MAKER: Product Development in One Week – Bucknell Fabrication Workshop (B-FAB)

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Introduction

Within the past decade or more, the increased technological capacity of incoming students – accompanied by a diminished skill-set with regard to traditional hands-on, "tinkering" skills has been discussed in both STEM education as well as mainstream media [1, 2]. Many students choose engineering because they want to learn how to design and build the solutions of tomorrow, yet they often do not have dedicated opportunities to expand their hands-on skill set within the engineering curriculum. Sadly, traditional curricular instruction in engineering is such that students spend the bulk of their first three years learning theory, and relatively little time contextualizing that theory and its associated limitations when creating physical hardware. From a pedagogical perspective, the student-perceived lack of practical application can lead to disengagement.

From a practical perspective, success in engineering is closely tied to experience, and the sooner students can start to accumulate experience with real hardware, the sooner they will begin to develop the intuition that, along with their grounding in engineering theory, will help them to succeed. To this end, we recently launched a one-week, extracurricular fabrication workshop, called B-Fab, in which rising sophomores and juniors are taught a range of fabrication skills that they ultimately use to develop their own consumer product inventions by the end of the workshop.

B-Fab begins with basic instruction in computer-aided design (CAD), and then moves quickly through a range fabrication projects involving woodworking, soldering, composites, 3D printing, and laser cutting. The workshop was intentionally designed to focus instruction on processes and techniques with a low barrier to entry, i.e. those that don't required years of practice to gain proficiency, to enable students to complete relatively high-quality work without extensive training or prior experience. Toward the end of the workshop we introduce topics related to product development including opportunity recognition, conceptual design, sourcing materials and hardware, and the characteristics of an effective prototype.

The workshop concludes with student teams presenting their consumer product invention, with prototype, in a public forum. This process enables students to fabricate a solution to an identified problem and then pitch the value of their solution to an audience. Additionally, providing this experience in parallel with their curricular, technical instruction, will help students to gain the intuition and experience that combines knowledge of practical, real-world tradeoffs with the technical theory, boosting students' confidence in their ability to develop and troubleshoot physical hardware based on technical, conceptual design.

Program Goals

The primary goal of the B-Fab program was to provide students with basic instruction in various fabrication techniques enabling them to design more effectively for ease of fabrication and prototype development. In addition we provided instruction on identifying market opportunities and developing concepts to take advantage of discovered opportunities. Thus in combination students would be able to identify a product need, come up with a possible product concept to

address that need, build multiple prototypes of their product, troubleshoot problems in their production process and product function, and prepare a final product and a supporting presentation (i.e. pitch) that could serve as one of the first steps in bringing their idea to market. Finally, it was our hope that the skills and projects included in B-Fab would serve to motivate students to want to learn more, and to build more – perhaps becoming lifelong Makers, or to at least improve their competency in using hands-on skills to develop proof of concept models, benchtop simulations, and other elements often utilized within the product design cycle for physical products.

Running the B-Fab Workshop

B-Fab was scheduled for five full days bracketed by a half day at the beginning and end (Table 1). The workshop was managed by three engineering faculty members, two student technicians, and a staff member who handled logistical planning. Eighteen students enrolled from a variety of engineering disciplines.

The content was arranged into two interrelated phases. The first phase included several workshops focused on learning and practicing fabrication techniques, along with instruction related to product development. This phase was heavy on faculty instruction and it was intense, with respect to the workload and time commitment, but the pace allowed the second phase to occur. The second phase focused on proof-of-concept modeling, beginning after the "essential fabrication skills" had been introduced. The students began their own process of product development that culminated in the fabrication of a prototype for a new consumer product along with a pitch describing the merits of the new product.

Table 1. B-Fab followed the following schedule for two half-days and five full days.

