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The Invention Studio: A University Maker Space and Culture

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ABSTRACT

Creativity, invention, and innovation are values championed as central pillars of engineering education. However, university environments that foster open-ended design-build projects are uncommon. Fabrication and prototyping spaces at universities are typically 'machine shops' where students relinquish actual fabrication activities to trained professionals or are only accessible for academic assignments to highly trained students. The desire to make design and prototyping more integral to the engineering experience led to the creation of The Invention Studio, a free-to-use, 3000 ft^2 maker space 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, 1000 student users per month create things (using $1M of capital equipment), meet, and mentor each other for at least 25 courses as well as independent personal projects. The Invention Studio is centrally managed and maintained by an undergraduate student group with support from the university staff and courses. In this descriptive program implementation report, the underlying motivation, organization, facilities, outreach, safety, funding, and challenges are presented in order to guide others in the creation of similar environments. The Invention Studio's primary uses and impacts on students are described.

The Invention Studio's facilities, infrastructure, and cultural transformation are demonstrating the value and sustainability of hands-on, design-build education to stimulate innovation, creativity, and entrepreneurship in engineering undergraduates.

Key Words: invention, makerspace, studio, design, manufacturing

INTRODUCTION

The Engineer of 2020 recognizes that creating, inventing, and innovating are essential skills for engineers (National Research Council 2004). It is the prospect of engaging and cultivating these skills that encourages many undergraduate students to consider studying engineering. However, in standard engineering curricula, students do not generally create or invent anything tangible until the culminating Capstone Design experience. This postponement can be credited to a shift in engineering education that occurred between 1935 and 1965 (Seely 1999, Lamancusa 2006). Engineering curricula changed from hands-on, practice-based curricula to theory-based approaches with a heavier emphasis on mathematical modeling. Consequently, many educators, such as the originators of the Conceive-Design-Implement-Operate (CDIO) initiative, (Crawley, Malmqvist, Lucas and Brodeur 2011) have identified industry needs for more capable engineering graduates with traits beyond technical knowledge, including personal maturity, interpersonal skills, and holistic, critical thinking regarding engineering systems (Crawley 2002). As counter-trends have emerged in recent years to re-introduce hands-on learning, some programs have initiated freshman design experiences (Sheppard and Jenison 1997, Dym, Agogino, Eris, Frey and Leifer 2005). The benefit of such experiences has been demonstrated at the University of Colorado Boulder, for example, where students who participated in an early design experience were retained at a statistically significantly higher rate than similar groups of engineering students without such introductory experiences (Knight, Carlson and Sullivan 2007). This finding speaks to the potential benefits of practicing creative activities early and often. The overarching goal of Georgia Tech's Invention Studio is to provide a place—a maker space—for students to apply classroom theory to, or simply mess about with, design-build projects, tools, materials, and mentoring within a community of their own management, independent of curricular requirements, classroom projects, or hierarchical structure of coursework.

BACKGROUND

In order to promote design experiences at the undergraduate level, community maker spaces are gaining popularity at universities. The currently known benefits of these spaces that have been researched appear to be two-fold: the documented benefits of *physical modeling* and the growth of *communities of practice*.

The Maker Movement originally started outside of universities in the 1990's as a technology-based extension of Do-It-Yourself (DIY) culture (Anderson 2012, Anderson 2012). Examples of such non-university "maker spaces" and "gym-like" design/prototyping spaces abound today including Tech-Shops (TechShop 2014) and NextFab Studio (NextFab 2014). In light of the benefits for engineers in terms of both physical modeling and the sense of community, this movement is now merging with the efforts to increase design-build curricula on university campuses. This movement has coupled with dramatic decreases in the price of 3D printers and related "maker" technology (Canessa, Fonda and Zennaro 2013) to drive development and expansion of maker spaces, resulting in new construction and renovation of university design facilities since the early 2000's (Lightner, Carlson, Sullivan, Brandemuehl and Reitsma 2000, Carlson and Sullivan 2006, Gedde, Silliman and Batill 2006, Griffin and Cortes 2006, University of Michigan Wilson Student Team Project Center 2013). These spaces, such as CU-Boulder's Integrated Teaching and Learning Laboratory (ITLL), aim to promote hands-on learning for enrolled engineering students and support theoretical coursework. Additionally, many such facilities serve as places of outreach and engagement with the non-engineering community (CU Boulder ITLL 2013). Other stated goals included enhancing creativity, team-oriented problem solving, and multidisciplinary collaboration skills (Carlson and Sullivan 2006, Griffin and Cortes 2006), goals which address industry needs for graduating engineers to have such skills (Crawley 2002, Lamancusa 2006). These spaces move well beyond traditional machine shops by providing meeting spaces for student design teams and integrating typical machine shop tools with a wider variety of rapid prototyping and low-tech building approaches. The construction of such spaces answers a call to improve American engineering education at the turn of the century (Carlson and Sullivan 2006, Gedde, Silliman and Batill 2006, Griffin and Cortes 2006) and to train engineers to engage increasingly complex challenges (National Research Council 2004).

More recently, design spaces have launched in schools specifically to welcome the hacker and maker cultures that are infiltrating student communities (Laskowski 2010, Collaborative 2012, BUILDS 2013, Studio 2013). Boston University's Association for Computing Machinery (ACM) chapter kicked off BUILDS (Boston University Information Lab & Design Space) in 2010 as a university-sponsored, student-built and run hackerspace, open to members who have card access (Laskowski 2010, BUILDS 2013). These spaces and others represent an effort to support "bottom-up" or grassroots student engineering and facilitate the pursuit of extracurricular personal projects and the exploration of manufacturing techniques.

A comparison can be drawn between a notable instance of a government-funded, "top-down" approach to updating design education—the Learning Factory curriculum—and the present case of a “bottom-up,” student-driven approach—the Invention Studio. The Manufacturing Engineering Education Partnership (MEEP) between Pennsylvania State University, University of Washington, and University of Puerto Rico produced the Learning Factory model for design and manufacturing curriculum in the mid-1990’s (Soyster and Lamancusa 1994, Morell, Zayas-Castro and Velez-Arocho 1998, NSF 2006). Enabled by $2.8 million from NSF and ARPA, and through collaboration with Sandia National Laboratories and hundreds of industry partners, the model drove curriculum and facilities updates at the three universities (Lamancusa, Jorgensen and Zayas-Castro 1997) and, between 1994 and 2006, the model expanded to other schools to reach thousands of students through real-world industry-sponsored projects (Lamancusa and Simpson 2004).

The Learning Factory model aimed to serve three stakeholder groups. First, industry leaders desired more talented, creative, and well-rounded engineers who were better prepared for innovative work. Second, students desired a richer, practice-based curriculum to augment their theoretical knowledge and make them more competitive in the job market. Third, faculty desired to connect their research with real-world problems and industry needs. Its success in meeting these needs was recognized by the National Academy of Engineering in 2006 (Lamancusa, Zayas, Soyster, Morell and Jorgensen 2008), and its approach is reflected in many design programs in universities across the country, including Georgia Tech’s Design Sequence and Capstone Design course (Georgia Tech 2014).

