

# Prototyping for Everyone: Rapid Assimilation of Skills & Tools for the Creation of Physical Prototypes

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## Abstract

Product development requires the successful fusion of concept, physical prototyping, market assessment, and business planning. The prototyping phase is critical, since a viable, well-designed, and tested realization of a proposed product is the foundation for all the other activities that bring the product to market. Prototyping requires a wide range of technical knowledge drawn from many fields of science and engineering. Here we describe our experience helping individuals assimilate and apply this broad range of knowledge, regardless of prior training or specialization. Our approach is based on the fact that students doing experimental scientific research must often quickly assimilate and apply knowledge of mechanics, electronics, optics, and other areas to successfully complete their project. We describe a curriculum that uses this mode of learning for the entrepreneurial development of new products and we report on our project to gather resources into a community version of the “ultimate inventor’s garage.”

## Introduction

Product development involves much more than creating gadgets: other elements include market assessment and validation, competitive analysis, design for manufacture, and, of course, sound business and financial planning. Yet a necessary condition for all of these aspects to matter is that a product concept is given a full realization. Crafty entrepreneurs may once have sold businesses based on “vaporware,” but wary investors now want to see the actual product.

We want to explore in this paper how individuals from varied backgrounds can learn quickly and effectively how to make working prototypes. We describe what we believe are effective strategies for overcoming time and resource constraints in order to quickly get to a product realization. Our model is the approach taken by many experimental scientists in making new laboratory apparatus. Essential to this model is the skill of learning just enough technical knowledge just in time to achieve a design goal, and this skill can be translated from the laboratory setting into the wider context of product prototyping. As students and small business entrepreneurs acquire confidence in learning technical topics in this manner, they realize that giving physical form to their ideas is more readily achievable.

How does an individual (including a student) inventor go from bright idea to prototype? This is the central question of this paper. One solution is to garner enough funds to hire a professional design firm to do the job, but the catch is that some sort of prototype is needed to win such funding. Moreover, communicating the concept to a professional firm usually requires a mature set of drawings and tangible artifacts; few if any firms design based on an inventor’s whim. Another solution, employed in larger corporations and many engineering schools, is to assemble teams of experts (or experts-in-training) to create a prototype, often with an elaborate process of design reviews. A more home-spun solution—and there are lots of anecdotes to support this, ranging from Hewlett & Packard to Jobs & Wozniak—is to team up with a friend or friends to combine existing skill sets into the resources needed to construct a prototype. But often individuals are compelled to start alone. Even in the case of groups of inventor friends (as well as engineering teams in school or industry), the typical prototype will require knowledge beyond that possessed by the people involved. So a means must be found to come up to speed quickly on technical knowledge sufficient to build a prototype, and to do this within tightly constrained resources of time, money, and space.

Formal curricula usually emphasize specialization. Degrees are granted based on study in depth of a particular subfield, such as digital high-speed design. This is driven by the need by larger corporations to hire specialists

and compete on the basis of expensive cutting-edge technology. Design-oriented courses are often preceded by prerequisites in order to develop a proper foundation. Unfortunately, this training model does not readily suit the single inventor or the small team embarking on a product concept with the need for *just enough* knowledge acquired *just in time* to surpass a technical barrier. When a design challenge occurs in creating a new product, it is necessary to cut to the chase quickly but also find a solution with a secure basis in proven approaches and basic principles.

Fortunately, good models exist for rapid and sufficient assimilation of several areas of knowledge. Experimental research students must often prototype parts of their apparatus. This applies even when grant funding provides turn-key instruments, because some aspect of the research demands a unique variation on prior approaches. Often these students are lucky enough to be part of a research group that forms a local design community: such groups usually have an in-house lore on how to make components of the relevant apparatus and this lore is passed informally from senior members to newcomers. An interesting review of the sociology of such communities—albeit not in a research group but instead in a local auto repair garage—is described by Douglas Harper in a book aptly titled *Working Knowledge: Skill and Community in a Small Shop* (1987).