Day	Morning Activity	Afternoon/ Evening Activity
Day 1 (Half)	Move In	BBQ and Design Challenge
Day 2 (Full)	CAD/Design Process	Woodworking, Composites
Day 3 (Full)	Digital Design: 3D Printing, Laser Cutting, Soldering, CNC	
Day 4 (Full)	Prototyping Techniques, Assembly	Project Intro, Product Pitch
Day 5 (Full)	Product Development Seminar	Prototype Development Project Work
Day 6 (Full)	Prototype Development Project Work	
Day 7 (Half)	Project Expo – Product Demonstrations and Pitches	---

B-Fab began with a half day session planned around a BBQ dinner during which we discussed the agenda for the week, discussed our program goals and talked with the students about their motives for enrolling in the program. To get the creative juices flowing, we ended the evening with a design challenge involving the construction of air power rockets based on an article in MAKE magazine [3]. This proved to be a good way for the students to meet each other and get

a feel for what the rest of the week would include over a casual dinner and a low stakes design experience.

The first full day of B-Fab included a half day of CAD and a half day of woodworking, which for many of the students meant a full day of new things to learn. The detailed agenda for the first full day is shown in Table 2, and the detailed agenda for the entire workshop is included as Appendix A. To connect the sessions into one common real world sequence, the students were tasked with designing and building a basic wooden tool box. First the students produced a CAD model of their toolbox and then using the drawing they generated, built their toolbox using traditional woodworking methods and tools. To give students a chance to individualize their toolbox, they were able to utilize a CNC router (ShopBot) to construct the handle of the toolbox which allowed for more elaborate features to be design in CAD and cut from wood.

Day one proved to be a learning experience for the instructors in that it quickly became apparent that the pace was too aggressive. So as not to push students beyond their capabilities on the first day, the schedule was adjusted by moving the composites session to day two and ending the day early. We were able to avoid accidents as well as maintain student engagement by making adjustments when appropriate, and thus, we routinely exercised our "executive powers" throughout B-Fab to change the daily agenda in ways that kept up the pace without affecting morale. Building flexibility into the program, turned out to be important for its success.

Table 2. The structural agenda for the first full day of B-Fab.

Time	Activity	Room / Location
8am – 9am	Breakfast	Engineering Classroom
9am – 1pm	Computer Aided Design (CAD) Workshop Design a Toolbox Fabrication Studio Safety Training	Engineering Classroom Machine Shop & Fabrication Studio
12pm – 1pm	Lunch	Engineering Lounge Area
1pm – 6pm	Woodworking Workshop Build a Toolbox	Art Dept. Woodworking Studio
6pm – 7pm	Dinner	Local Restaurant (Group Seating)
7pm – 9pm	Composite Workshop Build a ping pong paddle	Art Dept. Woodworking Studio

The next two days proceeded with a format similar to the first, with students practicing new skills that resulted either in something they would keep (e.g. tool box, composite ping pong paddle), or in something that they would use in a competition (e.g. paper rocket, potential energy vehicle). A detailed agenda of the entire workshop is presented in Appendix A.

We began instruction in product development during the second half of the third day with some discussion of opportunity recognition, market identification, and conceptual design. These topics were presented in the context of the objective of the B-Fab final project, which was to develop a consumer product for sale at a retail outlet such as Walmart. Day four included a scouting trip to Walmart, along with an idea generation session over dinner. During this session the students broke into teams and were asked to present their product ideas (multiple ideas from each team) to the group, which were subsequently critiqued by faculty members, include some not associated with B-Fab. This proved to make dinner very lively and resulted in a short list of product ideas for each of the teams, as well as the identification of likely technical challenges that would need to be addressed. By coupling instruction with the field trip and brainstorming session, many examples of the ideas we presented were discussed between the students and faculty members.

The final two and a half days were dedicated to the development and production of a new consumer product. We began by inviting a local inventor and business owner to speak with the students about his experiences with product development and starting and running a successful business based on products he had invented. This was a particularly valuable experience and included much discussion around the technical and non-technical aspects of running a successful, product-based business. Using what the students had learned about fabrication and product development from both the Bucknell faculty members and our guest speaker the students moved full tilt to finalizing their product design and building prototypes of their idea. This included many thoughtful discussions and multiple trips to the to the hardware store to purchase prototyping supplies. The students worked over the next one and a half days building their product prototypes using the techniques they had practiced earlier in the workshop. Their final task was to develop a short presentation focused primarily on establishing the value proposition for their product. B-Fab wrapped up the on the last half day with each team showcasing their product in a 10 minute presentation.

