Examples of Synergies between Research and Hands-on Design-Based Learning

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Abstract
Space and time are precious and limited resources in any university, and many faculty and administrators face a dilemma on how to adequately support both research and educational missions of the Institute. Research needs may conflict with the need to provide space and time to support and enhance undergraduate education. In order to meet the growing demands for hands-on education, it is essential to encourage shared utilization of resources to support both research and education. The goal of this paper is to inspire faculty and institutions by presenting six successful examples of integrating research and undergraduate education at a large, state university. Students are conducting real research, reconstructed to take place as a design lesson in Thermodynamics. Faculty are leveraging infrastructure to attract funding from Government agencies (e.g. the Department of Energy), which would mutually support both the course and the faculty’s specific research interests. Research labs open their doors to the classroom for active learning, and student maker spaces double as data collection sites. The success of these efforts is dependent upon mutual appreciation for the roles of education and research while still respecting autonomy of these spaces and their primary missions. The lessons learned show that research can support and benefit from educational involvement, student learning, and autonomy.

1. Introduction
Traditional models of faculty time management show distinct lines drawn between the areas of research and teaching. Junior faculty are tacitly advised to spend as little time on teaching as possible. In the book “What They Didn’t Teach You in Graduate School”¹, the authors echo the view of teaching and research as separate activities, “Some people want to become professors, love to teach, and believe research is a necessary evil to get their ticket punched.” Contrary to the traditional advice given to faculty and researchers, we are increasingly seeing crossovers between teaching and research activities. Many faculty care deeply about the education of future engineers, and the lines between the lab and the classroom are being constantly challenged in modern universities. In response to increasing space and time constraints, faculty are finding ways to integrate teaching and research. This paper seeks to provide an integrated model for university activities, one in which both students and researchers benefit from research, teaching and extracurricular activities.

A primary argumentative model, termed the scarcity model³, claims that research and teaching are in conflict due to time, energy, and commitment. Time, according to a meta-analysis by Hattie and Marsh³, may not be as influential as commonly thought. The data indicate that there is not a one-to-one replacement of teaching and research time. One study suggests that for every hour increase in research there is only 20 minutes decrease of teaching time². Additionally, teaching evaluations do not correlate with time spent on teaching. In fact, the data indicate that good researchers and poor researchers are similarly likely to be good teachers and vice versa.
Contrary to “conventional wisdom” that good research will result in good teaching, both good research and good teaching must be deliberately practiced\(^3\)\(^-\)\(^5\). As part of this deliberate practice, Prince et. al.\(^4\) and Hattie and Marsh\(^5\) state that the field must begin to ask “How should we enhance this relation [between research and teaching]?” Many of the discussions up to this point focus on models of the agents involved, (e.g. faculty, institutions, and students) and explanatory variables, (e.g. time, ability, effectiveness, and personality)\(^5\). These explanatory models are important for understanding motivators and larger system structures that can foster excellence in teaching and research and impact student retention\(^4\). This paper, however, seeks to create an activity-based model for faculty, students, and administrators who are interested in understanding the mechanisms for deliberate integration of research and teaching efforts. Thus, in asking “How should we enhance this relation?” we present actionable recommendations for deliberate and concurrent investment in teaching and research.

It seems that there may be a direct benefit to deliberately linking teaching with research activities, rather than traditional forms of teaching and texts\(^6\). The lack of correlation between time and teaching may indicate that professors do not know how to effectively spend time on teaching as they do on research. Professors are not trained in educational theory so that they can use teaching time optimally, but they are trained in research so that research time may be effective. Best teachers are believed to be those who train students at multiple levels of Bloom’s Taxonomy and also in critical thinking, knowledge transfer, and metacognition - all tasks that professors utilize in research\(^4\),\(^7\),\(^8\), but are not well covered in textbooks.

One of the primary recommendations by Prince et al.\(^4\) is that universities provide faculty development in both research and teaching and especially in mechanisms for creating synergies between the two. The mechanisms noted by Prince et al. centered on bringing research into the classroom, involving students in undergraduate research positions and programs, and broadening the model for academic scholarship by valuing educational research. Our paper further builds on these recommendations by presenting a number of examples that bring research into the classroom, the classroom into the lab, and both into extracurricular spaces. The next section of our paper, Section 2, seeks to further clarify what mechanisms might be explored and introduced into the study and development of synergistic teaching and research activities. Section 3 provides a series of synergistic examples in research labs, classrooms, and extracurricular spaces at the Georgia Institute of Technology (Georgia Tech). Section 4 discusses the lessons learned and recommendations from these examples as well as avenues for future research and development.