Our goal is to convert the learning process used by research students into a curriculum for rapid assimilation and to re-create the social support present in research groups into a community of working knowledge that is more widely available to students and to small-business entrepreneurs. Also, where research is devoted to knowledge for knowledge's sake (“science projects”), we want to adapt the methods of technical prototyping to a different culture: a culture of innovation and commercialization. We describe below how we have developed curriculum, community, and a physical location to achieve these aims.

### **Curriculum: A Certificate in the Scientific Foundations of Technical Innovation**

Prototyping requires experience and substantive technical knowledge. Experience comes from working on open-ended projects, while substantive knowledge comes from focused study of specific topics. We have designed a twelve-credit-hour certificate program that combines these two elements into a framework that prepares students and entrepreneurs to handle a wide range of prototyping challenges. This program will be offered through our university's extended studies program. Most components of the curriculum have already been taught as regular courses or as independent study. They are now being adapted to the certificate sequence.

The curriculum consists of two three-credit projects and six one-credit short courses. We first describe the short courses, which were originally developed and taught with funding from the National Science Foundation. Indeed, our original goal was to equip physics undergraduates with sufficient practical knowledge to be helpful in our research program, with the hope that this would also give these students some useful resume items in their search for jobs or graduate schools. We found that broader ranges of students, including engineering students and education students, were interested in these short courses. Ultimately, we came to the conclusion that such a series could be useful in a much larger arena as a basis for technical prototyping and innovation. We anticipate that even working professionals in small-to-medium sized firms would appreciate an effective means to cross-train in various technologies. K-12 teachers may even find the material effective for classroom equipment prototyping!

The short courses span a wide range of topics. The intent is to offer, over time, a menu of courses from which students will select at least six in order to complete the certificate. In each short course, students are expected to come up to speed in about sixty hours of total effort, equivalent to about fifteen hours of contact time and forty-five hours of additional study and project work. This is modeled on our experience working with research students to ensure sufficient functional knowledge to carry forward a project.

An initial core set of courses was designed and taught and is now being converted into an extended-studies format. The core set is:

PHYS 4401/5401: Materials for Design

Physical and mechanical properties of metals, polymers, ceramics & composites are compared in terms of usefulness for product design. Emphasis is placed on creating a mental “design space” of achievable values of properties such as stiffness or strength. A hands-on project uses

markup, sawing, drilling & filing of materials from all categories in order to give a direct sense of the issues involved in processing the materials for actual product manufacture.

#### PHYS 4402/5402: Mechanisms

Standard mechanical components such as shafts, bearings, gears, pulleys, belts, cams, and linkages are explored in the context of various design applications, making liberal use of examples from scientific instrument and consumer product design. A hands-on project requires creation of a device to manipulate a mirror.

#### PHYS 4403/5403: Actuators

Starting with the idea that actuators are devices that change the state of a system, attention is focused on various ways to change position, velocity, volume, and other state variables. Operating principles are explored for electric motors, pneumatics, hydraulics, piezoelectric and magnetostrictive devices, etc. A stepper motor system is built as a hands-on project.

#### PHYS 4404/5404: Electronic Components and Measurements

The types and physical models of passive electronic components are reviewed along with methods of measuring their properties and fundamental measurements of current and voltage. The tolerances of components under varying environmental conditions as well as limitations of measurement devices are explored. Construction of a power supply illustrates procedures for assembling and connecting electronic components.