What the Students Learned and Made

B-Fab included a number of workshops, or skills sessions, that were designed to teach fabrication techniques and processes having a low barrier to entry (i.e. not requiring year of training to gain proficiency), but that were applicable to a range of engineering and non-engineering projects. Over the course of the workshop the students practiced the following fabrication processes and techniques:

1. *Rapid Prototyping Techniques (3-2-1- Launch!)*
   Basic assembly using common materials (paper, duct tape, glue, etc.).

2. *Basic Project Planning and Design Techniques (Crash Course in CAD)*
   SolidWorks was used as the platform to introduce students to CAD [4]. Additionally, this session focused on the concept of thinking through design details required for assembly.

3. *Power Tools and Production Techniques (Wooden Toolbox Fabrication)*
   Basic woodworking and hand-tools including a sliding miter saw, table saw, hand sander, drill press, and circular saw with a fence, as well as a brad nailer. A CNC router was also used to demonstrate how complex geometry could be easily created from digital files.

4. *Composite and Advanced Material Fabrication (Composite Ping Pong Paddle)*
   Composite material construction using vacuum bagged carbon fiber - epoxy laminates, demonstrating the process required for fabrication with "high-tech" materials.

5. *Digital Design and Fabrication (Laser-cut Race Car)*
   A laser cutter and 3D printers were introduced as low-barrier-to-entry fabrication tools that combine the capacity to create complex geometry with acceptable precision and finish for most proof-of-concept prototypes.

6. *Electronic Soldering (Altoid Can Flashlight)*
   Basic soldering techniques were demonstrated for electronic circuit wiring and components.

7. *Bringing It All Together (Consumer Product Development)*
   The culminating activity focused on allowing students to practice using some of the recently learned prototyping skills by developing a proof-of-concept prototype. Each group utilized different sets of applied prototyping skills depending on the scope and direction of the project.

In general we attempted to teach the preceding skills and techniques in the context of projects that the students could take away from the workshop. Each project is summarized in the following pages, with a generalized materials list for each project broken out separately in Appendix B.

Rapid Prototyping Techniques (3-2-1- Launch!)

In the first project session each student designed and constructed a paper rocket to be launched from a pneumatic launcher. Both the launcher and rocket are shown in Figure 1. Everyone was given the same materials to work with, which included two sheets of 11"x17" paper, a 6"x6" square of poster board, and a roll of duct tape/masking tape. The tools that were provided included a ruler, scissors, box cutter, and pencil.