2. **Framework of Research and Education**

Most studies of synergies between research and teaching focus on the benefits to students rather than the benefits to faculty. The synergistic model and framework for this paper, shown in Figure 2 and contrasted with the traditional model of Figure 1, focuses on activities that mutually benefit faculty research and student learning. Figure 2 illustrates how investment in equipment for research can also be used as investment in educational tools and vice-versa. Active, project-
based, and research-based learning activities may synergistically challenge students to produce research data, test research outputs, and provide creative input to research findings in the classroom environment, undergraduate research, or extra-curricular environments. This section briefly summarizes the types of university spaces and activities that might benefit both students and research.

2.1 Classrooms
Professors default to teaching by lecture, often guided by textbooks. Sometimes videos or data or simplified problems may be inserted to enhance the course content, but many unrealized opportunities exist to integrate research processes as part of the inductive or project-based learning approach. By bringing experimentation, discussion, and equipment into the classroom, domain problem-solving skills could be taught with the professor serving as a model and guide.

The effective linking of research and classroom requires deliberate consideration and resolution of the different levels of knowledge required for research activities\(^4,9,10\). Traditionally, the integration of research lab and classroom may be achieved by performing experiments, rather than engaging in intellectual contributions (such as data analysis or forming research questions)\(^10\). Thus, it is essential to bring more research into the classroom beyond a procedural standpoint, as found in a typical chemistry or physics laboratory class. Such activities have the potential to go beyond many undergraduate research experiences. As Prince et al.\(^4\) suggest, students can benefit from learning even portion of the research process while in the classroom.

![Figure 1: A Traditional, Separated Model of Three Kinds of University Spaces](image1)

![Figure 2: The Integrated Approach to Research-Teaching Synergies Looks at Layered Levels of Low to High Fidelity Faculty and Student Activities](image2)
2.2 Research Labs
Faculty can leverage existing investments in core research facilities by inviting students into research labs. Most traditionally, students enter labs as a form of employment, as undergraduate research assistants or graduate research assistants. Nevertheless, a number of opportunities exist to use research spaces as learning environments outside of the normal mechanism of research assistantships while simultaneously funding or advancing research.

Elsen et al.\textsuperscript{6} and Healey\textsuperscript{11} describe four curriculum models for integrating research and teaching, with half engaging students as the audience and half engaging students as participants. As the audience, students in a class might visit a clean room or engine lab to supplement their theoretical work in class with a visual or demonstration. As participants, they may be given limited access to use the facilities as part of a project or run experiments as part of a quiz or homework.

Currently, faculty are experimenting with including students as participants, from primary through higher education. At Georgia Tech, for example, the newly opened “Robotarium”, is run by robotics faculty on campus and plans to house over 100 aerial and swarm robots\textsuperscript{12}. The facility is designed for faculty experiments as well as experiments and code submitted by both external research groups and student groups from primary through higher education. Labs can achieve the mission to foster collaboration and advance science by maximizing utilization of facilities that are often too expensive to build and maintain. Numerous opportunities like this exist for allowing students to participate in research activities such as data collection and experimental design. Thus, faculty may be simultaneously building research and educational facilities.

2.3 Extra-Curricular Spaces
Living laboratories, makerspaces, buildings, student clubs, recreational centers, and machine shops are all examples of university and donor-funded, extracurricular spaces that may be used for research and educational goals. Researchers and students may, for example, utilize such spaces for building design or for real world studies of human power generation during exercise. Makerspaces and living laboratories are examples of how universities are actively investing in more hands-on educational missions outside of the classroom, but these spaces may be used for core research activities as well.