#### PHYS 4405/5405: Signal Conditioning

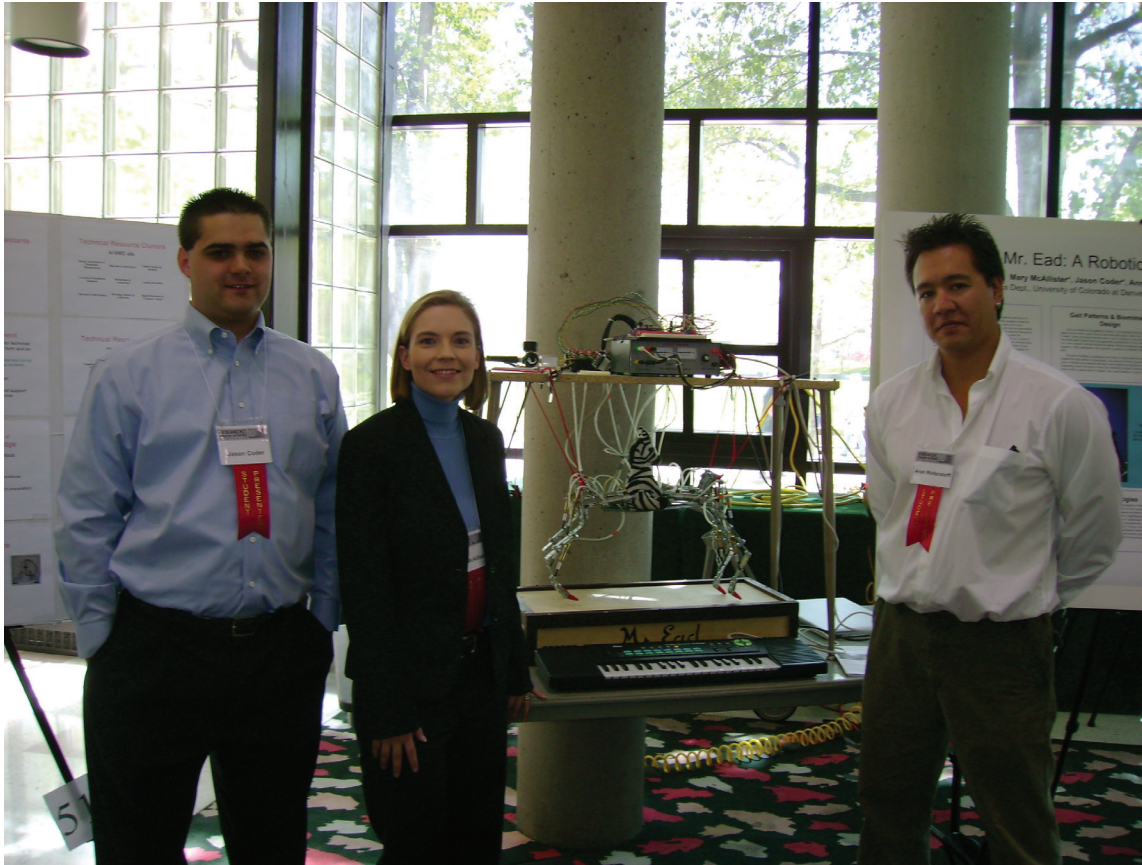
Various types of signals are characterized in the time and frequency domains. Practical signal conditioning circuits are built using passive components and active devices (principally op amps). A general framework of processing signals is developed around methods to provide gain, offset, filtering, and mathematical transform (e.g., differentiation) using analog techniques. A general-purpose small-signal amplifier is built and characterized.

#### PHYS 4406/5406: Sensors

In contrast with actuators, sensors are presented as devices to measure the state of system with minimal perturbation. Operating principles of sensors for temperature, pressure, position, velocity, acceleration, force and other state variables are developed through the use of real sensor components. A project to hand-build a sensor, such as a linear variable differential transform (LVDT) for position sensing, illustrates design tradeoffs and calibration issues.

Here it is important to state that we do not imply that these short courses supplant the careful training in various science and engineering disciplines that confers true expertise in these topics. We aim for sufficiency, not expertise. We wish to enable students to make useful subsystems, such as pre-amps or mechanical actuator systems (Fig. 1), even if these are not truly optimized. Moreover, an important aspect of the short course framework is to prepare students to seek experts and ask intelligent questions.

Figure 1. Mr. Ead, a robotic horse driven by pneumatic actuators controlled either by a piano keyboard or a microcontroller. Students (left to right) are Jason Coder (electrical engineering), Mary McAllister (biology), and Aron Wolterstorff (physics.).



In producing these short courses, we think it best to emphasize fundamental ideas, hence the use of the term “scientific foundations” in the certificate title. A fundamental idea is one that can be used as a launching platform for a wide range of specific implementations. For example, we approach signal conditioning from an initial discussion of signal types and signal characterization in time and frequency domains. This creates a point of view on how to describe what happens to signals before and after signal conditioning. Once this is established, we can get down to the practicalities of making op-amp circuits to provide gain, filtering, and other functions. The goal is to combine fundamentals and a sampling of practical realizations to give the students a scaffold from which to develop their prototype *and* to develop deeper understanding if and when the opportunity or need exists.