As later sections of this paper make evident, the Invention Studio at Georgia Tech offers a unique alternative for achieving many of the same outcomes as the Learning Factory approach. Without any reliance on grant funding, the Invention Studio has grown gradually, over 5 years, to incorporate ever-increasing facility space and equipment while leveraging a “bottom-up” approach from its beginning to give students primary responsibility for daily operation, maintenance, and equipment training for newcomers. Industry funds which support the Capstone Design course contribute the bulk of funding for the Studio, and industry partners have reacted positively to students gaining design and manufacturing skills in a self-driven environment while also working on sponsored projects. Faculty have embraced the Studio as a means of reinforcing fundamental theory from course lectures. Students, in turn, 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.

While the Maker Movement is growing across the country and within the university culture, the spaces which house them are under-studied as affordances for learning in the context of a community of practice. Developing an understanding of these spaces beyond the research already documented about physical modeling and the community of practice is a critical task toward producing guidelines for creating and implementing them in universities, as well as fully understanding the impacts on student learning.

Physical modeling

Physical models help designers visualize concepts, estimate implicit attributes of designs, validate assumptions, verify functionality of ideas, enhance communication between geographically-dispersed design teams, and select the best concept (McMohan 1994, Harrison and Minneman 1997, Horton 1997, Carlile 2002, Boujut and Blanco 2003, Lidwell, Holden and Butler 2003, Stowe 2008, Hannah 2009, Michaelraj 2009, Viswanathan and Linsey 2012). In fact, many researchers encourage the use of such models due to the variety of benefits (McKim 1972, Kelley and Littman 2001).

At a most basic level, prototypes and functional models help designers identify and rectify problems with their designs before production and eliminate some of the inefficiencies (Houde and Hill 1997). Physical models can capture information about the design which might not otherwise be apparent to the designers (Henderson 1999). There are numerous documented cases to support this claim. For example, Ward et al., (1995) observe that the use of physical models at Toyota enables flaw detection, thereby preventing the production of defective parts. Similarly, Bucciarelli (Bucciarelli 1994) demonstrates that building physical models aids in the identification of energy losses in the design of a photovoltaic desalination plant, and Faithfull et al., (2001) describe building physical models as a means to increase the efficiency of control system design and development.

In business, physical models minimize risks associated with initial assumptions regarding market acceptability, user features, and desired product functions (Andreasen and Hein 1987). Physical models also provide necessary information to designers, enabling them to iterate and improve upon their designs in an informed way while minimizing costs associated with product development and production (Dijk, Vergeest and Horváth 1998). Dow and Klemmer (2011) demonstrate that designers who are iterating on their ideas with the help of physical models can in fact outperform those who do not use physical models.

At the university level, student design teams also use physical models to identify problems and unexpected behaviors of their designs (Horton and Radcliffe 1995, Horton 1997, Raucent and Johnson 1997). However, Smith and Leong (1998) show that professional designers who use physical models value the practice of physical modeling more than design students do. Kiriyama and Yamamoto (1998) observe that graduate design teams use physical models to find the flaws in their designs. More recently, physical modeling in early stages of design has been correlated with improved information gathering (Ramduny-Ellis, Hare, Dix and Gill 2009), improved idea functionality (Viswanathan and Linsey 2012) and better design outcomes by students (Yang 2005). The availability of tools and support for prototyping student designs enables undergraduates to improve their ideas and develop a greater understanding of the iterative nature of design.

Cognitive Benefits of Physical Modeling

Physical prototypes and models have many benefits. To be effective innovators, students need building and testing skills. Physical representative likely reduce cognitive load that can, in turn, promote new visuo-spatial discoveries and inferences (Kim and Maher 2008). Physical representation, much like other external representations such as sketches (Schon 1983, Suwa and Tversky 1997), allow designers to reflect, thereby finding new interpretations, new design requirements and new design features (Kim and Maher 2008). Physical prototypes also assist engineers in supplementing erroneous mental models (Viswanathan and Linsey 2012, Viswanathan and Linsey 2013). Cognitive psychology has shown that people create efficient cognitive models of the world around only sophisticated enough to accomplish the tasks required (Gentner and Stevens 1983, Forbus 1984, McAfee and Proffitt 1991, Kuipers 1994, Markman 1999). These models are often surprisingly inaccurate and error prone unless significant experience or education has led to better models. Cognitive psychology has also demonstrated mental models tend to be qualitative (Forbus 1984). Engineering science provides a basis of knowledge, but there are many design issues that are not easily modeled or well-modeled quickly. Engineering science models also require the use of assumptions which are often based on 'engineering intuition', which are the engineer's mental models. Physical prototypes are an effective tool for identifying and correcting these errors. They are a tool for engineers to learn with over time.

Studies also demonstrate that the building and testing of designs is critical to assisting designers in overcoming design fixation to negative features and assists them in producing higher quality design concepts (Viswanathan and Linsey 2011, Viswanathan and Linsey 2011, Viswanathan and Linsey 2012, Viswanathan and Linsey 2012). Students must be proficient with a variety of prototyping tools because while physical models can provide many benefits they also have significant risk to cause design fixation due to the Sunk Cost Effect (Viswanathan and Linsey 2013). The Sunk Cost Effect occurs when a significant amount of time, money or effort has been applied to a course of action (Kahneman and Tversky 1979, Arkes and Blumer 1985), and leads a psychological bias where individuals tend to pursue the current course of action even when it would be more logical to change paths.

Community of practice

Maker spaces provide a venue for the enactment of a community of practice, or the emergent 'culture'. The situative perspective (Greeno and Middle School Mathematics through Applications Project Group 1998) contends that learning occurs within intact, recurring, and emergent systems of activity. These systems of activity comprise people, artifacts and structures that coalesce into the formation of communities of practice that have shared goals, values, methods and beliefs (Lave and Wenger 1991). Newcomers to such communities have the opportunity to take up and legitimately participate in community-valued activities. "A person's intentions to learn are engaged and the meaning of learning is configured through the process of becoming a full participant in the sociocultural practice" (Lave and Wenger 1991). Through regular and progressive participation in the varied and changing activities valued by that community, newcomers start to identify with that community, solidifying their relationship and commitment to the community values (Wenger 1998). Learning in such communities is very often a collaborative activity between novices and community mentors that is enacted through physical and cognitive apprenticeships (Brown, Collins and Duguid 1989). It is through these relationships that expert practitioners make tacit processes explicit to novices, furthering learning for both mentor and mentee.

