AC 2012-3885: STUDENT LEARNING IN MULTIPLE PROTOTYPE CYCLES

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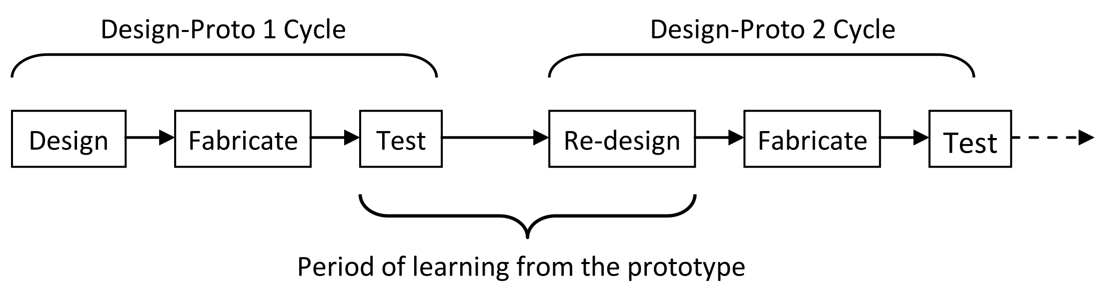
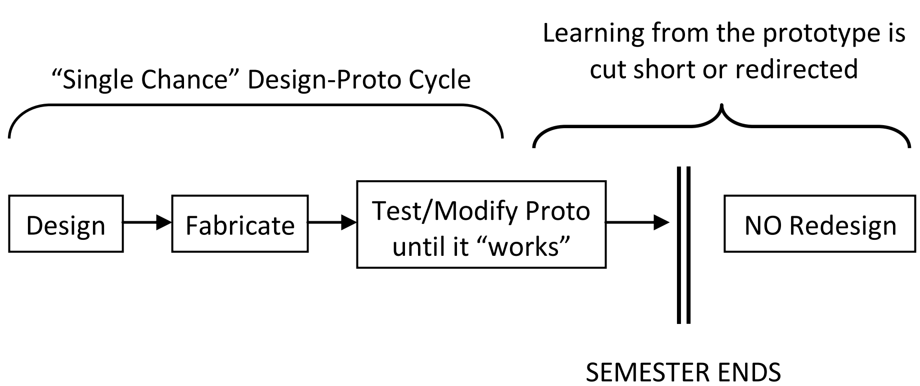
Student Learning in Double Design-Proto Cycles

There are striking differences between how new products are developed in industry and how engineering students are taught design in school. For example, design teams in industry are rarely staffed completely with novices, so considerable mentoring assistance is usually available. Design in industry is usually supported by a standing company culture and support staff, which is not available in school. Perhaps one of the larger differences is that in industry new products are usually developed in multiple design-proto cycles. Each cycle is composed of three sequential stages: design, fabrication, and prototype testing. The testing of the first prototype usually uncovers shortcomings in the design. These shortcomings represent "learning from the prototype" and this learning drives the redesign during the subsequent cycle. The process is shown in the figure below.



In contrast, design in school is usually taught with a single design-proto cycle. In this model, the first prototype is assembled and tested as the academic term ends. The end of term cuts short the opportunities to learn from the prototype and try out ideas gained from the prototype. This course structure is diagrammed below.



How students learn from a prototype is certainly relevant to design instruction. Furthermore, how they learn within an authentic framework, where the learning will be immediately applied to a redesign, seems even more relevant.

The intent of this exploratory study was to understand and describe how students learn from their prototypes within a double design-proto cycle. Though the data spans the entire double cycle, of specific interest was the period of learning beginning with assembly of the prototype in the first design-proto cycle following through to the testing of the prototype created in the second design-proto cycle. To narrow the focus of this study three questions were considered:

1. How did learning from the prototype affect the learning environment?
2. How did the physical prototype affect learning about the product being designed?
3. What learning opportunities did a double cycle create?

The motivations for this study are multiple. First, professional design engineers frequently need multiple cycles to design complicated products. If professionals need these iterations, it seems reasonable that novices would benefit from multiple iterations as well. Second, previous studies indicate that physical prototypes supplement designers' mental models[1] and help break fixations effects. [2] These benefits would tend to free-up cognitive resources that students could then reapply to *learning* design while designing. Third, prototypes are useful to surfacing naïveté in design ideas[3] which would be a common problem for novice designers, such as students. Finally, learning about the product being designed has been linked to learning to design in general.[4, 5] A double cycle provides students more ways to learn about the product they are designing which may positively impact learning of the design process.

Design Education Context

In *Educating Engineers*, Sheppard, Macatangay, Colby, and Sullivan describe the design process as non-linear where, "The engineer may return to an earlier stage at any time."[6] They continue to describe a spiral model of product development where design efforts loop through various stages and testing prototypes is one stage.