Students are encouraged to take a sufficient number of the core set to fill in gaps in their knowledge, as driven by their project needs or by personal interest. But as time progresses, we plan to implement a wider variety of topics that cut across a range of technical domains. Some of these were in fact already taught in recent years and are undergoing revision and refinement. Topics (with brief descriptions) include:

PHYS 4407/5407: Semiconductor Device Circuits

Emphasizes the use of transistors and thyristors for power control.

PHYS 4408/5408: High Frequency Electronics

The focus is on both passive and active components and circuits for use in the 1 MHz to 100 MHz range, including some antenna concepts.

PHYS 4409/5409: Servo Control

Position control and temperature control are used as case studies to illustrate general feedback control principles and practical trade-offs.

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PHYS 4410/5410: Digital Circuits

Gate logic, flip-flops, and encoding/decoding are implemented in both discrete components and through field programmable gate arrays.

PHYS 4411/5411: Computer-Aided Experiments

Computer control of experiments is demonstrated through two basic approaches: high-level programming languages such as BASIC and graphical programming such as LabVIEW.

PHYS 4412/5412: Microcontrollers

An introduction to embedded system design is given through a project to control a multi-actuator system such as a robotic horse.

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PHYS 4413/5413: Optical Systems

Basic layout of lens and mirror systems is done with attention to both optical and mechanical elements of the design.

PHYS 4414/5414: Optoelectronics

The operating principles of electronic components for producing, modulating, and sensing light are used as the basis for design of a measurement device such as an optical vibrometer.

PHYS 4415/5415: Imaging Technologies

Optical constraints on image quality and various image-recording methods (film, CCD-array, etc.) are related to applications such as surveillance video and laboratory experiment monitoring.

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PHYS 4431/5431: Optical Microscopy

Basic optical design of microscopes is discussed and variations such as phase contrast, fluorescence, and polarization microscopy are demonstrated.

PHYS 4432/5432: Advanced Optical Microscopy

The principles and applications of laser-scanning confocal microscopy, deconvolution methods, near-field scanning optical microscopy (NSOM), and other methods are explored through applications.

PHYS 44xx/54xx: Electrophysiological Instrumentation

Models of electrical propagation through nerves, muscle cells, and tissues are used as the basis for understanding electrocardiography, electromyography, electroencephalography, and related physiological measurement systems.

The last of these trios of topics represents our progress into the domain of medical instrument prototyping. The downtown Denver campus of the University of Colorado recently merged with the medical school and the physics department has elected to expand its offerings, both in curriculum and in research, in biophysics and medical physics. Current student prototyping projects in these domains require, amongst other things, knowledgeable use of microscopes. This last trio is new and will be developed over the next two years.

How are students assessed in these courses? There are standard quantitative calculations that students do as exercises to clarify concepts. Sometimes these problems require derivation of the details of underlying mathematical models; in other cases, the problems are more synthetic, in which students must find reasonable values of components to achieve a desired function. Students also do small lab investigations and complete a mini-project. For example, in the materials course, students fabricate a “Jacob’s Ladder” toy (Fig. 2) out of six different materials (steel, brass, aluminum, oak, ceramic, and Plexiglas® (PMMA)). Generally, we try to make the projects useful to students for future work, such as construction of a low-voltage power supply in the course on electronic components and measurements. The Jacobs Ladder toy is thus an exception, but it is a fun one that illustrates the different ways materials must be processed to achieve design goals. With both the power supply and Jacobs Ladder, the projects are used to show the practical realities of components and systems and give students experience in key steps of layout, construction and testing at the workbench.

Figure 2. A variation on the toy commonly called Jacob’s Ladder, but which we call Noah’s Ladder because it is constructed from pairs of different materials. Fiber-reinforced polymer measuring tape binds the pieces together in a flip-flop fashion.