OVERVIEW OF THE INVENTION STUDIO

In 2009, the Georgia Institute of Technology (Georgia Tech) recruited its first student volunteers to manage what would become the Invention Studio: a continually expanding, "student-run design-build-play space" open to all students. As of 2013, the Georgia Tech Invention Studio is a 3000 ft^2 state-of-the-art prototype fabrication facility used by 1000 different students per month (See Fig. 1). Each semester, 25 classes utilize the facility, and students may also use the space for personal projects. The facility is managed and maintained by the Makers Club, an 80-member undergraduate student club. Equipment valued at $1M includes 3D printers, laser cutters, waterjet cutter, injection molding, thermoforming, milling, and others, along with lounge, meeting, assembly, and testing space. Over 30 companies have donated to build and support the facility through the Invention Studio's connection to the Capstone Design Course. The Studio is free-to-use and is accessible 24/7. It is a multidisciplinary endeavor, staffed and utilized by students from the colleges of engineering, sciences, and architecture. The Invention Studio seeks to (1) provide students with free access to hands-on, state-of-the-art prototyping technologies; (2) serve as a cultural hub and meeting ground; bolster design (3) within curricula and (4) as an extra-curricular activity; (5) encourage collaboration between diverse teams of students from all years and majors, (6) welcome all types of projects, personal and professional; (7) excite students for careers involving creativity, design, innovation, and invention; (8) enable students to tackle open-ended, real world challenges; and to (9) serve as an exhibit and tour space to enhance the university's ability to recruit top students and showcase student work through local, national, and international news outlets.

The Invention Studio as a physical, intellectual and practice space engenders all aspects of a community of practice. As such, it has the potential to support situated learning through participation

Figure 1. Invention Studio at Georgia Tech, with 1000 student users per month.

in the life and activities of the maker community. In this way, the Invention Studio serves as a significant affordance for learning. The most unique aspects of the Invention Studio as compared to similar university and community maker spaces are as follows:

- Primarily student-run and "owned"
- Accessible 24/7 for Makers Club, daytime hours for all users
- Lacking restrictions on types of projects (e.g,. personal art projects are as welcome as course requirements)
- Free-to-use (caveat described below in funding section)
- State-of-the-art and comprehensively equipped
- Intimately linked to the curriculum
- Centrally located on campus

SURVEY METHODOLOGY

To broaden and augment the understanding that developed through years of observations and anecdotal data regarding the impact of the Invention Studio, a survey for graduates who had used and/or managed the Studio was administered. The Georgia Tech Institutional Review Board (IRB) was consulted prior to the survey being conducted and the need for approval and informed consent was waived for reasons provided in Section 12. The survey consisted of both quantitative Likert scale items and qualitative open-ended prompts and was conducted electronically and anonymously. A survey invitation was distributed electronically via email to 400 senior mechanical engineering and biomedical engineering students who had enrolled in Capstone Design during the preceding semester, as well as 50 Invention Studio Makers Club members from the past two years. A total of 50 self-selected responses from the above pool were collected, a non-randomized but representative pool from which results were aggregated. The survey consisted of quantitative and qualitative items regarding demographics, involvement level (e.g., user, mentor, leader), and their use of the Studio (i.e., personal use versus curricular). The survey asked whether the Invention Studio met our stated goals and to what extent the experience of using the Studio was impactful. The data is reported in Section 12 of this paper. All results shown in figures correspond directly with survey question responses and are self-reported with no interpretation or assessment. Rather than a comparative analysis or assessment of statistical significance, this survey is used exclusively for a description of the program implementation, its uses, and impacts.

SPACE, EQUIPMENT, AND RESOURCES

The 3000 ft^2 of space is divided into five rooms which include the following functionalities: rapid prototyping, woodworking, plastic working, metal working, CNC machine tools, mockup suite, assembly and testing areas, design spaces, and computational design spaces. Appendix A lists the equipment in each of these. There is overlap in physical space and use between these areas. For example, design white boards and chairs co-exist with butcher block tables and stools for assembly and testing (See Fig. 2). Computational design spaces are adjacent to rapid prototyping such as 3D printing to enable printing directly from CAD software on the same tabletop. A website hosts information for recent projects, hours, and training at inventionstudio.gatch.edu.

Consumable materials such as fasteners, stock, and off-the-shelf components are generally provided by the student users. Some exceptions include microcontrollers, wires, feedstock for the 3D printers and waterjet, and tooling. In some cases, materials and supplies are reimbursable from the 25 courses that rely on the Studio as a part of their curricula. Outside of coursework, as with art, costume, and Battlebot projects, students bring their own materials.

MANAGEMENT STRUCTURE

Makers Club

A student club called the Makers Club "owns" and runs the space. The club has approximately 80 volunteer members, comprised of undergraduates from a diverse set of majors and years. Students in the Makers club agree to staff the Invention Studio for 4 hours/week in exchange for 24 hour

Figure 2. Design spaces adjacent to assembly and testing spaces.

Figure 3. Undergraduate Lab Instructors (ULI's) teaching students how to use the Invention Studio machines.

keycard access. During this "shift" the Makers Club member on duty is called an Undergraduate Lab Instructor (ULI) and wears an identifiable arm band. While on duty, ULI's help their peers learn equipment, supervise safety, maintain equipment and the lab space, learn and advise about a wide variety of design and manufacturing tools, build their resumes with skills, and gain leadership experience (See Fig. 3). Twenty-four hour access is reward for these students and leads to weekend long hacking sessions involving everything from pumpkin carving to Battlebot building.

The Makers Club has spending authority on social activities, tooling repair and maintenance, and expansion of the equipment and space layout. In consultation with faculty and staff advisors, their needs are considered in major proposals and plans.

Their ownership of the space has led to unexpected, wonderful cultural roots, and spontaneous initiatives. For example, they regularly run evening workshops on topics such as microcontroller programming, motorized scooter design, stained glass window making, book binding, kitting, and others (See Fig. 4). The students write the curriculum and operate the courses for free or for a minimal fee to cover material costs. The club is a social hub as well, hosting ice cream making, contests, road trips, and parties like any vibrant college organization.

The club is led by a President, Vice President, Secretary, and Director of Programs elected annually each spring. In addition, "Masters" for each major class of equipment are elected. These are ULI's tasked with becoming domain experts on a particular class of Studio equipment (e.g., Laser Cutter, Waterjet, CNC, etc). They are ultimately responsible for upkeep and training other students on their respective machines.

ULI's schedule their own hours ad-hoc using Google docs (See Fig. 5). This reflects the organic process by which the entire Studio is run. While the officers meet each week to manage day to day concerns, there is only one mandatory ULI meeting per month. The Studio is staffed 10 am-7 pm

Figure 4. Makers club evening classes are created and run by the students.

during the week and there are 3-5 ULIs on duty at any time. Staffing accountability is ensured by ID card scanning to sign in/out. While machine specific training occurs on-demand by on-duty staff, there is an additional weekly event known as Makers Mondays intended to introduce new students to the Studio and maker community. These meetings generally begin with an introduction to the Studio and might follow with project show and tell, guest speakers, or specialized training on the machines.