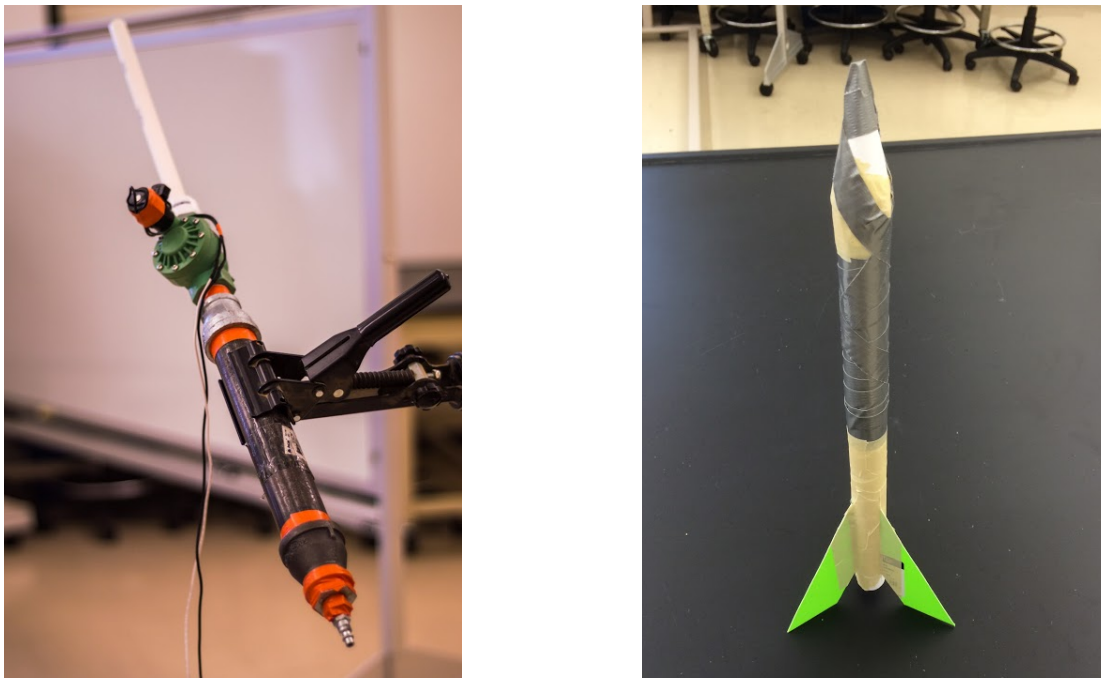

Figure 1. The pneumatic launcher and a rocket used in the first build session

The goal was to build the rocket that flew the longest distance. We have a bit of an overview on aerodynamic stability, including some equations and the "swinging string" test to experimentally evaluate stability, and then turned the students loose.

Basic Project Planning and Design Techniques (Crash Course in CAD)

A CAD drawing was the first step for many of the projects that we had planned for B-Fab. We included about five hours of instruction in the basics of SolidWorks, after having encouraged students to do supplied tutorials on their own time prior to the start of the workshop. We limited instruction to the basics including making a sketch, extruding the sketch to product a feature, and connecting the parts in an assembly.

A woodworking project to fabricate their own toolbox (from plywood) was the motivation for a crash-course in CAD, and thinking through design details such as how the thickness of the wood will influence other aspects of the design. This leads to detailed cut lists to ensure smooth fabrication.

Power Tools and Production Techniques (Wooden Toolbox Fabrication)

In the woodworking session students built the toolbox they designed out of AC plywood. Using the drawings they had generated with SolidWorks, the students measured and cut each of the pieces they would need to assemble their toolbox, and then assembled it using a variety of techniques.

Each student learned how to properly use the table saw, miter saw, jigsaw, drill press, hand drill, circular saw, and scroll saw to cut their wood pieces to size. Assembly was performed using a number of methods including mortise and tenon, doweling, and pocket hole screws. The handle of each toolbox was produced directly from SolidWorks files using the ShopBot CNC router. We chose to implement a woodworking workshop into B-Fab due to flexibility and strength of using wood to build a prototype in addition to its accessibility for future use.

Figure 2. Two toolboxes in various stages of completion – a basic toolbox using mortise and tenon joint handle (left), and a dinosaur handled toolbox (right). Curved components were made with a ShopBot CNC router.

Composite and Advanced Material Fabrication (Composite Ping Pong Paddle)

Composite laminates are used in many engineering applications ranging from structural components to purely aesthetic features. Students produced composite panels from woven carbon fiber cloth, aramid honeycomb, and two-part epoxy. The panels were vacuum bagged and allowed to cure overnight. Once cured, students cut the panels into the shape of a ping pong paddle using a scroll saw, and then made "custom" grips using the prototyping polymer Instamorph®. The vacuum bagged panels and a finished paddle are shown in Figure 3.

Figure 3. Vacuum bagged composite panels that ultimately turned into ping pong paddles (left) and students with their finished paddles (right).

Digital Design and Fabrication (Laser-cut Race Car)

Whereas in the first three workshops (CAD, woodworking and composites) the focus was largely on the technique and the process of using the technique appropriately through careful planning, the digital design workshop coupled learning two new fabrication processes with more individual product development and collaboration between students in groups of two. In the digital design workshop students were asked to design and build model dragsters to be raced the following morning. The dragsters were to be propelled from the conversion of potential energy to mechanical energy without the use of batteries or an electric motor. They had to start from a standing position with a one-handed flip of a switch. Vehicles were designed completely on paper or in SolidWorks prior to beginning construction. At least one part of the vehicle was required to be fabricated using the laser cutter or the 3D printer, to emphasize the students' previous training. A photo of one of the dragsters, powered by two mousetraps, is shown in Figure 4.

