The Experience of Simplifying and Packaging Creative Engineering K-12 Education into Innovative Products
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ABSTRACT
PaperBots is an educational technology developed at Tufts University’s Center for Engineering Education and Outreach (CEEO). PaperBots was developed as an inexpensive option to present engineering education and design-based lessons in classrooms, addressing a cost-driven opening in the educational technology marketplace. This paper serves as a case study of the initial development of this educational technology and the experiences gained and lessons learned by Tufts University graduate students. The development of PaperBots provided innovation and entrepreneurship experience in a very specialized and unique market. This paper examines the processes of product development, market analysis, stakeholder analysis, industry feedback, utilization of university resources, and other aspects of the product’s development. The experiences creating PaperBots provide an interesting case study for other graduate students looking to develop their own educational technologies.

Introduction
In the summer of 2011, Brian O’Connell, mechanical engineering graduate student at Tufts University and research assistant at Tufts University’s Center for Engineering Education and Outreach (CEEO), began designing PaperBots, an educational technology that uses common classroom materials to provide engineering education in Kindergarten through 12th grade classrooms. By using inexpensive materials, PaperBots aims to penetrate the lower cost region of a large marketplace that is currently dominated by some well-known, much more expensive competitors. The concept of complementing academic curricula with robotics has been discussed since the mid-1970s (Trotter 1973) and the means to do so at the K-12 level were made more available by LEGO as early as 1993 (Erwin, Cyr, and Rogers 2000, 181). Educators worldwide have struggled for years to raise the funds to bring robotics into the classroom. PaperBots seeks to provide a low-cost way for students to participate in hands-on science, technology, engineering, and math (STEM) activities and emphasizes creativity, engineering principles, team collaboration, and communication through the use of common classroom materials. Our ultimate goal is to develop a product that is successful in a worldwide marketplace with many isolating idiosyncrasies.

This paper discusses the initial development of PaperBots to provide a case study on the development of an educational technology in a graduate setting. The development process and knowledge learned during this process are included to provide context for many of the decisions that directed the process.

Initial Idea
Masao Ishihara, a Japanese distributor of LEGO products and other educational technologies, presented an interesting problem to Dr. Chris Rogers of
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the Center for Engineering Education Outreach (CEEEO). Expansion into the Indian marketplace proved difficult for Mr. Ishihara, due to the limited budgets in rural areas. This brought about the question, “What can be done to provide interactive design activities in schools with restricted budgets?” It was quickly noted that paper is available in all schools; this fact led to the main question behind PaperBots: How can we provide engineering education lessons using paper as our primary material? As part of their advisor/student relationship, Dr. Rogers gave this idea to Brian to work on for his thesis for his Master of Science in Mechanical Engineering degree. This exchange of innovative ideas is an interesting aspect of graduate communities and allows for development and ownership of many innovations by students who may not be the direct owner of the initial idea. Credit will always be given to the originators of the idea, and further legal connection between any emerging companies and the university will need consideration. This aspect is far less daunting in an academic environment than in a more corporate one, since universities are prepared for and encourage industrial development of the ideas birthed there.

Product Development
The journey from idea to prototype is not a simple one. Concepts have to be proven and capabilities must be ensured. Brian examined the capabilities of paper, studying existing paper craft projects and developing simple mechanisms, such as structures, cams, ratchets, cranks, and levers, out of paper. Creating working mechanisms out of paper is relatively simple for someone experienced with paper craft, but creating such devices seems nearly impossible to inexperienced students. Katarina Morowsky, a human factors engineering graduate student at Tufts University, was brought on to the team to ensure that the educational activities would be properly suited for inexperienced students and teachers. The next priority was the development of useful educational activities using paper.

The team worked together to create activities that would align PaperBots with the project’s defined purpose. After initial prototypes were created, a heuristic analysis was performed to identify areas for improvement in the design that would minimize build time and difficulties while assembling. Individual parts were redesigned and assemblies were scaled to better accommodate for a range of dexterity. Parts were also consolidated to minimize the need for non-paper materials and decrease the workload required to follow the assembly instructions. Once the changes were implemented, lesson plans and instructions were created, and observations were conducted with groups of college students to identify further areas of improvement for each activity. These observations identified the need to further promote creativity and collaboration in the activities. Observations also confirmed that students were learning new concepts and enjoying themselves while performing the PaperBots activities. These observations and tests served to build confidence in the product’s ability to compete with other educational technologies.