Living laboratories seek to build on the extensive research support for team-based, active, project-based, and design-based learning to create spaces that support hands-on, open-ended learning throughout the curriculum. The Integrated Teaching Learning Laboratory (ITLL) at the University of Colorado Boulder is a pioneering example of such a space. Opened in 1997, the ITLL supports a computer simulation lab, integrated networks of experimental equipment, two large laboratory plazas, design studios, project showcases, kinetic sculpture galleries, group work
areas and makerspaces. It is not just a stationary space, but includes online access and transferrable modules for off-campus users and activity carts and equipment that can be relocated to classrooms on-campus. Funded by the university and industry partners, and designed with input from industry and faculty from six departments, the space provides deep disciplinary learning opportunities in addition to offering opportunities for multidisciplinary learning. Including those at ITLL, Barrett et al.\textsuperscript{13} identified 40 different makerspaces in operation from the 127 top undergraduate institutions as ranked by US News & World Report. Thus, there is a tremendous resource for sharing equipment, engaging students, and collecting data on day-to-day activities of novice and professional engineers.

Such extra- and co-curricular spaces have proven benefits for learning and retention, but the benefits they provide to faculty through research and the opportunities for connecting learning and research activities are less explored and reported. Moreover, student activities provide numerous opportunities for real world data collection.

The following section provides a limited, but illustrative set of concrete examples of synergies at Georgia Tech.

3. **Examples of Synergies**

We present six different examples, summarized in Table 1, where faculty at Georgia Tech have identified creative ways to balance research with teaching and better leverage existing infrastructure (courses, space, equipment) to be successful as faculty in a top-tier research university. The examples are categorized on the basis of primary/major mechanisms involved: faculty research labs, extracurricular spaces and academic courses.

3.1 **Examples of Synergy in Academic Courses**

The three examples presented in this section 3.1 show how research can be integrated into academic courses to not only benefit the faculty, but also provide a novel and engaging learning experience for students.
Table 1: Summary of Examples and Benefits to Students and Faculty

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Examples</th>
<th>Faculty benefit</th>
<th>Student benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic Courses</td>
<td>Relocating and Scaling a Liquid Piston Engine Experiment for the Classroom</td>
<td>Publications, crowd learning of research</td>
<td>Hands-on engaged learning</td>
</tr>
<tr>
<td>Serving both Education and Research</td>
<td>Machining Software Research and Development through Classroom Use</td>
<td>Data and user feedback for scaling-up project</td>
<td>Experience with industry relevant skills</td>
</tr>
<tr>
<td>Research</td>
<td>Department of Energy Sponsored Capstone Design</td>
<td>Projects that might also be related to research, industry engagement for R&amp;D projects with industry</td>
<td>Real world projects, course credits, IP, job prospects with sponsor(s)</td>
</tr>
<tr>
<td>Research Labs</td>
<td>Manufacturing Research Lab Invites Class Students to Participate in Lab Meetings</td>
<td>Recruitment of in-class, trained students who previously used equipment; feedback with fresh perspective</td>
<td>Research experience, jobs</td>
</tr>
<tr>
<td>Doubling as Educational Spaces</td>
<td>Environmental Studies of Waste and Operation from 3D Printers in MakerSpace</td>
<td>Publications, research data and access to “free” space and student researchers</td>
<td>Training on effective use and 3D printers, undergraduate research, new equipment</td>
</tr>
<tr>
<td>Extracurricular Spaces Serving both Education and Research</td>
<td>Educational Studies of Students in Makerspace</td>
<td>Publications, research data, access to both “free” space and large number of students</td>
<td>Hands-on learning</td>
</tr>
</tbody>
</table>

3.1.1 Liquid Piston Engine Research in a Thermodynamics Class

This first example demonstrates how experimental set ups (experimental set ups in Figure 2) may be utilized in both the lab and in the classroom. Two separate research teams combined unique research proposals to create a thermodynamics lab activity that served as both a project-based learning study and as pilot studies for research. One research team sought to examine the effects of design-based learning activities on conceptual understanding of fundamental theoretical knowledge. The second team sought to increase the efficiency of a liquid piston engine. The researchers collaborated to create an in class activity with 12 different engine designs with which students could experiment. By working with the students through the class activity, shown in Figure 3, the researchers were able to dramatically increase the number of design variations being tested.

Motivation & Background

Most engines require complex manufacturing of parts such as linkages and timing mechanisms. One of the Principal Investigators (PIs) for this project, developed a type of liquid piston heat engine that could be batch fabricated from simple machined parts (e.g., acrylic). This PI's team tested one cylinder and two cylinder engines manufactured by CNC machining and thermally
bonding acrylic. During testing, the cylinders were filled with a liquid (e.g., water) to act as pistons and simultaneously entrap air that acted as a working fluid. The air which had thermal contact between hot and cold regions and two columns of liquid, thus resonated to create oscillatory motion of the liquid. The concept of this new engine was first published in Applied Physics Letters in 2014\textsuperscript{14}, with the lead author being an undergraduate researcher. For this current project, the PI sought to raise the efficiency of the engine by exploring the use of heat recovery and the effect of channel dimensions and design.