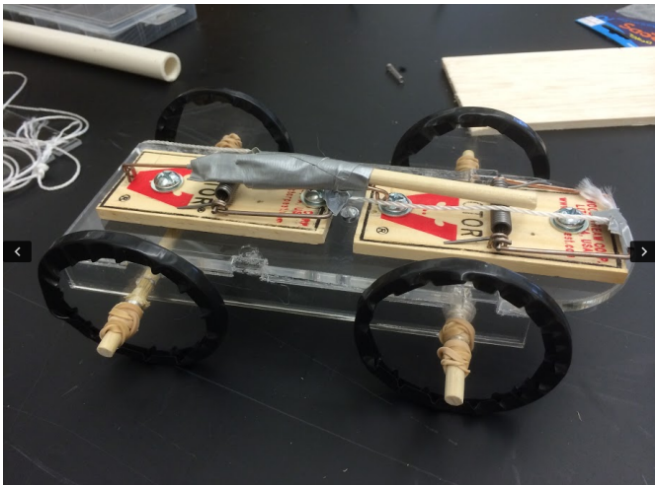

Figure 4. A mousetrap powered race car with a laser cut acrylic body and wheels.

Electronic Soldering (Altoid Can Flashlight)

The final B-Fab skill session included a short how-to lecture on soldering and practice in the technique by having each student solder together their own Altoid Can Flashlight. We used kits from Brown Dog Gadgets [5], which required students to solder four wire-to-wire connections together and solder the legs of the switch to the appropriate wire connections. This activity gave the students practice with soldering and to review basic circuitry. All of the students ended up with working flashlights at the end, very fresh breath, and mostly nice looking soldered joints.

Bringing It All Together (Consumer Product Development)

The students spent the final days of B-Fab inventing and prototyping their own consumer products. We began with a group brainstorming and critique session that resulted in a short list of product ideas shown in Figure 5. The idea board started early in the workshop as we implored students to be thinking of product ideas inside and outside of B-Fab, and updated it informally in speaking with the students individually. We also made more formal additions to the board during brainstorming sessions that led to a multitude of ideas being created. We attempted to show the

students how making things and building ideas was a continuous process that extended beyond the workshop.

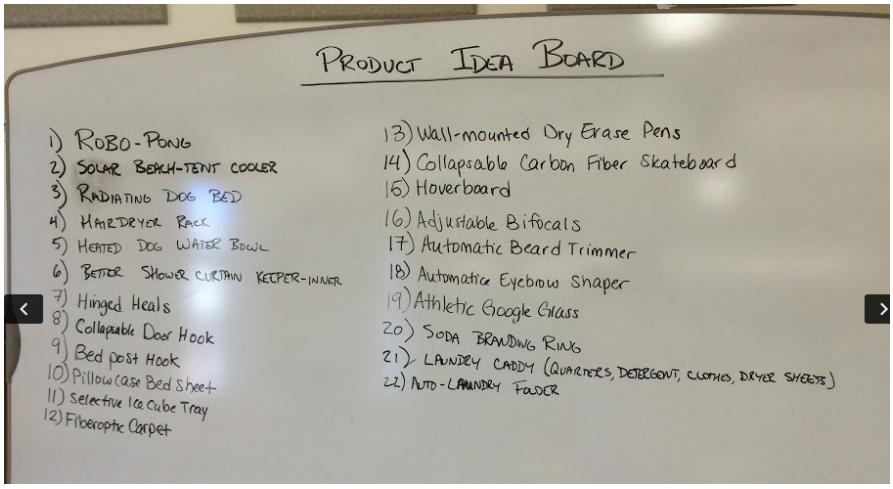

Figure 5. Student project ideas were brainstormed during several group meals and were collected on a common project idea board leading up to the second-half of the week.