University staff

The ULI's are peripherally supported, not managed or overseen, in their mission by several paid university staff. These personnel and the percentage of their time dedicated to supporting the Invention Studio is as follows:

Figure 5. Online documents enable rapid and efficient student staff scheduling

- Technician who performs complex machine tool repair (50% time) and assists research faculty with cost-reimbursable jobs in support of the university research mission (50% time)
- Machine shop professional who runs an adjacent professional university shop assists with training on the most complex machine tools (20% time)
- Academic professional who interfaces between the Makers club and university staff regarding major initiatives such as equipment moving, electrical and pneumatic supply installation, and budgeting (10% time), in cooperation with facilities, marketing, communications functions of the university
- Administrative assistant who performed purchases requested by the Makers Club, communications and marketing support staff, and coordinates large event logistics (20% time)
- Faculty advisor who assists the Makers Club with vision and fundraising (3% time)

SAFETY

Ultimately, safety and responsibility must be maintained in a delicate balance with freedom, accessibility, and creativity in a space that endeavors to encourage undergraduate students to use powerful machines, sometimes in the middle of the night. How does one promote and encourage such as balance in individuals through a culture of personal responsibility and self-awareness?

To promote and reward creativity, there are few strict rules in the Invention Studio. Importantly, the student leadership promotes an ethic of responsibility, safety and community ownership. In this way, students can explore and develop unconventional ideas in a supportive environment. The culture of ownership, personal awareness, and responsibility is absolutely vital to the success of this endeavor. Traditionally at universities, a safety culture is directed from the "top-down" through signage and by employing expert staff. Instead, in the Invention Studio these values are inculcated through peer pressure, public awareness of violations, and camaraderie.

Upon visiting the Studio or requesting access to equipment, ULI's offer tours and safety orientation for untrained users both generally and for specific machines. They explain the culture of awareness and personal responsibility and that the Studio is run by their volunteer peers. Complex equipment training is handled exclusively by equipment "masters," who are fully knowledgeable about machine safety, maintenance, and operation. The most complex machine tools, such as CNC mills and lathes, is handled by a university staff machine shop professional because such complex skills are difficult to pass through generations of transient student ULI's. ID card interlocks have been implemented as a training verification method for a few dangerous machines (e.g., manual lathe).

Rules are short and simple: clean up after yourself, do not hurt yourself or the machines, respect the people and culture, do not do anything foolish (e.g., wear safety classes, keep hair short or pulled back, wear closed toed shoes). Penalties for disrespecting these few rules are severe and swift: one strike and violators are out. Approximately once per semester, a student who is disrespectful to the ULI's or the equipment is banned from the Studio. It is important that students realize that Studio use is a privilege and not a right. In this way, the students are encouraged to be careful and aware of their surroundings, fostering a culture of safety through personal responsibility and ownership rather than top-down rules.

The most commonly used machines in the Invention Studio have relatively low risk of injury: 3D printers, laser cutters, waterjet cutters, and electronics prototyping stations. More dangerous machines are housed in a separate, restricted-access room and are forbidden from operation by students working alone. University liability insurance applies; no additional insurance has been obtained. It is conceivable that, as most engineering programs already have professional machine shops, similar fabrication space initiatives would choose to not stock the facility with manual mills or lathes and instead leave these tools under the purview of an established shop.

INTELLECTUAL PROPERTY

University intellectual property policies vary; fortunately, the policy at Georgia Tech is that students who are not employees of the Institute, are not performing research under a sponsored program, or are not using significant resources of the Institute do not have an obligation to assign their intellectual property rights to Georgia Tech Research Corporation (GTRC). Simply put, undergraduates working in the Invention Studio to create inventions keep all the rights to their own ideas. Use of the Invention Studio is not considered significant resources of the Institute. Graduate student users, staff, and faculty who are employees may be considered differently depending on the project on which they are working.

FUNDING AND EXPENSES

Funding has been provided by a combination of university internal and external sources. Costs are on the order of $40/student user per semester for operations, and an additional $40/student user per semester for capital equipment purchase and depreciation. For the 3000 ft^2 Invention Studio with approximately 1000 users per month, this amounts to approximately $100k of operations costs and $100k of equipment costs per semester.

The largest fraction of the support, approximately 50%, has been obtained through the Invention Studio's connection to the Capstone Design course. Across the United States, undergraduate engineering university programs commonly culminate in a Capstone Design course, an integrative course in which student teams synthesize solutions to open-ended, real-world problems (Dym, Agogino, Eris, Frey and Leifer 2005), occasionally in interdisciplinary teams (Hotaling, Fasse, Bost, Hermann and Forest 2012). The Capstone Design course staff solicits industry sponsors for the team's projects. The sponsoring companies receive the team's semester long effort: reports and a prototype of their solution to the project, along with recruiting opportunities and branding. The university and team, in turn, receive an open-ended project, cash donation, and a technical mentor from the company. Since the student teams require a facility to design and fabricate their prototypes, the industry funds can support the maintenance and operation of the Invention Studio in addition to other course expenses.

Approximately 30% of the Invention Studio support comes from a "Technology Fee Fund." This campus-wide fund is collected from enrolled students as a per-semester fee to fund efforts to improve academic and instructional capabilities. Through an internal competitive proposal solicitation, the Invention Studio receives funding for capital equipment purchases to support student engagement with cutting-edge prototyping equipment.

Approximately 15% of funding comes for cost reimbursement for support of university research. Faculty led research projects in the Invention Studio are usually free, except in the case of costly 3D printing or waterjet cutting. In these cases, a so-called "cost center" has been established to recoup costs incurred at a rate that is comparable to services available from private vendors. One full time non-student staff member manages these research project fabrication services and reimbursements. A small fraction, on the order of 5%, of the funding comes from direct donations, either industry or individuals such as alumni, from student government.

OUTREACH

The recent NAE study "Changing the Conversation" reveals that high school students often do not understand engineering (National Academy of Engineering 2013). This is especially problematic with women and under-represented minorities. The Invention Studio and similar maker spaces can help solve this problem by showcasing the excitement that engineering offers. Moreover, its unique focus on the essence of engineering—design, creativity and innovation—enhances the public perception of engineering and Georgia Tech's image as a driver and supporter of innovation.

The success of the Invention Studio has led to its involvement in various campus outreach activities such as freshmen orientation (all incoming freshmen in this orientation program visit the Invention

Studio) and daily guided tours (for parents with prospective students, industry representatives, alumni donors with grandchildren, groups of grammar school students, science clubs from high school, summer science camps, "parents day" visitors, visiting professors, freshmen orientation and students) ranging in size from 1-50 persons.

Recently, the Invention Studio's vital role as campus supporting infrastructure was leveraged as part of a funded $7.3M NSF-funded Math and Science Partnership grant at Georgia Tech entitled Advanced Manufacturing and Prototyping Integrated to Unlock Potential (AMP-IT-UP). AMP-IT-UP is led by the Georgia Tech School of Mechanical Engineering, in close collaboration with Georgia Tech's Center for Education Integrating Science Mathematics and Computing (CEISMC). While AMP-IT-UP is primarily aimed at developing hands-on engineering curricula for middle and high school classrooms, the grant includes an annual Makers summer camp at Georgia Tech as well as the implementation of junior Makers Clubs at partnering middle and high schools.