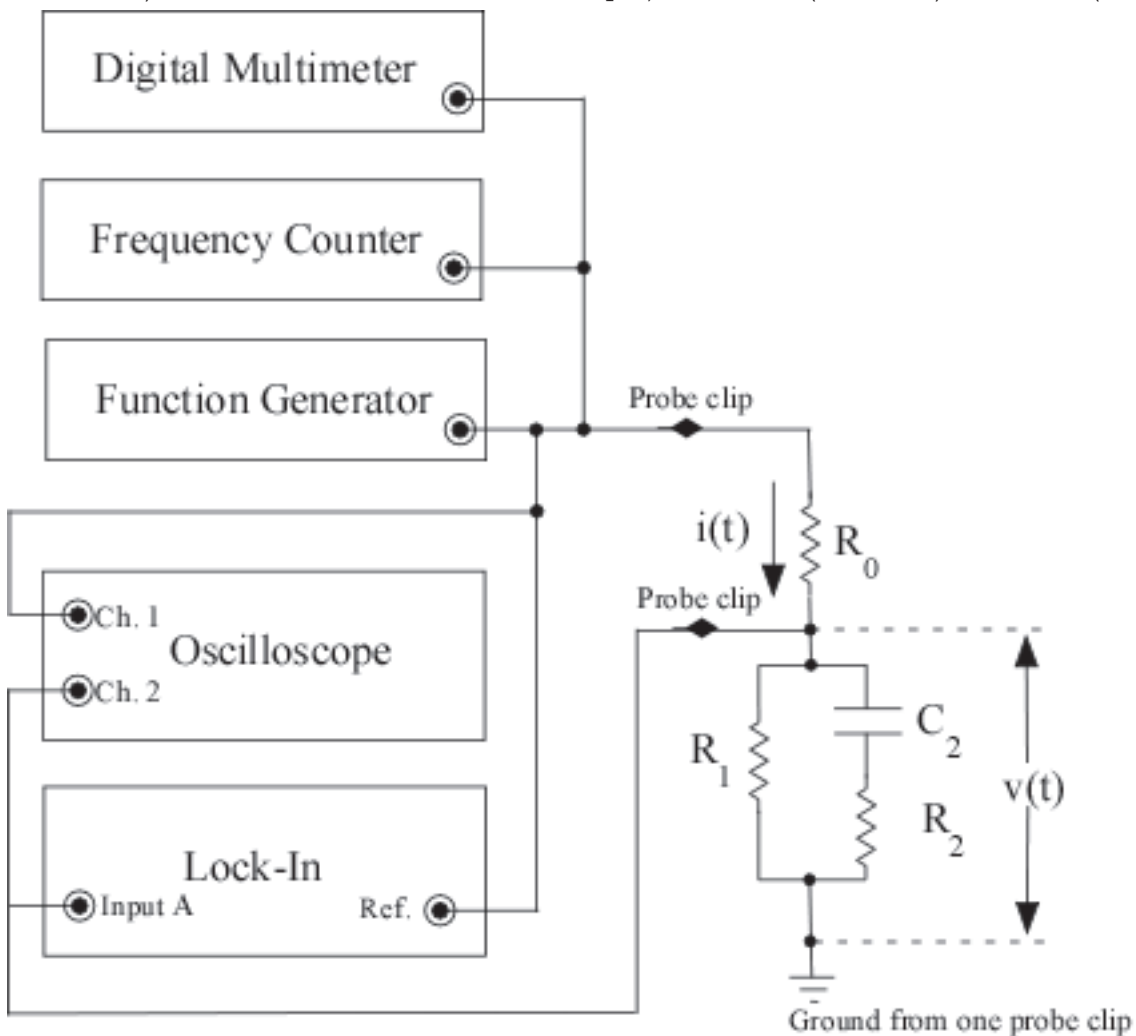


Students ultimately are asked to assemble their problem solutions, laboratory investigations, and mini-project documentation (including design drawings) into a “solutions” portfolio. The goal is to teach students the habit of creating their own depository of design lore that they can refer to later on when dealing with new technical challenges. The use of the term “lore” here means an integration of fundamental ideas with solutions to practical design challenges; it is emphatically *not* just a collection of recipes. Note: we also have found that the portfolio is useful in job interviews.