Educational Marketplace
The educational technology market is a $7.5 billion industry in the United States alone (Watters 2011). Both industry and government have made increased investments in this market over the last few years. The Silicon Valley, home of the world’s largest technology companies, invested $177 million into educational technology companies in 2010, three times the investment
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made in 2007 (MacMillan 2011). The American Recovery and Reinvestment act of 2009 provided $650 million specifically for educational technology (US Department of Education 2009). This investment has also been seen in policy. Current Massachusetts state guidelines require 90% of all teachers to be using technology in the classroom by 2015 (Mass Department of Education 2010). This will require local financial support to provide classrooms with appropriate technologies.

LEGO Education, the most well-known provider of educational technology, is geared toward physical interaction and student learning. LEGO Group reported $3.495 billion in revenue for 2011; LEGO Education accounts for $304 million. LEGO Mindstorm, their signature product, retails for $279.99 and has been integrated into classrooms around the world (LEGO Group 2011). The cost of their product is LEGO’s biggest obstacle in terms of entering more classrooms. For a standard US classroom size of 23.1 students (Rampell 2009), ten kits would be needed for effective use, requiring a $2,800 investment per class. Less expensive building kits, such as Engino and K’nex, are available, but each kit only focuses on one topic and costs at least $25. Fully outfitting a classroom to accommodate all students and lessons would conservatively cost a minimum of $1,350 per classroom.

Stakeholders
A product requires a customer and a good product design team seeks to understand that customer. Students who will use the product directly are our most important stakeholders. The primary goal of PaperBots is to provide students with an effective and fun learning experience; if students do not have fun and learn from the PaperBots activities, then it is not an effective educational technology product.

Teachers are the second largest group of stakeholders. They will make the initial and greatest investments in both time and money to bring PaperBots into the classroom. Administration, parents, and aides are also stakeholders, because they are interested in the product’s educational results as well as how it works in the classroom. It has become an accepted practice among school districts to expect teachers to spend a significant amount of their own money each year on classroom resources. A National School Supply and Equipment Association study showed that US teachers spent $3.5 billion outside of their provided budget in the 2009-2010 school year, $1.3 billion of which was from their own money. That’s an average of $356 per teacher spent on supplies and instructional equipment not provided by their school district, through grants, or from parent or PTA support (Nagel 2010). This amount is 26% of the amount required to outfit a classroom with the resources currently available in the educational marketplace. These expenditures are commonly written off in taxes, but this does not always fully reimburse the teacher.

Business and Distribution Model
An understanding of the capabilities and the psychology of the stakeholders helped develop the business and distribution model of PaperBots. The revenue plan comes in three tiers. The first tier was designed specifically to be the most helpful and attractive to teachers. Since teachers are expected to provide many resources for their classroom out of their own pockets, we will start by providing teachers free lesson plans and templates through our
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website. We will also provide templates and support for the lesson plans, and introduce new activities on our website, all free to download. The major issue with this route is the preparation time involved. Many of the PaperBots activities require cutting the pieces out of the printed templates. If students do it, wasted class time becomes a consideration and if the teacher does it, they would drastically increase their preparation time. To address this issue, we intend to provide booklets and activity packages that provide all the materials needed for the lessons. We are currently searching for publishers, with the intention of keeping the price to outfit a classroom with several activities below $250, less than a single LEGO Mindstorm kit. This price point is based on conversations with teachers and educational technology specialists, and on the psychology behind their purchasing. Although a yearly consumable may seem wasteful, anything more expensive is unlikely to be considered.

According to Ethan Danahy, a Tufts University Research Assistant Professor, it can take many years and many teachers using a product or method before their school will take notice and make the larger investments, and most teachers would rather make an annual investment than pursue greater funds. At this price point, rather than pursue the approvals for a large long-term investment, a teacher can make an annual $250 investment which can be written off in taxes or budgetary slush funds.

The final tier will provide craft cutters or laser cutters, so that teachers can cut out the required components in an automated and efficient manner. This tier allows schools to make a long-term investment in the product line and is best implemented when multiple teachers within one school are using the PaperBots activities. Professional development seminars will eventually be developed as another product for schools to purchase as a means to help teachers utilize PaperBots across grade levels and develop their own activities.