In 2013, the first Makers Camp was held in the Georgia Tech Invention Studio. In its first implementation, 24 high school students (rising 10^{th}-12^{th} graders) were hosted for a week. Members of the Makers Club developed the curriculum for the camp, which included laser-cut nametags, quadcopters, and racquetball launchers. Makers Club members also staffed the camp, providing on-the-spot training and safety supervision.

For this first iteration, the learning goals were the following:

- Students will design and build artifacts using the waterjet, laser cutter, 3D printer, and woodworking tools.
- Students will design and implement a problem solution using limited resources.
- Students will discover the iterative nature of design while working in a team.
- Students will consider feasibility of real-world manufacturing techniques while building design artifacts.

While only formative assessments were used in the pilot of the camp, future iterations of the camp will be evaluated with respect to the learning objectives. In general, students seemed to enjoy the camp, and they worked in teams to build solutions to design problems. In addition to the students, however, the Makers who participated in the camp learned a lot themselves and generally found the experience to be rewarding. The effects of outreach on the Makers will also be studied formally in future iterations.

Beyond the summer camp, the Makers Club organizes the Atlanta Maker Faire, an exhibition of dozens of booths by local artisans and builders, high school robotics teams, and faculty inventors. Now in its third year, the event typically draws 10,000 attendees per year.

As the Invention Studio continues to grow, outreach efforts are expected to grow as well. In the future, online mentoring will foster the establishment of junior Makers Clubs at Georgia Middle and

High Schools. Additionally, more summer camps are likely to make use of the Invention Studio facility. On a broader scale, the Invention Studio infrastructure and community is serving as a model for engineering curriculum and extracurricular activities that promotes engineering at younger grade levels nationwide.

IMPACT ON STUDENTS

An alumni survey was conducted to develop a preliminary understanding of the impact of the Invention Studio on participants. The survey consists of 20 Likert scale items, each of which is followed by a field for comments in the participant's own words. Additionally, there are 4 open-ended questions prompting for the following: the Studio's impact on the participant's life, the best and worst experience in the Invention Studio, biggest challenges for the Invention Studio, and general comments, suggestions, and concerns about the Invention Studio. These questions are not serving to develop theory; therefore, a traditional Grounded Theory methodology was not used in the analysis. Rather, the prompts themselves served to pre-categorize the data. The qualitative responses are used to identify and substantiate trends in the quantitative data.

Fifty recent graduates (from 2011 or later) of Georgia Tech responded to the survey. Of those who responded, 92% were BS graduates, and majors included mechanical engineering (78%), biomedical engineering (BME), (18%), electrical engineering (4%), aerospace engineering (2%), and computer science (2%). Respondents' GPAs ranged from 2.0 to 4.0, which is consistent with the average College of Engineering undergraduate GPA of approximately 3.08. Roughly 70% had done an internship or co-op during their tenure at GT. Of the respondents, 22.5% were female, which is representative of the College of Engineering population, although an under-representation of female BME majors. The Georgia Tech Institutional Review Board (IRB) was consulted prior to the survey being conducted and the need for approval and informed consent was waived for two reasons. First, the primary goal of this paper is to offer a description of the Invention Studio for other institutions desiring to implement something similar, as opposed to a formal research study about its impacts. Secondly, survey participants represent a convenience sample of alumni reached through independent avenues (versus official Institute channels) who are no longer affiliated with Georgia Tech as students or employees. Participants are anonymous and autonomous adults and participated in the survey voluntarily. For the above reasons, the IRB waived the need for approval and informed consent.

Survey respondents comprised many different types of users—some used the Studio for only one semester to work on a project while others reported sustained engagement as ULIs or in a leadership

1. Provide students with free access to hands-on, state-of-the-art prototyping technologies	4.69
2. Serve as a cultural hub and meeting ground	4.05
3. Bolster design within curricula including: introductory design courses, multidisciplinary design courses, Capstone design courses	4.28
4. Bolster design in extracurricular activities, organizations, and teams such as vehicle design competitions and invention competitions	4.37
5. Encourage collaboration between diverse teams of students from all years and majors	4.30
6. Welcome all types of projects, personal and professional	4.40
7. Excite students for careers involving creativity, design, innovation, and invention	4.52
8. Enable students to tackle open-ended, real world challenges	4.37
9. Serve as an exhibit and tour space to enhance the university's ability to recruit top students and showcase student work through local, national, and international news outlets	4.19

Table 1. Invention Studio goals and assessment from surveying 50 recent graduates. Scale: 1 (not at all) to 5 (very much), in response to the question, "To what extent do you feel that the Invention Studio achieved the following?"

role in the Makers Club. Most respondents (76%) had used the Studio in the past year, with the remaining having done so within the past three years.

As an initial assessment of how well the Studio's goals were met, survey respondents used a 5-point Likert scale ("not at all" to "very much") to respond to the following prompt: "to what extent do you feel that the Invention Studio achieved the [stated goal]". The mean response for each of our expressed Studio goals is in Table 1.

The data indicate that the Studio is achieving its expressed goals at a better than proficient level. In future studies, it may be beneficial to revisit the list of goals and use more detailed instruments that can tease apart the meaning of these responses in order to better understand the specific ways in which the Studio supports each goal as well as to understand the negative cases where students did not feel the goal was supported.

To get a sense for how much time students spent in the Studio, they were asked for an average number of hours per week as well as a maximum number of hours that they had ever spent in a week. On average, students reported that they spent 6.5 hours per week in the Studio, with a median value of 4 hours per week and a mode of 2 hours per week. Only 4 of the 50 respondents claimed to have averaged 20+ hours per week. However, in response to the maximum number of hours they had spent in a week, the average was 20.4 hours, with a median response of 15 hours per week and a mode of 10 hours per week. Seventeen respondents reported to have used the Studio for more than 20 hours in one week during their personal peak usage. From these results it is clear that the Invention Studio plays an important role in these students' college experience. As one survey

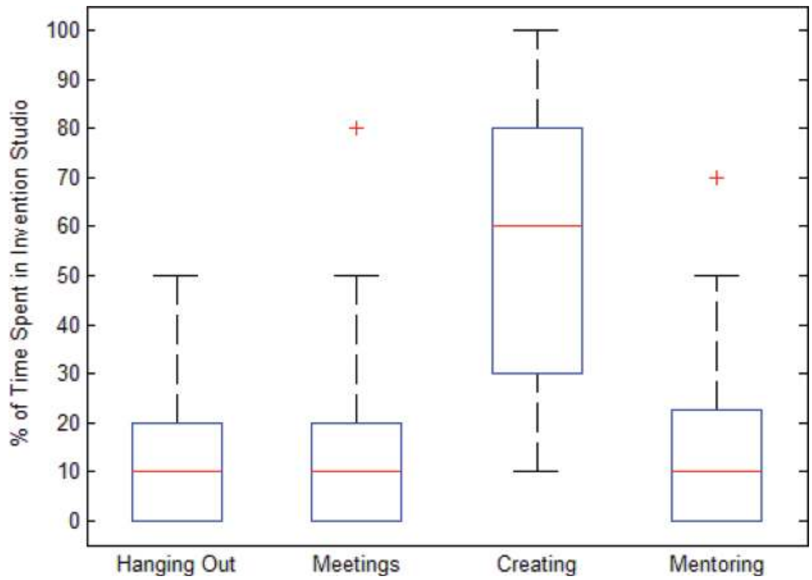

Figure 6. Results of Alumni Survey – User Time in the Invention Studio.

participant wrote when prompted for a word or phrase describing the Invention Studio: "*the place I miss most*". According to the surveyed alumni, creating hardware represented the most common use of their time (median 60%) with their time, generally, equally distributed (median 10%) across the other three factors.