As stated at the beginning of this section, the total learning package requires experience with real open-ended projects. Here we blend aspects of the community building that will be described more fully below. We are creating, through collaboration with a non-profit called Micro Business Development, an opportunity for students to develop prototypes for real clients. In fact, we are boldly throwing students in the “deep end” and having them work right away on creating an early prototype for an actual client, even while they are assimilating detailed technical knowledge through the short courses or by other means.

Actually, the client base is broader; with funding from NCIIA, we currently engage students in prototyping for medical applications driven by collaborations with the medical school. Thus, in the new certificate program, students will choose to work either on a one-semester early prototype for a small business client or an early prototype of a medical device. Clearly, the projects need to be limited in scope to be achievable in a short time-frame: an example is a rudimentary impedance spectrometer that demonstrated the use of phase-sensitive detection as a means of extracting impedance data from circuit models of tissues using low injection currents (Fig. 3).

Figure 3. Block diagram of impedance spectrometer test set-up, including a three-component circuit model ( $R_1$ ,  $R_2$ , and  $C_2$ ) of tissue. This was the senior thesis project of Sarah (Chrismer) Ruderman (2006).



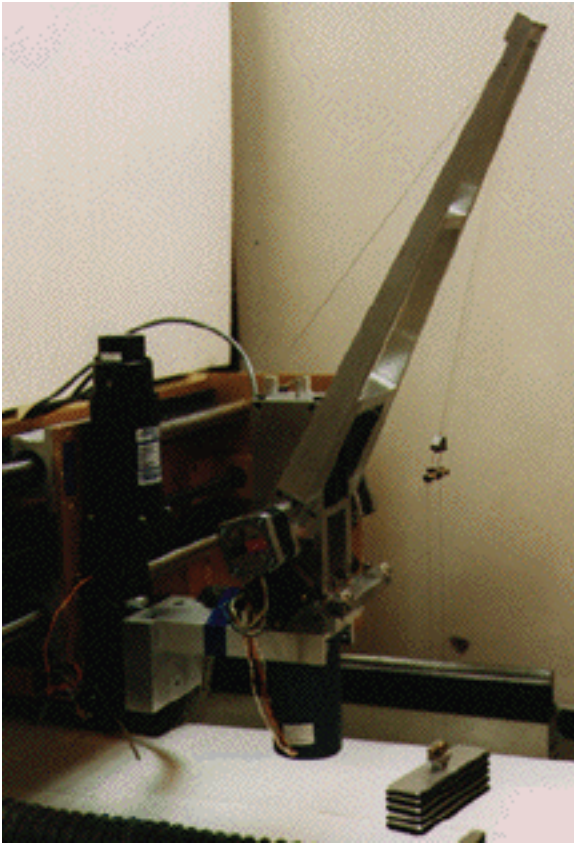
In having students work for real clients (either small business entrepreneurs or medical practitioners), a key issue is ownership of intellectual property. We seek to engage students with the idea that prototypes and their attendant intellectual property belong to the client, and appropriate signed agreements will attest to this fact. However, we have a plan to reward students for this generosity through a sequence called “Invent it Forward” (Weeda and Landry 2007). After a student completes an early prototype for a client, done within a single semester, the student is then eligible to work on his or her own invention. Moreover, the student is also eligible for scholarship funding to apply towards the completion of the certificate.

We anticipate that many of the client-oriented projects will require further effort beyond a single semester and, in this extended effort, we expect a more varied and flexible negotiation of intellectual property rights. Clearly these are issues that will require further experience and adjustment; the key point is that we want to combine service learning experience gained working for a client with project-based learning ultimately done by the student for his or her own gain.

We have many years of experience in fostering student projects that are oriented towards the student’s intellectual growth. Such growth is defined in terms of synthesis of prior knowledge, context-driven learning of new principles, practical experience, and acquired confidence in handling open-ended problems. A summary of many of these has been published in a website on student-centered research (Tagg 2001). These projects originated in research rather than entrepreneurial development. However, these research projects have been key to developing our capacity to guide students, primarily undergraduates, through short-term prototyping. Significantly, some of the funded research was also done with immediate application in mind. An example was a

project sponsored by the Office of Naval Research to explore applications of nonlinear dynamics (including chaos theory) to the control of cranes on ships at sea (Fig. 4).

