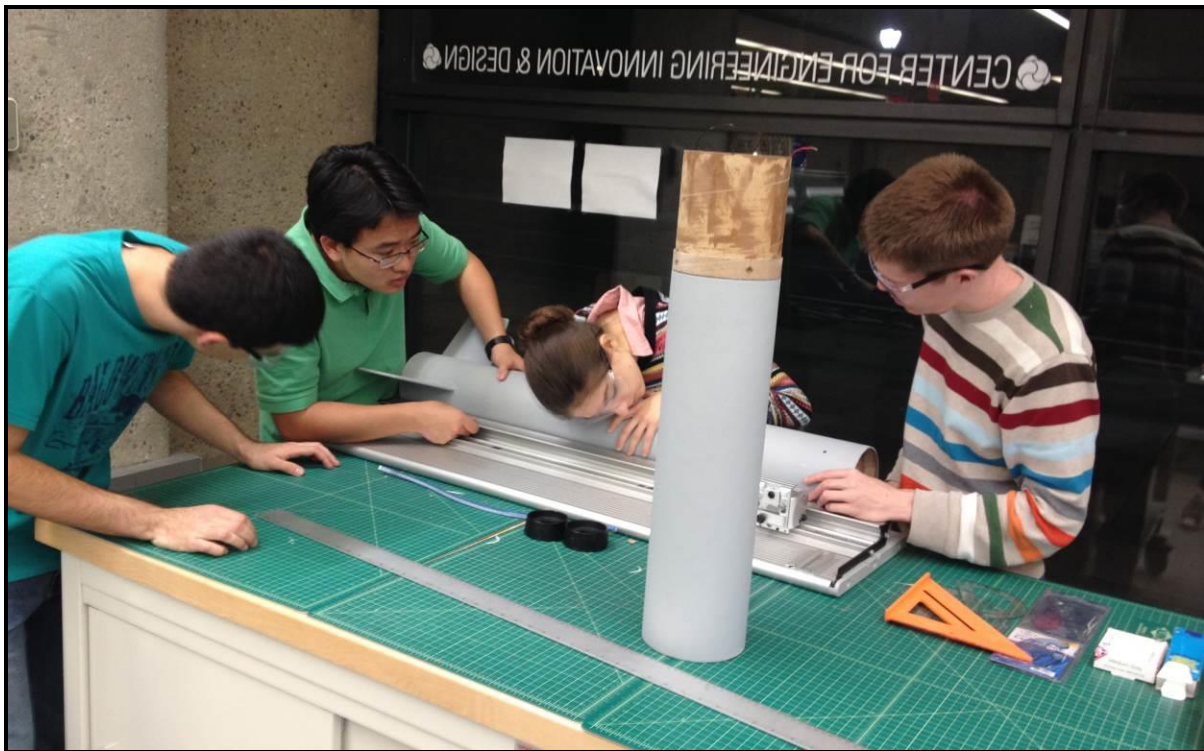
The staff is responsible for all aspects of operating the Center including indoctrinating new members, training and certifying members to use the Center's equipment, and organizing the Center's programming. Collectively these roles position the staff as design mentors who assist individuals and teams design and build objects and systems. Fittingly so, the management of the

Center is innovative and entrepreneurial and the Center's staff is open to new ideas that help members learn and collaborate. As one example, the staff assisted a radiologist who was creating 3-D prints of medical images for patient instruction. As another example, a staff member assisted a biomedical engineering class design medical technologies for developing countries by teaching the students how to design and print paper-based chemical sensing tests. A wide range of skills and talents support the wide spectrum of ideas that are pursued in the Center.