The students were asked to develop their product idea in pairs, to ensure that both team members had an active role in every stage of the project. Over the final two days of the workshop each pair worked finalize their product idea by considering the advantages and disadvantages of each idea, bring the idea from a concept to detailed drawings to a prototype that captivated their idea in physical form. Each pair pitched their idea and its merits in presentations on the final morning of the workshop. Some of the product prototypes, presented on the last day of B-Fab, are shown in the following figures (Figures 6 - 10).

Figure 6. A moving crate that converts to a chair and a "no touch" foot actuated toilet seat that automatically drops down.

Figure 7. A hairbrush with storage in the handle as well as a mirror mounted to the back.

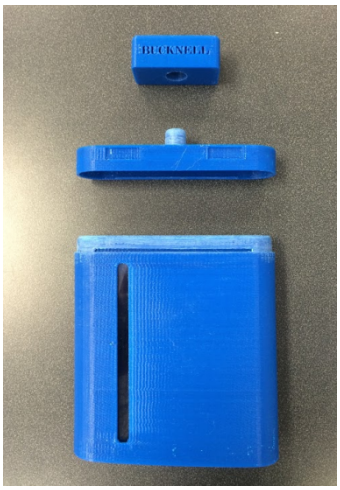

Figure 8. An easy to clean flask with a removable top.

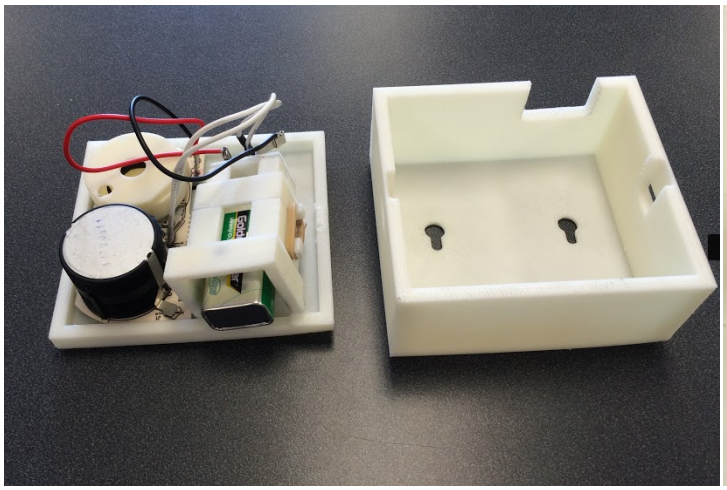

Figure 9. A smoke alarm with push button battery removal.

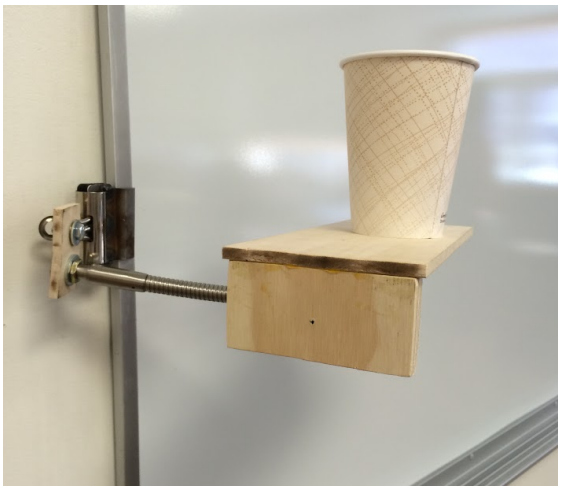

Figure 10. A clip on "caddy" for use in dorm rooms.

Moving Forward

B-Fab was a fast-paced weeklong seminar focused on introducing students to a range of fabrication processes, and to product development in general. Our intent was to take students with little former fabrication experience, and familiarize them with techniques and processes available to them at Bucknell and bring them up to a confidence and competence level that would enable them to continue honing their skills in future self-directed projects. While we haven't yet analyzed all of the feedback from the students, we can say that B-Fab was generally viewed by the students as a valuable experience. We plan to run the workshop again in the summer of 2015 and will likely keep much of the overall format, with some changes possible with regard to the specific workshops/projects offered. Ultimately the future of B-Fab will be closely connected with the evolution of the nascent Maker movement on campus at Bucknell;

new facilities coming online in 2015 and interest in *Making* outside of the College of Engineering could take B-Fab in new and interesting directions.