Feedback
We found dozens of individuals from the Tufts student body who were eager to try the activities, provide feedback, and help to further develop our product line. Without utilizing this resource, many issues that were identified in a controlled environment of our peers would not have been discovered until beta-testing in the public domain. In addition, through our connections with Tufts faculty, we had the opportunity to receive feedback on our product and business model from the CEOs of Templeman Automation and Sparkfun Electronics, a cognitive psychologist and professor of Human Factors, an educational technology expert and professor of computer technology, and several others. Their feedback provided us with added perspectives and ideas we hadn’t considered. Some redirected our scope to include values other than those that were purely academic:
Overall, I can see a lot of value in using these 4 activities for an after school workshop that combines engineering education, with a focus on problem solving, and emotional and social skill development. By learning about problem solving, the participants have to learn to be patient, to dig into problems and try to figure them out. If forced to work in pairs or small groups, they will also have to learn to manage the various relationships and develop social skills. By practicing problem solving, they learn to develop patience and increase emotional regulation. Through their successes, they will be building self-esteem and gaining skills that are transferable into everyday life.

-Dr. Daniel Hannon, Cognitive Psychologist

Other interviews provided us with great amount of support and increased our confidence in the project.

As soon as I saw this I thought, my nephew, he is nine years old and he would eat this up. It's not so much about cost or anything else, it's something that you can just give him and he can do and immediately he's like that's awesome, now what.

- Nathan Seidle, CEO of SparkFun Electronics

People were like “I didn't know paper could do that. That blew my mind.” People were really drawn in by the accessibility of the materials.

- Dr. Ethan Danahy, Tufts University Research Assistant Professor in Computer Science, Observations from the 19th International Congress on Modeling and Simulation

Another CEO made clear some selling points that we had previously overlooked and have now become an important aspect of many of our pitches.

These paper robots seem much more realistic [than other traditional education construction systems] because in the real world things bend, and things wobble, because of how not everything is exactly right. As we're developing new products in our shop, things don't fit together exactly how they should because all the parts have different tolerances. And so showing students that when they make a gear, that gear has tolerances, that gear has considerations they need to adjust for. That's more real world. That's more real engineering.

- Chris Templeman, President and CEO of Templeman Automation

This is fantastic, put this on a webpage right now. So what if it breaks after the fifteenth revolution. I think you still have enough value here to get going.

- Nathan Seidle, CEO of SparkFun Electronics

Encouragement from these experts helped us take steps we had previously hesitated on. We registered our domain and started putting ourselves out there through our website, http://paperbots.k12engineering.com. Through these university contacts, we were also able to find means to introduce our product to the public and gain some additional feedback. In the greater Boston area, there are several educational outreach groups, like Maker groups and the Cambridge Science Festival, that utilize universities as a source of new educational activities and resources. These groups organize many outreach opportunities to introduce fun science activities to the community. Pa-
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perBots fit well into those events and allowed us to get feedback directly from our target stakeholders.

Problems/Lessons Learned
Throughout the design process, we ran into numerous challenges and learned lessons accordingly. The PaperBots concept was originally created to address the current barrier experienced by LEGO when introducing robotics kits in India; we quickly saw the correlation to many budget issues in the United States. Once we began testing the product, its possibilities grew even further. This became a problem, as we tried to design for the needs of every potential user. We had to limit the scope of our testing to address the needs of only our biggest stakeholders: students. We further split “students” into three sub-groups—students in the United States, students in developing countries, and students with special needs—and then chose to focus on just one sub-group. Thus far, the products and lesson plans have been geared toward students in the United States, since that is the largest population we can access. This has made development much easier. We plan to eventually use our findings from the initial group to inform the design of products and lesson plans for students in third world countries, as well as those with cognitive disabilities. As we proceed in our designs for the later groups, it will be crucial to identify the cultural limitations and social constructs, as well as the physical and cognitive abilities of each targeted user group.

When we first began to create the classroom activities and projects, we had self-imposed limitations about what materials could be used in the designs and what principles we were aiming to integrate into the lesson plans. Initially we had planned to use only paper. This became extremely limiting, as well as tedious—it took more time and effort to fold the paper into connections and shafts, when things like tape, glue, straws, brass fasteners, and other craft and office supplies are freely available in the classroom. Adding already budgeted classroom craft materials was a fairly simple way to modify our initial concept without changing our goals.

Even working with our expanded concept, we struggled to think of more out-of-the-box ways to provide teachers with a full complement of lesson plans. We ultimately succumbed to adding hobby level supplies, such as battery-powered motors, in order to drive some of the paper mechanisms. We still adhered to our goals by providing both lessons that require classroom materials only and lessons that require very low cost hobby supplies. While still working within a tight budget, we opened up new levels of learning for the students and ourselves by challenging our initial restrictions.