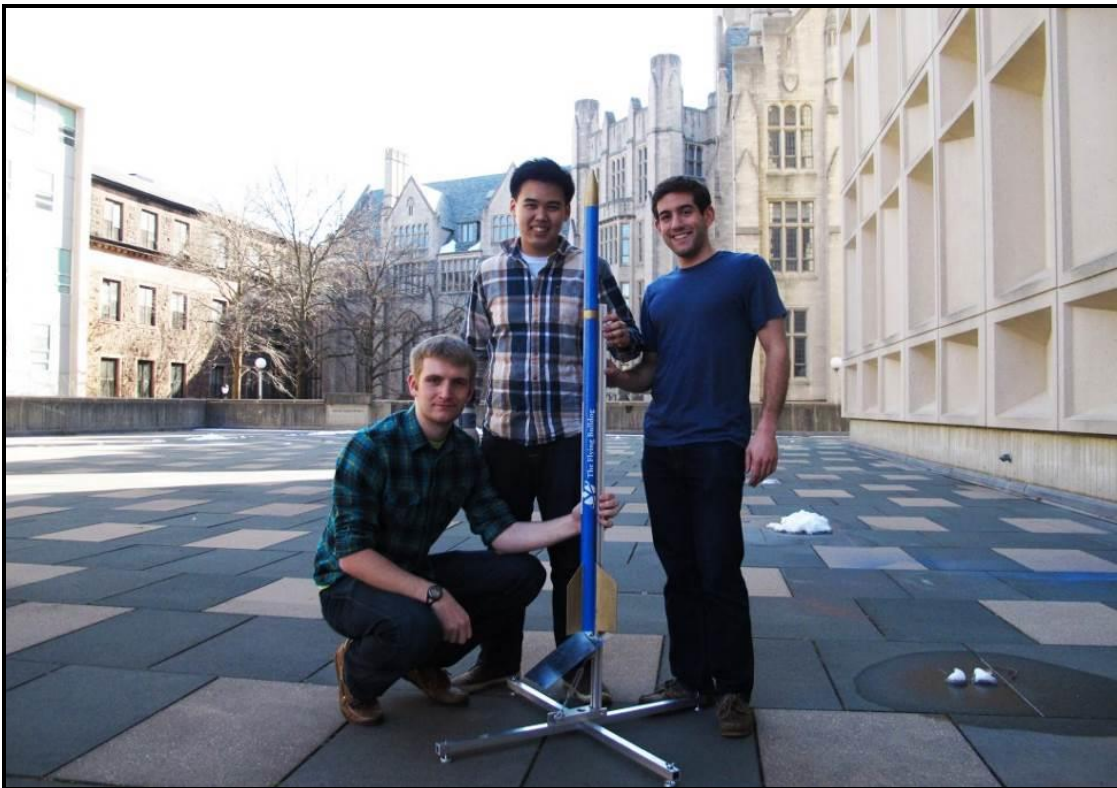
Access to the Center is provided to individuals who have become members. Membership in the Center allows 24/7 access to the studio and meeting space and is awarded to Yale students, faculty and research staff following completion of an on-line indoctrination program and an on-site orientation in the Center. Access to the Center's major equipment, such as the 3-D printers and laser engraver, is granted after individual members are trained to operate the equipment, with some use only allowed when monitored by the Center's staff.

The Center's membership model establishes a sense of community, responsibility and ownership where users shape the value system and norms of the space through their own actions and by helping other members. Members use the space to pursue any of their design interests with an appropriate amount of staff oversight to ensure that the projects are safe and conform to the Center's norms. Projects in the Center are pursued as personal interests, club activities, research quests, and as class components.



The space is a collaborative environment where members offer their expertise to others and welcome such input. The open architecture of the space promotes an open-source collaborative culture. In general, makers are proud to share their ideas and are inquisitive about the work of others, and this also holds true for the members in the Center. The orientation program instills this open mindset and the members foster the teamwork and cooperation that have been essential to the Center's effectiveness as a place to make, share, and learn. The concept of collaboration is

routinely demonstrated not only in the studio and workshops, but also in the meeting rooms which are often used as group study spaces. Teams of students use the meeting rooms for problem sessions and peer-to-peer tutoring. These uses illustrate the Center's role as a magnet for like-minded individuals who want to learn from each other.



There are currently 1,100 members of the Yale Center for Engineering Innovation and Design. Members come from all programs at Yale, with an affiliation in the School of Engineering being the most prevalent, followed by members who are affiliated with the School of Management. The university-wide membership model has resulted in collaborations between members from the Yale School of Medicine, the Yale School of Art and the Yale School of Drama. In addition to the tools provided in the Yale Center for Engineering Innovation and Design, the Center also provided access to individuals who willingly contributed their expertise to projects conducted by other members. As such, the Center routinely associated individuals who otherwise would not

have met but have since collaborated because of their common interests in design and innovation.

Center Programs

In addition to serving as an open and accessible space for members to meet, design and create, the Yale Center for Engineering Innovation and Design also hosts curricular and extracurricular activities. The curricular activities are design-oriented instruction that range from introductory to capstone design courses. Theme-based project-oriented classes have also been taught in the Center. The hands-on instruction in these classes is supported by lectures that provide a framework for the activities.

As one example, the freshmen-level class Introduction to Engineering Innovation and Design was created to take advantage of the Center and included instructional sessions on computer modeling, programming, electronics and project management. Hands-on activities were integrated with this instruction where students 3-D printed their computer modeled components, created Arduino-driven LED light displays, and solved client-based problems such as designing enclosures for scientific sensors that were subsequently used in Africa.