Survey respondents were asked about percentage of time doing the following activities: hanging out, having meetings, creating or building something, and mentoring. Fig. 6 shows a boxplot of how user time was allocated while using the Invention Studio. The red line is the median of the data, the ends of the boxes are the 25th and 75th quartiles, and the ends of the whiskers capture the full spectrum of the data not including outliers, which are indicated by '+' symbols. From the results, most users spent the majority of their time building or creating something. Not surprisingly, 'creating' is a key need that a maker space must meet. In this survey the percentages were required to sum to 100% of their time, but in subsequent work overlapping factors and other use cases will be explored. For example, mentoring and hanging out might occur simultaneously with creating.

In addition, some users value the community aspects more heavily than others. For many students the relationship opportunity as a member of a community is meaningful, as described by one participant:

> *I have never felt as close to another group of people, and probably never will. It taught me that the best way to keep a group of people focused on the same goal is to always*

communicate openly and to help them find what they are good at such that they feel integral to the process.

This claim is reinforced by responses regarding the number of individuals that the respondents keep in touch with from the Invention Studio. On average, alumni report that they keep in touch with 12.3 friends made in the Studio, but the median response is only 5 friends and the mode is actually 0—this is because there is a non-negligible contingent of users who choose to build something for a particular project and but do not become a part of the community. Conversely, some respondents valued the community aspects of the Studio and reported keeping in touch with as many as 100 individuals. This data demonstrates that the ability to create is tantamount to all others, but maker spaces also need other affordances to assist in community building, including meeting space and areas for students to hang out. Peer mentoring is another clear service provided by the Invention Studio, and many of the student leaders spent a non-negligible percentage (i.e., >10%) of their time engaging in this activity. In future studies, the number of maintained acquaintances from the Invention Studio will be compared with maintained relationships in general or from other clubs. Additionally, the ways in which relationship and community-building empower and transform students working side-by-side as peers, mentors, and leaders will be studied. Further study is also needed in regards to gaining expertise in an applied environment and how that environment cultivates a professional identity. As described by this participant:

The Invention Studio gave valuable experience with dealing with people in an industrial environment. Additionally, the Studio offered the chance to be a part of something close to a start-up without the high risk. Learning how to machine brought a better understanding of the topics taught in class. Lastly, in any position, especially tool master, one developed actual leadership skills while trying to attain a goal.

A follow-up question asked the alumni what types of projects they worked on in the Invention Studio. Respondents could select all project genres that applied. The results from this question are shown in Figure. 7.

Interestingly, over 80% of respondents used the Studio for at least one class project, and even the majority of personal projects had an engineering focus. In future studies, it would be useful to study the causality of Studio usage—was it a personal project or required (class or research) project that caused the user to first enter the Invention Studio? Studying the ‘hook’ that brought them into the Studio and how the shift occurred from “almost required” participation to voluntary participation, that is, from school project to personal exploration, is a compelling area for future studies.

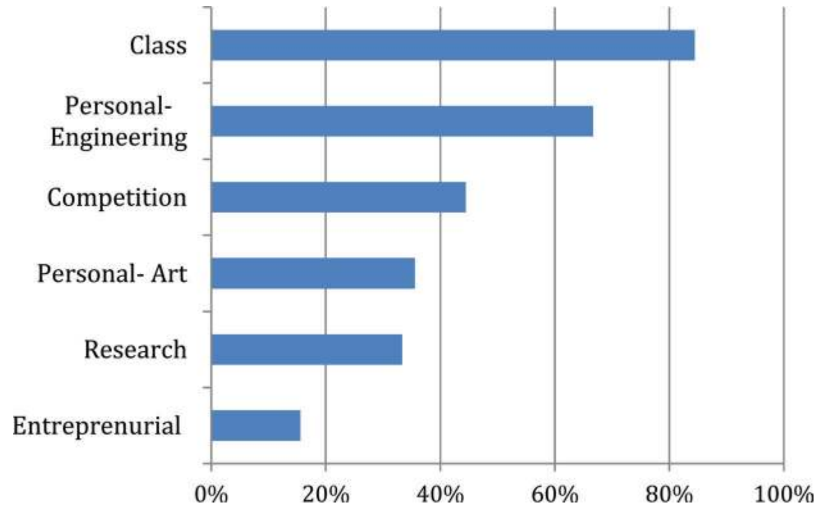

Figure 7. Alumni survey results: Types of projects for which respondents used the Invention Studio.

It is important to note the high use of the Invention Studio for personal projects. Many traditional building spaces such as machine shops do not allow students to pursue non-university related projects. This may be a critical feature for the long-term engagement of students and community building, which will be studied in future research.

Finally, survey respondents were asked about the impacts that their Invention Studio experiences had on various aspects of their personal and engineering skills development. Respondents were asked to rate each potential impact, as listed, from 'Very Negative' to 'Very Positive' using a 5-point Likert scale. The categories were determined by asking ten randomly selected student users for potential impacts on personal and engineering skills. These are self-reported responses, not a quantitative assessment. Results are shown in Fig. 8. For each bar in the graph, the percentage of respondents who reported each degree of impact is provided by color. Over 90% of respondents reported that the Invention Studio had a somewhat or very positive impact on their design skills, while approximately 88% of respondents reported a positive impact on their outlook on engineering. Additionally, more than 80% of respondents reported a positive impact on their manufacturing skills and their safety. Over 70% reported net positive impacts on their employment after graduation and teamwork skills. Finally, over 65% reported a positive impact on friends, and over 50% reported a positive impact on GPA (though only 10% reported a very positive impact).

Additional impacts surveyed include Leadership, Financial Management, Time Management, Ethics, and Community Service, but the reported impact on these characteristics is largely neutral and so they are not included in the figure.