Figure 4. Ship crane; our instrument maker, Brad Busley, designed the model crane in consultation with students in the research project. However, several students were involved in actual machining of a second version of this crane (also designed by Busley) that was shipped to the Naval Research Laboratory for use on model vessels in the Naval Testing Basin at Carderock, Maryland.)



As with the short courses, a major element of the assessment for the two projects is the use of portfolios that document key technical achievements. We encourage students to regard critical steps in their prototyping as “technical quanta.” Each achievement is documented by calculations, drawings, and text summaries. We also require students to maintain bound laboratory notebooks that record daily progress; in the context of the new certificate program, we emphasize the need for scrupulous attention to the laboratory notebook process, including signatures and witnesses, that are required to validate intellectual property claims. The laboratory notebook provides much of the raw material that is summarized in the portfolio.

A major outcome of this curriculum is the generation of a mindset in students, clients, and mentors that encourages them to be champions of interdisciplinary thinking. The use of real product development projects to provide context for learning forces the issue; real-world products and processes require knowledge across many disciplines and a willingness to think outside of disciplinary boundaries.

## **Community and Location**

A major step forward in our plans to engage students in real-world prototyping came through a recent partnership with the non-profit organization called Micro Business Development (MBD). As noted above, this organization is the source of one of the groups of clients for whom students create prototypes. The partnership came about through the mediation of the City of Denver’s Office of Economic Development and through the insight and support of MBD’s CEO, Kersten Hostetter. In March 2007, we began setting up a lab in the MBD headquarters building one mile from our campus. We have named this lab the Community Prototyping Lab (CPL).

CPL is an extension of our on-campus student projects lab. Its function is to house many of the materials and tools needed for prototyping, including advanced equipment that we obtain through university and other surplus sources. The design of the lab enables students and clients to quickly gather resources needed for prototyping work.

The lab is organized into eight technical resource clusters. These are:

- 1) Machining and fabrication
- 2) Electronics
- 3) Optics
- 4) Mechanisms and actuators
- 5) Sensors and measurement
- 6) Thermal and fluid systems
- 7) Mechanical dynamics (acoustics and rotational/vibrational testing)
- 8) Sustainable systems (renewable energy, sustainable manufacturing process development, etc.)

The technical resource clusters stockpile components, provide appropriate tools and instruments, and have adjoining work spaces and work benches. These clusters are augmented by resources back on campus, such as high frequency equipment and advanced microscopes. Part of the vision of CPL is to create a microcosm of the prototyping facilities that are available at advanced development labs. One of the authors (Tagg) gained his earliest research experience at the Caltech/NASA's Jet Propulsion Lab, where he enjoyed remarkable freedom to use technical resources across this huge facility. Thus we consider the Community Prototyping Lab to be a spin-off of advanced research and exploration: "from JPL to CPL."

An advantage of developing the Community Prototyping Lab under the auspices of a university is the access we have to instrumentation and scientific equipment. Such equipment often becomes available from research groups that no longer need or have room for items. Also, the university receives many in-kind donations from corporations. Thus the CPL provides extended life for expensive technical resources and makes these available to serve the needs of small businesses that otherwise could never afford such items.

Some additional elements set up in the Community Prototyping Lab to foster innovative design include:

- 1) Materials supplies—stockpiles of metals, plastics, composites, and other materials.
- 2) Wunderkammer (curiosity cabinets)—stockpiles of odd objects and shapes with little evident use but infinite combinability with other objects to solve design problems (Wechsler 1996).
- 3) Toy cabinets—close relatives of the Wunderkammer that take advantage of clever design toys, starting with wooden blocks and Tinker Toys® and progressing to Lego Technics®, Erector Sets®, etc.
- 4) Donated equipment storage—in addition to the equipment used in the technical work areas, we store additional equipment in the "back room" for potential use in projects. A student is presently developing an online photo-inventory of the stored equipment.
- 5) Thrift store triage—collections of items to disassemble as a method for learning design. Using items that have either been donated or which are purchased at minimal cost from thrift stores, we can keep a steady stream of technical solutions flowing in front of students as they disassemble existing products. In part, this is an exercise in reverse engineering as a means to discover known solutions to design problems. But it is also a source for creative re-assembly, where subsystems and components from existing products can be combined, even if only in a mock-up prototype, to create a new product.