**Synergies**

The education researchers were looking to create a design based learning activity for thermodynamics, a course that is often counter-intuitive and difficult for students. In doing so, they connected with a thermodynamics instructor who was coincidently collaborating on the engine project. In order to adapt the experiments to the classroom, the engine researchers decomposed the engine design into a set of reconfigurable factors and components: the choice of working fluid, the absence or presence of a heat regenerator, and the dimensions of the liquid channels. These served as both creative parameters for the students and important scientific parameters that could be examined in pilot studies. Students were given autonomy to select pre-built configurations based upon their own preliminary analysis and then allowed freedom to make additional changes to the engine design that the researchers may not have explored. Students then analyzed the operation of the engine using video recordings with their cell phones followed by video analysis with open source software. The students documented their findings as reports with records of the cylinder oscillations, amplitudes, frequencies and a calculation of the operating efficiencies. The PI could then quickly see how different parameters seemed to change efficiency. Thus, the activity became both engaging and educational for the students and exploratory for the professors.

![Figure 3: Students Work On an Experimental Engine Design In a Classroom Designed for Lectures](image-url)
**Recommendations**

Students were required to determine how to extract the pertinent data, calculate the efficiency themselves, and explain how and why their engines operated. This act of explanation of a non-traditional problem exposed some understandings and misunderstandings that might have otherwise not been observed. The initial design activity, despite having this reflection component, did not close the loop to address or correct these misunderstandings. Given that each group of students had very different experiences, more sharing and group analysis could improve the educational aspects and further aid the researchers’ data analysis.

A key element to this activity was clearly presenting the task as research. This helped set the students’ expectations by showing that the professor did not have all the answers, and that it was an open ended exercise. This fact was reinforced by use of a research paper describing the work as part of the lesson. The research paper reported that the device followed a “Stirling” cycle, but further research showed that it may be a modified Rankine cycle instead. The use of the title “Stirling” in the research paper may have misled students in analyzing their engine as they were not cognizant enough to correct the assumption based on their observations and thermodynamic analysis.

### 3.1.2 Sophomore Design and Manufacturing Course as Customer and Test Bed for Process Planning Research

This second example demonstrates how experimentation and development of software and algorithms (experimental set ups in Figure 2) may also provide a teaching opportunity in a classroom. In a separate example, another PI and an industry partner implemented a novel process planning algorithm for SculptPrint, a software implementation package that provides a high degree of automation in the generation of G-code for CNC machines. The method whereby SculptPrint produces this machine code occurs as soon as SculptPrint receives the input model and converts it to a compressed, voxelized representation of the part which then enables rapid geometric analysis using parallel computing platforms. Prior success in this research by the PI and co-PIs led to an opportunity through NSF to implement their system in an educational setting. The course was piloted in spring 2016 and the project is funded by a federal agency and involves students in courses at Georgia Tech, Virginia Tech, and Penn State.

**Motivation & Background**

Engineering students are often unaware of manufacturing challenges that are introduced during the design process. Students sometimes design parts that are either very difficult or impossible to manufacture because they are unaware of the intricacies and limitations of various manufacturing processes. After developing a high-performance computing (HPC) accelerated parallelized trajectory planning software package, i.e., SculptPrint, a group of researchers were asked to implement this software in courses. The software will enable students to visualize the subtractive manufacturability of parts they design and will include the development of a manufacturability analysis tool for Additive Manufacturing (AM). Using the software in class will show students how their designs impact ease and cost of manufacturing. It will also help develop a distributed...
virtual machine architecture that will allow students and others to perform manufacturability analysis without physical access to HPC hardware.