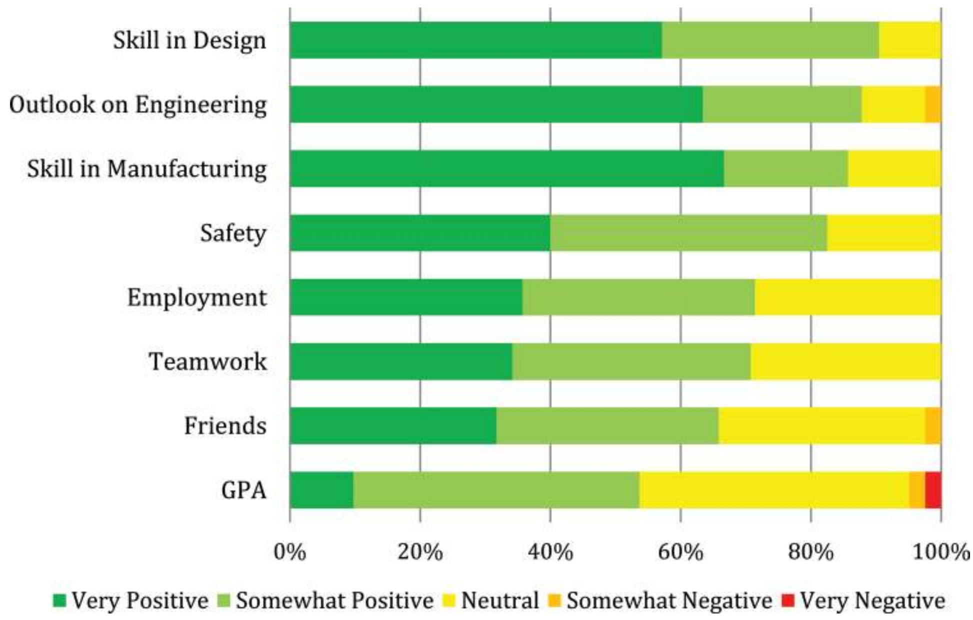

Figure 8. Alumni survey results: impact of Invention Studio engagement on participants.

In order to develop a rich understanding of the power of the Invention Studio, survey respondents were asked to describe the impact that the Studio has had on their lives. The responses are best represented by the following quotes from three different students:

> *The Studio has had a transformative effect on my education, job prospects, and career. During my years at Georgia Tech, engineering coursework was heavily weighted towards theory and abstraction. Furthermore, because of test (versus project based) assessment, my peers and I were heavily influenced to learn the bare minimum to get by instead of true mastery of concepts and material. Time spent in the Invention Studio gave me an intuitive understanding of design principles and rekindled my enjoyment of engineering and fabrication. Furthermore, the skills I learned while at the Studio were directly related to positive job prospects post- graduation.*

> *I left [Georgia] Tech and immediately took a job as a small manufacturing startup's only engineer/designer. Experience with the Invention Studio . . . allowed me to design and manufacture effective parts from day one. The portfolio built from the Invention Studio . . . allowed me to skip ~5 years as a junior engineer and move straight into a leadership role.*

I was able to learn so much and create so much using the tools of the Invention Studio. I say tools, but that doesn't just mean the physical machines. The community of knowledge that the Invention Studio brought together enabled me to learn new skills that I would never have been able to learn on my own.

These comments reflect the broad and deep impact of these facilities and community.

CHALLENGES AND OPPORTUNITIES

The Invention Studio as a physical, intellectual, and practice space engenders all aspects of a community of practice. As such, it has the potential to support situated learning, defined as learning that takes place in the same context in which it is applied, through participation in the life and activities of the maker community. In this way, the Invention Studio can serve as a significant affordance for learning. The Invention Studio and other university maker spaces can serve as a living laboratory to answer some of the most compelling questions in engineering education. Does working with one's hands on self-identified projects help to promote an engineering identity, a deeper understanding of engineering fundamentals, and/or an appreciation for representations in design? Does it improve retention for poorly performing students? There is a scarcity of academic research in the area of university maker spaces, and there is much to be learned through ethnographic study of how these spaces impact the lives of students. Most specifically, design self-efficacy, motivation, and commitment to major will be studied in future work.

The balance between safety, oversight, and individual freedom is an area of continued exploration, as well as between university policies and student ownership. Growth and success leads to new frontiers with these questions and continual assessment of how to maximize accessibility and to leverage student passion within the limitations of a university environment. A once small intimate club that grows to hundreds of members, thousands of users with hundreds of thousands of dollars of funding per semester can stress student leadership, culture, faculty mentorship, and staff responsibilities. Cultural divisions, such as elitism or exclusivity, can emerge and should be managed carefully. One must navigate these waters with the students' best interests at heart.

RECOMMENDED STRATEGIES FOR REPLICATING THE INVENTION STUDIO

Visitors touring the Invention Studio often ask, "How did this start and how can we start one at our university?" The simplest answer is to have a faculty champion to empower the students. The Invention

Studio was created by giving keys to a nascent shop, equipped with a drill press, grinder, and hand tools, to 10 students out of 200 in a Capstone Design course. With financial assistance from a successful sophomore design course (ME 2110) (Vaughan, Fortgang, Singhose, Donnell and Kurfess 2008), the first major piece of equipment, a waterjet cutter, was purchased as well. These 10 volunteers needed to use the shop for their Capstone Design projects and so they gained a distinct advantage over the other teams in the course from this 24 hour access. They were selected by the faculty champion based on existing skills in machine shop use obtained through internships or upbringing. In exchange for the key, they were asked to volunteer three hours per week to help others (their peers in the class). Using this method, the Invention Studio opened for 30 hours per week. The link to the capstone design course was a crucial catalyst for the Invention Studio because it ensured that the founding ULI's *needed* to use the Studio to be successful in their required projects and that the *industry funding* for the capstone course could support the Studio. This link to capstone design for funding and facilities has persisted and remains vital infrastructure. Students are recruited to use the space and participate in the Makers Club through word of mouth, advertising, and course mentions by faculty (e.g., Capstone Design). Students are engaged once recruited by keeping barriers to entry very low and allowing freedom, creativity, and ownership. The key role of the faculty and staff supporters then becomes the constant balancing of space, money, and people. Rather than deciding beforehand which will be most difficult at a particular institution, the primary goal should be to get started and discover it. Regarding safety and liability, do not be afraid to start small and let the students surprise you with their maturity and responsibility for safety. Universities have liability insurance; better to ask forgiveness than permission (from the lawyers).

The emergence of a distinct club (i.e., Makers Club) that staffs the Invention Studio separately from the Capstone Design course was affected when the 10 volunteers included students not enrolled in the course, from other majors and years. This has the important benefits of ensuring that knowledge can be handed down through generations of students and that the Makers Club can grow to include a large and diverse student population. As Capstone funding and Technology Fee funding have enabled additional equipment purchases, the facility expanded, at a rate of approximately one room per year for the past five years. The Makers Club has grown proportionally at a rate of approximately twenty ULI's/year net. Students are eager to own their own spaces, equipment, and projects. Georgia Tech faculty have been amazed by the initiative, independence, and resourcefulness of the Makers Club. All of this results from trusting and empowering the students, which is the most significant challenge to replicating this model.