In coming up with ideas for our fourth and final lesson plan, we hit a brainstorming wall. We had already covered concepts of potential and kinetic energy, cams, linkages, and motors, and weren’t sure where to go next. After reflecting on the problems we commonly encountered in industry and academia, we decided that our lesson plan needed to focus on the engineering design process, free-form design, teamwork, and collaboration. But even after identifying the concepts this lesson would address, we could not come up with an original design. The idea of a Rube Goldberg machine came up, but there was initial hesitation because we didn’t feel it was original enough. We finally decided to put our own spin on the idea, limiting the types of allowable materials and each group’s usable build space. We learned that in design, you
do not always need a brand new idea; you can seek a new application of an old idea instead.

Many assumed from the name PaperBots that the designs would focus solely on robotics, and this became an issue. Meeting the expectations of our stakeholders also became a challenge. While we have begun to expand into the robotics domain, the majority of our preliminary work has been focused on activities that lead up to robotics activities. Students must first understand energy conversion and mechanisms, as well as sensors and reaction, before they can appreciate robotics. Misconceptions based on the name of the product have not greatly limited interest from stakeholders, but it did become a marketing concern.

Our original concerns with the materials were that they would prove to be too innocuous and delicate, making the children concerned with their use. We found that users had expectations of their own abilities as well. Children were much more willing to dive into the design process than adults were. Adults struggled with creativity and were initially overwhelmed at the thought that they could build the Hexabot out of paper, only becoming more confident when we talked them through the building process step by step. Children were more apt to delve into the project. If the paper ripped, they just asked for another piece. While adults worried about assembly mistakes or tearing their paper creation, kids had no issues with it being imperfect. The everyday nature of the material allowed for an easier acceptance of failure among the children, a factor we had not even considered in our designs.

Once the initial designs and lesson plans had been created, we began to submit our work to design competitions and apply for grants. During our first wave of submissions, we had high hopes for success because we were competing against many medical products that were extremely expensive and would have many more barriers to market release than our product. We assumed that a well-researched product with a low cost and developed distribution model would perform well, but that assumption ultimately led to disappointment. The majority of awards were granted to medically based research. Researching past recipients of potential grants or awards, as well as the fields of interest of the committee members, helped us identify trends for what the prizes favored and saved us effort in some cases. It is important to acknowledge that every shoe will not fit and if you have limited time and resources to submit proposals, make sure that your product or concept aligns with the guidelines specified and is related in some way to past recipients.

Another point of interest is that the uses originally envisioned for the design are rarely the sole application. When we first created the Rube Goldberg classroom activity, we hoped to foster creativity and problem solving through teamwork and communication skills. We never thought that one of our professors, a practicing family and children’s cognitive psychological therapist, would use the Rube Goldberg lesson with his patients. The materials used differed since the project did not occur in the classroom (the space was minimized to an office) and the design was created by one child instead of a group of children, but the professor was still able to use the activity to isolate problems in his patient’s daily routines. When new applications develop from a design, it is important to revisit earlier assumptions about the potential users and environments.
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The last area that is essential to address is time delegation. When starting new research or a company, it is imperative that the time constraints imposed by other obligations, such as other schoolwork, jobs, or other research are acknowledged and taken into account when defining a project timeframe. As obvious a lesson as this is, graduate students often tend to overestimate available hours in a semester.

Future Work
Our experiences in developing PaperBots have led us to many new options that require consideration. There are many issues to consider when deciding the best path forward. Further product and system development is always needed. Discussion of the current team’s capabilities is needed to determine if additional expertise is required. Do we search for others within the university or outside of it, and would they become full partners or part-time consultants? Should we pursue other funding options? We could pursue further National Science Foundation (NSF) funding or NSF small business grants. Kickstarter.com could provide the means to fund the project as well. Kickstarter is an interesting option that would also provide excellent marketing for the product. Our interest in publishing PaperBots punch-out books led us to investigate established educational publishers. Might we pursue partnering with an established group such as Scholastic or Klutz in order to use their resources to help us market and distribute the product? Faculty contacts have made this option a possibility, but removing PaperBots from Tufts brings up our legal requirements to the university and how we can handle the product outside its walls.

Conclusion
Product development of an innovation requires many considerations. This paper discusses some that we expected to come across and several that we did not. This case study will hopefully provide many lessons for other graduate students pursuing the development of their own innovations. The lessons learned along the way are not unique to graduate student pursuits, but many of the resources available to graduate students are. Through our connections to the university, we gained insight into intended markets, and we had access to experienced professionals in educational technology and entrepreneurship. University staff from outside our own discipline provided valuable insights, and students participated in testing groups, allowing for a much faster development of the product.

PaperBots is continually being improved upon. By the release of this paper, expect PaperBots to have been publicly released as an available educational technology. As this innovation becomes a marketed product, many new and difficult trials will present themselves. We hope others are able to learn from our experiences.
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References