**Synergies**
The university provided a vital role by hosting the research software on user-accessible virtual machines. This allowed the faculty and industry partners to provide the software and licenses to a large number of students for use in class. In one class, students are tasked to design and build automated machines, this included the manufacture (e.g., machining, additive manufacturing) of component parts. For many of the students, this class is their first introduction to design and manufacturing. By using the software as part of their class projects, the students will be able to develop their design ideas and realize more correct-by-construction components for their machines. It is expected that time to manufacture will be reduced as many students spend over 10 hours a week working on their projects - including prototyping and manufacturing tasks. Implementing this software in the class will simultaneously provide large quantities of usage data and case studies for further development of automated manufacturability analysis systems as the researchers continue developing the processing capabilities and user-friendliness of the software.

**Recommendations**
Preliminary tests were successful; a student with little 5-axis machining experience was able to fully utilize a dormant machine tool that had been unused for years due to the complexity associated with generating feasible machine instructions and code. Within a matter of weeks and with no formal training, the student was creating complex 5-axis parts using the manufacturability analysis software of SculptPrint. It is expected that the implementation of this software more broadly in project-based coursework will provide students with additional, modern professional skills. Students are already solicited for co-ops and internships with industry partners after design-build courses and this experience with advanced machinery and techniques will increase their portfolio of skills.

Connecting with university resources to make use of distributed computing and virtual servers helps reach a large portion of the student body and increase availability for use outside of class. Without this connection, researchers would have to provide dedicated machines for using the software, which reduces access. The virtual desktop implementation will allow students to perform manufacturability analysis at home or anywhere they have internet access.

Finally, the teaching and research team is transparent about the role of students as part of the testing and learning process. In the team’s previous experiences testing the introduction of novel devices (e.g., National Instruments MyRio controllers) to the curriculum, students were kept informed of their role as pioneers, and involved as stakeholders providing feedback. It is critical that these new teaching tools meet the needs of the student projects and learning environment.
3.1.3 Building Research Ties with Industry through Department of Energy Funded Capstone

This third example demonstrates how funding for research equipment may be shared in classroom and research settings (equipment in Figure 2). A Department of Energy (DOE) sponsored research contract was used to sponsor building energy efficiency capstone projects and procure materials and supplies that could be utilized in class and research. The DOE does not have particular educational mission, but they do seek to support workforce development. Aligned with this mission, the Building Technologies Office within DOE established a program, called Building University Innovators and Leaders Development (BUILD), to support undergraduate student engagement and education with the building energy efficiency industry. Georgia Tech received funding from this program to conduct 20+ building energy efficiency senior capstone projects over two years. Successfully completing the senior capstone course is a graduation requirement. Some of the projects conducted on this contract go to support faculty research interests in developing new energy efficiency technologies for buildings. This also helps seed and facilitate research connections between industry and research labs at Georgia Tech. Students gain exposure to university and industry research as part of their education in the capstone course.

Motivation & Background

The motivation for this DOE sponsored research contract was to support the capstone design course by providing students with opportunities to solve impactful real-world, energy related problems. This research-education project introduces students to a joint university-industry research effort to significantly improve energy efficiency with a scaling target of 0.25 quadrillion BTUs/yr energy savings (or 0.25% of US primary energy consumption) was the aggregate motivation for the portfolio of projects. In these projects, an industry or faculty sponsor would pose an open-ended research problem. Through the capstone course the students would then need to solve that problem and produce a functional prototype.

Synergies

Funds from the research contract were used to support the student’s materials and supplies cost to conduct the research and produce the prototypes. In this manner, research faculty sponsors had the opportunity to work with a student team to pilot new research directions without incurring expenses or needing to look for research seed funding. Industry sponsors had the opportunity to work with students to develop research solutions to problems they would otherwise not commit the resources to solve. Students were able to receive real-world exposure to problems as well as job prospects with sponsors; many students were even able to file for intellectual property based on their projects. Georgia Tech provided space and funds to seed some specialized equipment and recovered costs through indirect (e.g., overhead) on the sponsored research. This further benefited the university as it opened up opportunity for more sponsored research with industry mentors (e.g., development).

Recommendations
This approach opened an uncommon funding avenue with the DOE where sponsored research projects could be leveraged to directly support education. Others can readily adopt this approach by examining and redefining research tasks such that undergraduate students and courses could accomplish those tasks. However, we openly acknowledge this was a special case for DOE. The research funding call was specifically targeted to undergraduate projects; as part of the funding call, more than 50% of funds had to go directly to support undergraduate research efforts. While not all research contracts could be used in this manner, we recommend others considering ways of combining research and education in funding requests.