A key feature of the Community Prototyping Lab is the fact that it is embedded in the larger facility owned by MBD. The headquarters contains several features such as meeting rooms, a computer room, an office-services room, a library of resources for business development, and a kitchenette. In addition, space has been allocated to CPL for an Innovation Reading Area with its own library of several thousand books. Most importantly, the

location at MBD puts students into contact with the staff that serve the business needs of the clients. Thus there is the opportunity for ready exchange of ideas that transcend the purely technical aspect of prototyping and broach the wider issues involved in product development for successful entrepreneurship.

Networking to wider resources is an important element of the Community Prototyping Lab and is facilitated by the collaboration with MBD. Client-oriented projects require us to accumulate contacts with vendors of materials and equipment, fabrication services, short-run manufacturers, etc. Networking also is important in establishing a business framework for the projects, so that clients and students both have access to people to go to the next steps toward product launch once a prototype is developed. One important “next step” is provided through our university’s Bard Center for Entrepreneurship, where one of the authors (Meyers) holds a joint appointment. Good opportunities to foster these further steps are the NCIIA I2V (Invention to Venture) symposia, one of which was run on our campus last year (2006).

MBD has a strong orientation towards community outreach, and the Community Prototyping Lab fits into this. The location is in an active art district near downtown Denver, and MBD and CPL participate in monthly “First Friday” art walks. Indeed, the interplay with artists is an element we wish to foster to create a wider community around the prototyping work. Outreach also includes youth groups. We ran (on campus) a trial project to engage middle school students in technical invention by guiding these students through disassembly of several common products (microwave ovens, document scanners, printers, etc.). (Steinhoff, Ruderman, Ruderman, and Tagg 2007) In partnership with MBD, we plan to develop youth inventor activities to take place in CPL’s own space.

Our vision is that the Community Prototyping Lab should take its place amongst other public institutions, such as libraries and museums. The partnership with Micro Business Development came about because MBD had many clients over the years that expressed the need for access to low-cost assistance in the design and development of product ideas. Our goal is to create prototypes of sufficient quality and function to enable clients to seek further funding for full product development, including professional design and manufacturing services.

The Community Prototyping Lab is essentially a midwife in the process of birthing new ideas (Tagliavia 1999), helping to advance clients’ interests to the next level of funding. Thus it is critical that fees to clients for CPL’s activities are kept small and that funding for space, staff, and students is developed through outside support (primarily grants and gifts). Note, however, that we are developing a business model in which clients who are successful with the products will turn some of the proceeds back to CPL for its support.

## **Conclusion**

A special combination of curriculum and resources has been set up to provide a unique experience for students in the development of new products, either for businesses or medical services. A flexible curriculum fosters just-in-time learning so that students can create a scaffold of technical knowledge sufficient to create and test these prototypes. In this curriculum, a menu of short courses and two projects provide both substantive knowledge and practical experience in prototyping. Individuals are able to assimilate a breadth of knowledge that is effective and practical, but which is also the starting point for more extended study should the students desire genuine expertise.

This activity is housed in a physical setting, the Community Prototyping Lab (CPL), which we believe is an innovation in its own right. We hope that CPL will evolve into a resource similar to other community services, such as libraries or museums. Importantly, the lab is a result of a collaboration between the university and a non-profit organization (Micro Business Development). This collaboration provides complementary strengths and assets and connects students to the outside community of small businesses, artists, youth groups, etc. Several stakeholders (small businesses, university, nonprofit organizations, city, community) benefit from this collaboration.

While this is only one model for wider engagement of students and entrepreneurs in the early prototyping of product ideas, we think that many of these elements are transferable to other locations. The key conclusion is that effective prototyping can be done by individuals or small teams with limited resources of time and money.

This is a critical first step into the wider realm of product development that will ultimately require the many business elements needed for successful entrepreneurship.

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