Workshops are conducted in the Center to instruct members on technical topics such as 3-D printing, computer coding and solid modeling. These workshops are often led by members who share their knowledge and simultaneously strengthen the sense of community that defines the Center. While some workshops are very Center-focused in their content, such as how to use SolidWorks to create models that can be printed on the Center's MakerBot, others are less

Center-centric. The Center also sponsors lectures by design leaders. The weekly presentations included the physics of knitting, using mathematical formulas to create physical objects, and the increased loss of privacy in a big-data world.



Case Studies of Center Projects

Four case studies are presented to illustrate the range of activities that have taken place at the Yale Center for Engineering Innovation and Design during its first 18-months of existence.

Kickstarting a Tree House - The Tree House at Yale is a Kickstarter project that attracted \$10,536 of support for its original \$5K goal. A Yale architecture student Griffin Collier fancied that Yale needed a tree house that was built by the community, for the community. In Griffin's words, "Yale is a place where people from all places, backgrounds, industries, and experiences come together and turn ideas into realities." And what better place on campus to house the idea to build a tree house than the Yale Center for Engineering Innovation and Design.

Griffin's childhood dream to build a tree house resonated with others on campus, including over 50 fellow students as well as faculty and staff – people who always wanted to build a tree house, but never really had the chance to do so. Griffin's group was not simply one component of Yale but rather a cross section of Yale that included students, structural engineers, forest managers, architects, and even the Assistant Director of the Yale CEID. The Assistant Director, who in addition to his day (and night) job running the Center, advises a number of student teams at Yale.

Because this could not just be any tree house, after all the project was being advised by safety engineers and architecture professors, the Yale Tree House had to be something above and beyond what one could assemble in an afternoon. Once a host tree was determined, the tree was modeled in 3-D and the tree house was created in the digital domain. True to the design process, sketch models of the tree and tree house were constructed, followed by manufacturing a prototype frame using 4x4 pieces of lumber, with each step guided by the computer model. Once the prototype was carted to the forest and installed, the design was validated and the real frame could be fabricated.

In addition to being a location for the 50-person team to gather for meetings and safety training, the Yale Center for Engineering Innovation and Design was the place to make the tree house real. To do so, 4x4, 3x3, 2x4, and 2x2 aluminum box beams had to be cut to size and drilled for easy assembly in the field. With the 3-D model, the characteristic of each structural member was readily defined. The CIED's CNC mills made quick (and accurate) work drilling and finishing each piece to allow their assembly on the tree.



Deep in the woods near campus, the aluminum frame of the Yale tree house now glistens. The juxtaposition of the inanimate linear metal frame supported by a gnarly living oak tree is fitting for the Yale tree house and its relationship to Yale's CEID. How else could a bunch of childhood memory driven students build a tree house at a campus more known for liberal arts than liberated machining? People, tools and ideas seamlessly came together according to a plan at the Yale Center for Engineering Innovation and Design.

Feeding Just the Chickens – The Yale Farm is located about a mile from Yale's CEID. One of the problems with raising chickens – a most invasive species to an urban environment – is that their food can also feed the native urban wildlife of mice and rats. While these mixed forms of

nature are not a problem on most farms, they most certainly are on a university farm where most of the volunteer employees – students – are not necessarily comfortable around rodents.

While searching for real-life problems that needed a design solution, Yale's CEID Director was delighted to hear that rats were eating scattered chicken feed at the farm. A solution to the chicken-and-the-rat dilemma could not only solve the Yale farm's problem, but it could also solve the Director's problem finding campus based projects for the new freshman design class. The class, which was created to make use of the Center to teach freshmen innovation and design skills, needed challenges for students to solve, and this was a good one.

Four freshmen were eager to transform a semester's worth of new knowledge of CAD, 3-D printing, Arduino programming, microfluidics and project management into something they could sink their teeth (or at least the chickens' beaks) into. Yale's resident farmer pitched the problem to the class with an animated presentation on how chickens eat. Mimicking the movement of a feeding chicken's head swaying back and forth at a feed trough illustrated the resulting mess that generally surrounds feed stations – a fact that only delights the resident rats. The team went to town on the farm problem, generating prototypes that were field tested at the farm. The final design - a self-opening feed station – was fabricated at the design center using plywood that was cut using the laser cutter. The design included a large No-Rats-Allowed laser-engraving on the front of the feed station (being Yale rats, they are very intelligent rodents) to serve as a backup system to keep the rats out of the chicken feed.



The feed is secured behind a door that is raised when a chicken perches on a PVC pipe connected by a fulcrum attached to the feed door. When an appropriately weighted chicken perches on the PVC pipe, the door lifts, the chicken eats, and any sprayed feed is contained in the feeder. Should a rat not heed the No-Rats-Allowed sign and perch on the PVC pipe, its weight would not be sufficient to raise the feed door. The triggering force of the door can be adjusted, with the system working as designed as long as the

lightest chicken weighs more than the heaviest rat. Over the course of the semester, a group of freshmen with no prior experience working in a shop, nor with any prior knowledge of the design process, designed and fabricated a working product.