References

[1] Reynolds GH (2007) In Age of High-Tech, Are Americans Losing Touch with DIY Skills? Popular Mechanics. Retrieved April 3, 2015 from http://www.popularmechanics.com/home/how-to/a2104/4221637/

[2] Brown TT (2012) The Death Of Shop Class And America's Skilled Workforce. Forbes Magazine. Retrieved April 3, 2015 from http://www.forbes.com/sites/tarabrown/2012/05/30/the-death-of-shop-class-and-americas-high-skilled-workforce/

[3] Schertle R (2008) Compressed Air Rocket. MAKE Volume 15: 102-113.

[4] Solidworks® Education Edition, 2013, SP3.0, © 1995-2013 Dassault Systemes

[5] Brown Dog Gadgets (2015) Altoids Flashlight Kit. Retrieved April 3, 2015 from http://www.browndoggadgets.com/products/altoids-flashlight-kit

Acknowledgements

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Appendix A: Full B-Fab Agenda

DAY 1 - KICKOFF (HALF-DAY)

Time	Activity
12pm – 4pm	Move in
4pm – 8pm	Welcome Barbeque Program Overview Warm-up Design Challenge: *3-2-1- Launch!*

DAY 2 – WORKSHOPS (FULL DAY)

Time	Activity
8am – 9am	Breakfast
9am – 1pm	Basic Project Planning and Design Techniques: Crash Course in CAD Fabrication Studio Safety Training
12pm – 1pm	Lunch
1pm – 6pm	Power Tools and Production Techniques: Wooden Toolbox Fabrication
6pm – 7pm	Dinner
7pm – 9pm	Composite and Advanced Material Fabrication: Composite Ping Pong Paddle

DAY 3 – WORKSHOPS (FULL DAY)

Time	Activity
8am – 9am	Breakfast
9am – 11am	Composite and Advanced Material Fabrication: Composite Ping Pong Paddle (Part 2: Finish Paddles)
11am – 5pm	Digital Design and Fabrication: Laser-cut Race Car CAD/Laser Engraver/3D Printer
12pm – 1pm	Lunch
5pm – 6pm	Dinner
6pm – 9pm	Electronic Soldering: Altoid Can Flashlight Continue Race Car Construction

DAY 4 – WORKSHOPS (FULL DAY)

Time	Activity
8am – 9am	Breakfast
9am – 11am	Laser-cut Race Car Dragster Race Competition
11am – 1pm	Bringing It All Together (Consumer Product Development) Introduction Pitch Deck Discussion
12am – 1pm	Lunch
1pm – 4pm	Brainstorming Session Trip to Walmart
4pm – 9pm	Fabrication Tricks of the Trade
6pm – 7pm	Dinner
9pm – 11pm	Ping Pong Tournament

DAY 5 – PROJECT (FULL DAY)

Time	Activity
8am – 9am	Breakfast
9am – 11am	Product Development Guest Lecture
11am – 5pm	Bringing It All Together (Consumer Product Development): Concept Development – Design, Procure, Build
12pm – 1pm	Lunch
1pm	Shuttles to Lowes and Walmart
4pm	Shuttles to Hardware Store
5pm – 6pm	Dinner
6pm – 8pm	Design Review

DAY 6 – PROJECT (FULL DAY)

Time	Activity
8am – 9am	Breakfast
9am – 9pm	Project Work
12pm – 1pm	Lunch
1pm	Progress Update
5pm	"How to give a pitch" Workshop
5pm – 6pm	Dinner Barbeque

DAY 7 – PRESENTATIONS & WRAP-UP (HALF DAY)

Time	Activity
8am – 9am	Breakfast
9am – 12pm	Final Presentations

Appendix B: Materials List for B-Fab Project Activities

Rapid Prototyping Techniques (3-2-1- Launch!)