CONCLUSION

The Invention Studio is changing the culture of Georgia Tech, the largest engineering school in the United States, by demonstrating the value and sustainability of hands-on, design-build education to stimulate innovation, creativity, and entrepreneurship in engineering undergraduates. The Invention Studio provides daily evidence that undergraduates can grow and maintain a high-end design-build facility. While this tremendous growth has created new challenges, we embrace them because of the exciting impact that it has already had and can have in the future at this university and others. We continue to balance the culture of safety with access. This report represents a snapshot in time, as we continue to grow the Makers Club, funding, equipment, and facilities for the Invention Studio. Indeed, the facilities, infrastructure, and cultural transformation occurring as a result of this endeavor are laying the groundwork for a new building on campus, tentatively called the Burdell Center. This proposed $75 million, 75,000 ft^2 facility, would be a focal point for innovative design/build activities across the Georgia Tech campus and would serve as an interdisciplinary environment for design education and a public portal for campus tours and media visits.

See https://www.youtube.com/watch?v=mOsX6xKdqzQ for a five minute tour of the Invention Studio or https://www.youtube.com/watch?v=YTIjvVmTQLY for a shorter version.

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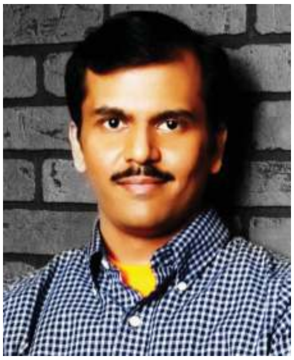
Craig Forest joined Georgia Tech in August 2008. He is an Associate Professor of Mechanical Engineering and also holds program faculty positions in Bioengineering and Biomedical Engineering. He conducts research on miniaturized, high-throughput robotic instrumentation to advance neuroscience and genetic science, working at the intersection of bioMEMS, precision machine design, optics, and microfabrication. He is cofounder/organizer of one of the largest undergraduate invention competitions in the US—The InVenture Prize, and founder/organizer of one of the largest student-run prototyping facilities in the US—The Invention Studio. He was a Sandia National Laboratories MEMS Fellow, NSF Graduate Research Fellow, was awarded the Georgia Tech Institute for BioEngineering and BioSciences Junior Faculty Award (2010) and was named Engineer of the Year in Education for the state of Georgia (2013). In 2007, he was a finalist on the ABC reality TV show "American Inventor."

Roxanne A. Moore is currently a postdoctoral fellow and adjunct professor in the George W. Woodruff School of Mechanical Engineering and Center for Education Integrating Mathematics, Science, and Computing (CEISMC) at the Georgia Institute of Technology. She received her M.S. and Ph.D. in Mechanical Engineering from Georgia Tech in 2009 and 2012, respectively, and her B.S. in Mechanical Engineering from the University of Illinois Urbana-Champaign in 2007. Her doctoral research was focused on optimization algorithms for engineering design. She is passionate about engineering education, from elementary school through post-secondary. She is currently writing hands-on engineering curriculum for middle and high school classrooms as part of the NSF funded "AMP-IT-UP" grant while teaching a sophomore-level design course for mechanical engineering students at Georgia Tech.

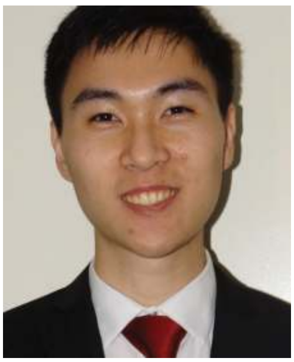


Amit Jariwala is currently the Director of Design & Innovation for the School of Mechanical Engineering at Georgia Tech. He graduated with a Bachelor's Degree in Production Engineering from the University of Mumbai, India with honors in 2005 and received Masters of Technology degree in Mechanical Engineering in 2007 from IIT Bombay, India. He received his Ph.D. in Mechanical Engineering from Georgia Tech in 2013, with a minor in Entrepreneurship. Dr. Jariwala has more than nine years of research experience in modeling, simulation, engineering design, and manufacturing process development, with research focus on design of polymer based micro additive manufacturing process. During his Ph.D. studies, he was a participant of the innovative TI:GER® program (funded by NSF:IGERT), which prepares students to commercialize high impact scientific research results. At Georgia Tech, he is responsible for enhancing corporate support for design courses, managing design and fabrication/prototyping facilities, coordinating the design competitions/expo and teaching design courses, with a strong focus on creating and enabling interdisciplinary educational experiences.

Barbara Burks Fasse is the Director of Learning Sciences Innovation and Research in the Coulter Department of Biomedical Engineering (BME) at Georgia Tech. Dr. Fasse studies the efficacy and value of student-centered learning initiatives, specifically Problem-Based and Project-Based Learning, in classrooms, instructional and design labs, capstone design, multi-disciplinary teams, and undergraduate research experiences. She joined the BME faculty in 2007 following ten years in Georgia Tech's College of Computing. In addition to her duties in BME, she is an advisor to the interdisciplinary research team conducting the Science Learning: Integrating Design, Engineering, and Robotics (SLIDER) project.

Julie Linsey's research focuses on design methods, design cognition and engineering education with a particular focus on innovation and design-by-analogy. Her research seeks to understand designers' cognitive processes with the goal of creating better tools and approaches to enhance innovation. She has authored over fifty technical publications including five book chapters and she holds two patents. She holds a B.S.E. (University of Michigan), M.S. (University of Texas) and a Ph.D. (University of Texas) in mechanical engineering.

Wendy C. Newstetter is the Director of Educational Research and Innovation in the College of Engineering at Georgia Tech. Trained as a cognitive and learning scientist, she studies engineering knowing and learning in classrooms, in laboratories and in-the wild. Towards that end, she uses ethnographic methods to study in vivo learning and problem solving in research laboratories---tissue engineering, neuroengineering and biorobotics--- where the nature of the problems demands multidisciplinary teams with complimentary skills and knowledge. She uses this research to then inform the design of problem-based learning (PBL) classrooms designed to support the development of integrative knowledge building and reasoning strategies. Most recently, she has been working to develop PBL models for instructional laboratories where students use techniques learned to tackle student-generated problems on the bench top.



Peter Ngo completed his M.S. in Mechanical Engineering at Georgia Tech in May 2014. He previously completed his B.S. in Mechanical Engineering at Caltech in June 2012. As a diversion from his Master's thesis work in conceptual design methods, Peter enjoyed contributing to research efforts surrounding the Maker Movement, makerspaces, and their impact on engineering innovation and education. He is a former user and an avid fan of the Invention Studio, owing much to its open environment and creative community.

Christopher Quintero graduated in 2012 from Georgia Tech with a B.S. in Mechanical Engineering. Along with many other students he was heavily involved in the creation of the Invention Studio. He is currently the Program Manager at Bolt- a startup accelerator based in Boston that invests in and helps hardware startups get to market. Prior to Bolt Chris worked on engineering and entrepreneurial projects in Chile, Cambodia, Vietnam, and Cameroon.