Off to the Races – The Center’s Assistant Director also helped a student team of car enthusiasts capture first place in the Society of Automotive Engineers Formula Hybrid International Competition at the New Hampshire Motor Speedway in April, 2012. Building a car to race at 60 mph is a real challenge, and doing so with a hybrid propulsion system that relies on both gas and

electricity as power sources is an even harder nut to crack.



The Center's 3-D printing and CNC milling facilities were essential to the team's overall success. To preserve resources, the Yale team needed to be careful with their budget.

Machining the wrong mounting pattern into a \$400 block of 7075 Aluminum is a good way to make an expensive paperweight. On the other hand, machining the correct caliber mounts into a drive system upright is a good way to make a functional upright.

To make sure they were fabricating uprights and not paperweights, the Yale Bulldog Racing Team first printed the upright they designed on the Center's Stratasys Dimension Elite printer. The plastic part was used to ensure the correct form and fit of the upright. With the form and fit confirmed, the part's ".stl file" was converted to G-code for the CNC mill. Given the cost of the raw stock and the time needed to machine away 75% of the base material to fabricate the upright, a foam block was first milled to make sure that the ".stl code" was correctly converted into a set of instructions for the mill. The foam test saved the team from making a paperweight as the first version of the G-code included an unplanned penetration of the upright – a design feature that would have rendered the part useless. Once the G-code was corrected and confirmed using another piece of foam, the final product was made correctly the first time the expensive block of aluminum was milled.

Code Classes for the Masses - A peer to peer instruction philosophy within the Center helps foster a collaborative community and serves as a supply of both educators and learners.

HackYale is a 200-student strong organization that runs multi-week workshops on writing computer code. With enrollment in Yale's introductory computer coding class growing six-fold over the last three years, undergraduate coding gurus surfaced to remedy the demand and supply problem by providing practical instruction in coding. With HackYale "courses" ranging from a few weeks to an entire semester, the instruction is targeted to each group of registered participants and focuses on the of skill level of that set of students.

Like the HackYale curriculum, the CEID accommodates varying needs by being reconfigurable. In this case the walls of the Center's small meeting rooms collapsed and a large space for

teaching HTML, CSS and JavaScript in the HackYale course “Introduction to Web Development” was created. HackYale’s adoption of the Yale CEID as its home was facilitated by the physical design of the space and the sense of community. The open instructional area is ideal for larger classes and the upper meeting rooms accommodate smaller groups.

Though these courses are not for credit and in fact have no association with academic courses, HackYale students are every bit as focused as if the course affected their GPA. For it is not the graded performance that drives the students in HackYale, but rather their inner drive to learn a new skill, start a new company, and, just maybe, be selected to teach a HackYale course. And this whole underground coding world runs without a faculty member in sight.

Establishing an Academic Maker Community

The intersection of three elements – makers, staff and infrastructure – propelled a traditional hub of learning, a library, into a modern Center of learning: an academic maker space. Reflecting the “if you build it, they will come” philosophy, the creation of a design and innovation space attracted a cross section of people at Yale who were interested in making things. The open access policy enabled the Center to serve as a meeting place to find others who were interested in design and innovation. While the Center provided the tools, guidance and expertise to convert ideas into physical realities, more significantly the center inspired people to design and fabricate solutions. By being open to all, the Center broke down academic boundaries and accelerated collaborations among design enthusiasts from a variety of backgrounds.

The impact of the Center though is not limited to the members themselves as the design and innovation culture has prompted advances in many other areas. There is greater interest in hands-on learning. More student-led engineering organizations are being established to take on projects in a variety of disciplines. There are increased levels of activity in the entrepreneurial space. And, fulfilling one of the fundamental reasons for creating the Center, there is renewed interest in the role of design in engineering education.



Future Plans

The Yale Center for Engineering Innovation and Design has become an oasis for making and a magnet for like-minded members, whether they are students, faculty or staff. The challenge is to sustain this initial momentum and remain an open and accessible space for a community to prosper. Like other organizations, the Center hopes to discover how to remain small while

growing large, and retain the membership-based ownership model that accelerated its original development.

An even greater challenge is to expand the renewed interest in design and innovation at Yale to an even larger audience by extending this maker-based collaborative learning philosophy across the entire School of Engineering and throughout Yale. Perhaps the current Yale Center for Engineering Innovation and Design will be a network of spaces across campus, all devoted to helping people learn, design, innovate and create.