3.2 Examples of Synergies in Faculty Research Labs
Some of the most universally precious resources for faculty and researchers are research assistants, space, equipment and time. Undergraduate research experiences are a universal method for engaging students in research, either for credit or pay. These experiences are known to be beneficial to students, especially in engaging minorities or recruiting top students to graduate school. Nevertheless, hiring students for special topics credit or other programs is not the only method for engaging education in the laboratory.

3.2.1 Open Research Lab Meetings as an Extension of Educational Space
This fourth example demonstrates how students can be exposed to research discussion and application of theory by participating in lab group meetings (research discussions in Figure 2). One faculty member regularly invites students from his sophomore level design class to attend his research lab meetings. The research lab meetings are held weekly at 8am. Despite the early time slot, interested students show up and get involved in the meeting discussions.

Motivation & Background
The faculty member teaches a required design course in the School of Mechanical Engineering and his class has an enrollment of over 200 students each semester. His class lectures are very interactive and yet he pursues to increase his engagement with students beyond the classroom. He considers inviting undergraduate students at research meetings as a means to bring fresh perspective on research challenges.

Synergies
While inviting students to attend and participate in research lab meetings might sound simple and ineffective, observations suggest otherwise. Nonetheless, the faculty member does use some resources to entice students through free food, but the outcomes are many fold. Attendance of undergraduate students at research lab meetings tends to serve as a source of new questions which challenges the research process and puts forth fresh ideas. In other words, the research questions and hypothesis studied by the faculty’s research group receives examination by a fresh set of eyes. It is not uncommon for students who attend the meetings to get excited about the research problem and apply as researchers in the faculty’s lab. These students already have the basic design and problem solving skills from the classroom which they can apply in the faculty’s research lab. From the student’s perspective, this is yet another avenue to increase engagement
with the faculty, learn about research and explore if they prefer research without a substantial commitment on their part. If they think they might be interested in doing research, they receive preferential treatment when applying for part-time positions or for credit positions in the lab as they build their research credentials and prepare for graduate school.

**Recommendations**

Students from the class have been consistently attending the research meetings and participating actively in the discussions. Inviting students to attend research lab meetings has been quite beneficial for both faculty and students. The faculty member has observed that the students will step up to the plate and take on a few additional research tasks to better contribute at research meetings. It is important to note that the faculty must be careful to not overwhelm the students with too many activities outside the class-room which may adversely affect their coursework.

3.3 Examples of Synergy in Extracurricular Spaces

The examples in this section show how investment in educational fabrication spaces and course infrastructure by the institution and faculty have mutual benefits for maintenance and creation of real world data as well as procuring external funding and industry investment. Most of these examples utilize the unique resources of the Invention Studio at Georgia Tech. It is a 4,500 ft² facility that includes over $1M of prototyping equipment and tools along with design, assembly, and testing spaces. The Invention Studio, shown in Figure 4, is operated and maintained by a small supporting staff and a large active staff of undergraduate volunteers. It is open to anyone on campus.

![Invention Studio](image)

*Figure 4: The Invention Studio is Open to Anyone on Campus for Personal, Class and Research Projects*

3.3.1 Makerspaces as Industrial Environments for Study of 3D Printing Waste and Energy

This fifth example demonstrates how equipment used for extracurricular activities can also be used for collecting research data (equipment in the model from Figure 2). One faculty at Georgia Tech is working with the student makerspace to collect data for assessing environmental impacts
of 3D printing, resulting in shared equipment, shared student resources, and ample real world data on manufacturing.

**Motivation & Background**

Fused deposition modeling (FDM) is a prominent technology for additive manufacturing of functional parts. FDM is the technology utilized by most open source printers and popular companies, such as the MakerBot. The Invention Studio houses an open space with over 40 FDM machines open for the students to learn and print products. This educational environment provided a unique venue for the faculty member to examine realistic operating loads on the machines.

FDM feeds a plastic filament through a nozzle that melts and extrudes the plastic to build parts layer by layer. It often utilizes a "raft" platform for the bottom area of the part and breakable supports for overhangs. FDM and competing additive manufacturing technologies are generally assumed to be more environmentally sustainable than conventional manufacturing methods because the additive process minimizes tooling, material waste, and chemical fluids. A 2009 NSF-sponsored workshop identified multiple research needs relating to sustainability, including material performance data, measures of process sustainability, and comparisons with other manufacturing methods\textsuperscript{17}. Since then, a studies have looked at the material and energy use of additive technologies such as laser sintering\textsuperscript{18-20} and FDM\textsuperscript{21}.