1. **Materials Supplied**
    a. Two sheets of 11”x17” copy paper – intended for rocket body
    b. 6”x6” sheet of poster board – intended for rocket wings/stabilizers
    c. Duct tape and masking tape – intended for assembly
2. **Tools Available for Fabrication**
    a. Rulers
    b. Scissors
    c. Box cutters
    d. Pencils
    e. Hot glue
3. **Equipment for Implementation**
    a. Pneumatic Launcher [3]
        i. Pressurized cylinder with the pump attached to one end and a piece of PVC pipe attached to the other
        ii. Electronic switch to hold and release cylinder pressure into PVC pipe to propel rocket
        iii. Pump to pressurize cylinder

Basic Project Planning and Design Techniques (Crash Course in CAD)

1. Student version of Solidworks Education Edition 2013 [4]
2. Tutorial and Instruction notes on basic Solidworks commands and command sequences

Power Tools and Production Techniques (Wooden Toolbox Fabrication)

1. **Materials Supplied**
    a. 4’ x 11” piece of ¾” AC plywood (11” defined to get 8 pieces from 4’x8’ sheet of plywood – intended for the body of the toolbox
    b. Extra 4’x8’ sheets of ¾” AC plywood for toolbox handles
    c. 3/8” diameter dowel rods
    d. Brad nails
    e. Screws
    f. Wood glue
2. **Tools Available for Fabrication**
    a. Table saw
    b. Miter saw
    c. Jigsaw
    d. Drill press
    e. Hand drill
    f. Drill bits
    g. Circular saw
    h. Scroll saw
    i. Nail gun
    j. ShopBot CNC router

Composite and Advanced Material Fabrication (Composite Ping Pong Paddle)

1. **Materials Supplied**
    a. Woven carbon fiber cloth (or fiber glass) – at least two sheets per person depending on thickness, large enough to cut out paddle and handle
    b. Aramid honeycomb (or some other lightweight structural foam) – one sheet per person the same size as the carbon fiber cloth
    c. Two part epoxy
    d. Instamorph® - intended for handle construction
2. **Tools Available for Fabrication**
    a. Mixing buckets for epoxy mixture
    b. Stir sticks
    c. Stencil of paddle and handle
    d. Scroll Saw to cut out paddle from composite layup
    e. 280 grit wet/dry sand paper – for paddle surface
    f. Spray adhesive – for attaching sand paper to the paddle
3. **Equipment Needed**
    a. Vacuum pump
    b. Waxed aluminum table
    c. Vacuum bag
    d. Breather fabric
    e. Release film
    f. Sealant tape – to seal edges between plastic and the table

Digital Design and Fabrication (Laser-cut Race Car)

1. **Materials Supplied**
    a. Acrylic sheet
    b. Acrylic cement – for joining acrylic pieces
    c. 3/8" diameter wooden dowels – intended for axles
    d. Foam board
    e. $20 spending money at the local hardware store
2. **Tools Available for Fabrication**
    a. Laser cutter
    b. 3D printer
    c. Hand drill
    d. Hand saw
    e. Box cutters
    f. Hot glue gun
    g. Duct tape
    h. Rulers
    i. Pencils
    j. Solidworks 2013
3. **Equipment Needed**
    i. Track for races

Electronic Soldering (Altoid Can Flashlight)

1. **Materials Supplied**
    a. Brown Dog Gadgets Altoids Flashlight Kit [5]
        i. 2 clear 5mm LEDs
        ii. 2 5mm LED holders
        iii. 2 100 ohm resistors
        iv. AA battery holder that holds two batteries
        v. Button or toggle switch
    b. Altoids Tin
    c. 2 AA batteries
2. **Tools Available for Fabrication**
    a. Soldering iron
    b. Brass sponge
    c. Solder
    d. Drill – to drill holes for the LEDs and the switch
    e. Wire strippers
    f. Electrical tape
    g. Extra wire
    h. Multimeter