Controlled experiments exist to measure material and energy consumption, but little research includes potential operational errors and waste from consumers. In preliminary data collection through partnership with the Invention Studio, it was found that the mass of material lost to failed builds was about 70% of the total mass of material created by external supports. This indicates that material loss is about 1.7 times what might be estimated in a controlled process study.

**Synergies**

The Invention Studio provided a unique and accessible environment for the PI to combine resources on campus, utilizing the machines in the studios and utilizing data collection equipment with the needs of the makerspace and staff. Results will be used to improve operation of the space in addition to contributions to the fields of sustainable design and manufacturing.

The PI quickly started a preliminary collection of waste material with nominal effort. The machines and facilities were already being operated, and waste material was simply diverted for measurement and storage. The preliminary data collection and conversations with student staff of the Invention Studio inspired a cost-benefit study for introducing a filament recycling system. Subsequently, the PI purchased a filament recycling system to be monitored, maintained, housed, operated, and studied by the Invention Studio staff.
Utilizing the network of students who are passionate and involved in the studio, the PI hired an undergraduate researcher, who works as an apprentice on the printer system, to additionally help with the research. This connection opened further opportunities for additional studies and insights as the undergraduate student had close familiarity with the systems and their 24 hour operation and maintenance.

Future synergies are being explored, synergies such as monitoring systems that can record printing processes initiated by the researchers and printing progress by the students. It is envisioned that the studies and data collected will further benefit the student makerspace by (1) providing information that can help understand throughput and inefficiencies, (2) increase student awareness of sustainability, and (3) foster more efficient use practices to be taught in the studio and in courses using the studio. Very simple methods for increasing awareness include providing slides of best practices for the instructors as well as creating visual educational posters strategically displayed in the makerspace.

**Recommendations**

The success of the 3D printing study rests upon respect by the PI for the primary educational mission of the makerspace and the desire to keep it open for free use. By purchasing recycling equipment, the PI demonstrated a firm commitment to the makerspace early in the project. The student staff were consulted before preliminary data collection. Their ideas and interests were used to help shape the research procedures. The original plan for working within the space was revised for these pilot studies.

The separation of the makerspace and the PI’s primary research facilities has increased the need for regular communication and physical presence. The PI plans to take a more active role in working with the makerspace staff by joining staff meetings to better understand the needs of the space and how to manage the research project with their help and support.

**3.3.2 Makerspaces as Hands-On Educational Environments**

This sixth example demonstrates how equipment and space for extracurricular activities may also be used for research in education as well as fundamental educational missions (equipment and research discussions integration in Figure 2). Another PI within Georgia Tech researches and develops new methods and tools to support the early phases of the design process with a particular focus on innovation and conceptual design. The PI’s research studies makerspaces with emphasis on their impact on engineering education, particularly with regards to retention, creativity and design.

**Motivation & Background**

Community run makerspaces at universities are gaining popularity to promote design experiences at the undergraduate level. Barrett et al.’s review of 40 different makerspaces shows that makerspaces have an opportunity to revolutionize the current educational system by
providing an extracurricular means for students to engage in more hands-on projects and develop a large range of the skills that are currently being underdeveloped. This project is a collaboration across Georgia Tech, Texas State – San Marcos, and James Madison University to measure the impact that makerspaces have on engineering idea generation skills, design self-efficacy, retention and minority/female engagement.

The Invention Studio at Georgia Tech provides a large pool of engineers in training for study, as it is used by students enrolled in over 25 different courses and numerous other students who just want to build things for fun. As noted at the beginning of Section 3.2, this facility is open to anyone on campus for personal use and additionally serves the need for a hands-on prototyping facility for undergraduate design and manufacturing courses.

**Synergies**

There is an ongoing need to develop better estimates for the number of students using the Invention Studio. Usage data could assist with better prediction of machine downtimes, tool replacement and budgeting for materials. With a generic estimate of around 1000 student users every month, it is not quite straightforward for the administration to allocate appropriate resources to support the space. The faculty conducting research in the Invention Studio is also keen to gather data on usage statistics for the Invention Studio in order to evaluate educational and diversity impacts. As a result of this need, the PI hired a research assistant to install a non-invasive counter in one of the rooms of the Invention Studio to track the number of users utilizing the space. A few student staff volunteers also benefited from this interaction with faculty and their graduate students by gaining firsthand experience on how research is conducted. They received support for developing software that not only helped faculty’s research but also aided in developing better metrics with regards to equipment usage. The data was shared with the student volunteers and the administration and was quite useful in determining realistic estimates on the material and tooling needs for the space. The student leaders and the administration shared the data obtained from the research activity with current and potential sponsors/donors of the makerspace.

**Recommendations**

The approach of partnering with the Invention Studio helped faculty leverage the pool of student volunteers who staff the space as well as users to gather relevant data for research. It was crucial to develop a good rapport between the faculty and the student staff prior to starting the research data collection and, so, the PI decided it was beneficial to the success of the project to attend regular staff meetings. It was also important that students were taken into confidence that they were not being exploited as research subjects. Likewise, faculty were able to show students the process of conducting research in the makerspace would indirectly benefit the space and the culture.

Projects like this show that undergraduate students can serve as an incredible source of creativity as long as they are considered equal partners and given the trust in the quest to discover new
knowledge. However, faculty have to be careful that they do not overwhelm the students to the extent that they get sidetracked from their primary learning objective. Students can gain creative confidence by engaging themselves in hands-on projects within extra-curricular spaces. These spaces stand to benefit even more when they are staffed by passionate and enthusiastic student users who take ownership of the space and develop usage policies that best fit the students’ interests. It is important to make sure the faculty leveraging teaching spaces for research respect the primary educational mission of the space and involve students when developing proposals and designing experiments.

4. Limitations
The intuitive argument for looking at synergistic activities is that one may develop experiments for the lab and classroom concurrently, or generate notes on research articles that can be used for class and research presentations. Hattie and Marsh established this is not usually the case, but the examples in this paper may guide faculty and universities in deliberate efforts to combine teaching and research activities.

A significant limitation of combining research and teaching, and an opportunity for further research, is that there may be inherent mismatches between student knowledge and the level of detail required for some research tasks. Colbeck conducted structured observations of 12 faculty in four departments over a five day period. Although as much as 34% of a faculty member’s time was spent on synergistic activities between classroom teaching Colbeck observed that the disconnect in level of knowledge between the classroom and research lab prevented overlap in many cases.

5. Lessons Learned and Recommendations
The examples shared in this paper are ongoing forays into sharing research between faculty labs, classrooms and extra-curricular spaces. The primary motivations were to leverage existing infrastructure (whether it be research or extra-curricular spaces, equipment or expertise), stimulate student interest and engagement in learning all the while supporting faculty’s primary research programs. The success of these examples was the alignment, clear communication and concern for the interests of all stakeholders (faculty, students, administration). Each participant benefitted from the others without paying a substantial cost (in terms of space or time). The general structure for finding synergies rests on faculty being able to transfer experiments from the lab to the classroom or extracurricular spaces, share equipment from across these spaces, and bring educational activities into labs and makerspaces (Figure 2).

These experiences revealed that students must be engaged in a transparent way and that activities must be structured to meet the appropriate knowledge levels and learning goals. Students must be clearly informed in their role as researchers or contributors to research. As part of this role, they should be given some level of autonomy, such as the ability to tweak the experiment or given access to equipment or tools for their creative projects. Despite the level of autonomy that students thrive on, it is important that faculty realize students may be slow to question a
hypothesis when engaging in experiments. They thus require mentoring and reflection with regards to research methods. Faculty must also invest in these activities by purchasing or providing access to equipment, or consulting with students regularly. Additionally, many of these projects utilized existing university resources (e.g. computing or manufacturing infrastructures) or external funding to help create the projects and spaces.

It is recommended that more directed research explore how state-of-the-art experimental techniques can be brought into the classroom or how students, especially in large classes, may be engaged in the lab. While the examples in this paper provide a few ideas, educational research can provide more fundamental insight into scoping and scaling experiments to meet learning objectives. Since researchers are rarely trained in communicating cognitive procedures, tasks such as reflection were skipped in the above examples but could have increased the learning experience beyond being a fun activity where students gain confidence and researchers collect data.

6. References