Common textbooks in design[7, 8, 9] describe the design process as similar to an open-ended problem solving process. In general, the engineer moves through design phases beginning with defining the design target and continuing through concept generation, down-selection, parametric design, detail design, and prototype testing. The process is iterative so that the designer may return to previous phases as needed. However, these textbooks are silent about a second design-proto cycle and leave the impression that problems are well-resolved before the first prototype is fabricated. In fact, most common textbooks do not include a prototype phase in their diagrams of the design process at all. In these texts the design process concludes with completion of, or transmittal of, design documentation. One exception to this pattern is found in *Product Design and Development*[10] which mentions multiple design-prototype cycles as part of a spiral product development process, but the treatise is less than a page.

To be fair to the textbooks, the design process includes many steps that take place before the design/fabricate/test steps in the simplified diagrams above. The textbooks describe these activities in depth as well as elucidate the many sub-steps in the "design" step. However, the thorough coverage on many aspect of design combined with the silence about learning from prototypes leaves the impression that designers do not use prototypes as a primary way of learning about and improving their designs. Furthermore, a course based on a single design-proto cycle, which by structure excludes redesign based on prototype testing, could reinforce the silence in the textbooks.

The textbooks present the design process, but not design cognition. A recent study of a typical design class[5] found that students incorporated misconceptions into their understandings of how their designs worked. It appeared that students were learning about the product they were designing as they were designing it. Their developing understanding of their own design included resilient misconceptions. These misconceptions were quite robust even when the students tested their prototypes. Additionally, these misconceptions prevented the students from identifying errors in their design before constructing a prototype.

The findings of the above study pedagogically stand at odds with a class based on a single design-proto cycle. Since students' misconceptions ultimately manifest themselves in the prototype and students can have difficulty dislodging those misconceptions even with a physical prototype, then making full use of the prototype to learn is essential. The redesign step in a double cycle is an authentic way to focus students to learn from the prototype.

Class Structure and Design Projects in this Study

This study was conducted in a Mechanical Engineering design class of 29 students working on four-person design teams. Three separate design projects, each utilizing a double design-proto cycle, were completed during the semester. To fit the six design/fabricate/test cycles into the 15-week semester, quick fabrication techniques were set by the instructor. The first two design projects spanned the first four weeks of the semester. During the first two projects supplemental design topics were presented in lecture and applied to the projects. Such topics as open-ended problem solving, part and assembly costing, and design reviews were presented. The third project spanned the final nine weeks of the semester when a formal design process and supplemental topics relevant to technologies in the third project were provided in lecture.

The first project was to design a machine to manipulate poker chips. Poker chips were fed to the machine by a gravity chute in a single layer. The machine was required to have one control operated by a blindfolded operator. The control removed chips individually and stacked them two inches below. These devices were constructed of corrugated cardboard and hot-melt glue, which reduced fabrication time to 1-2 hours.

The second design project was an expansion on the first. These machines removed chips alternately from two separate chutes and created a collated stack. Again, only a single control was allowed and the machine was to be run be a blindfolded operator. These machines were also constructed of corrugated cardboard and hot melt glue.

During the first two projects the students were instructed to follow a team-agreed-upon problem-solving strategy that included a "sketch then build" process. In general, the teams created very basic concept sketches that showed little detail. Once the teams began working with lab materials, a "build it and try it" strategy predominated. Throughout these projects, the teams were instructed to monitor and improve their problem solving strategies. The teams were also instructed to improve the quality of their concept sketches to expedite idea refinement as well as decrease prototype build time. The teams made moderate progress on these two fronts.

The third project was to design machines that automatically loaded two colors of marbles into patterns on metal trays. When the first tray was full, the machine was required to advance an empty tray into the loading area and continue loading marbles. The marbles were fed to the machines through two tubes, one for each color of marble. Each team was provided with four double acting pneumatic cylinders, trays for marbles, and flanged marble tubes. A computer to control pneumatic valves with simple software was provided in the lab for teams to use. Each team wrote their own program to control their machine.

To reduce fabrication time on the third project, all parts were fabricated from 20 gage sheet steel. The students designed parts in 3D-CAD which were then blanked out overnight with a CNC plasma cutter. The parts were formed with a hand operated finger and/or press brake. The parts were assembled with specified 6-32 screws and hex-nuts to further reduce part purchasing logistics. Further, 3D-CAD models of all fasteners and pneumatic cylinders were available in a CAD reference library to reduce student modeling time of stock parts. At the end of the third project, a competition was held where machines were evaluated on the speed and accuracy of loading trays as well as for manufacturability and assemblability.

The third project was paced by the formal design process (define, generate concepts, down-select, detail, etc.) being presented in lecture. Formally the teams followed this process because of the course structure, however informally each team appeared to embody an idiosyncratic process. Data was not collected to track team processes, so more information is not available. As the project progressed, each team reviewed progress with the instructor twice weekly for mentoring and design feedback.

Methods and Data Collection

This study employed qualitative methods because the intent was to understand the experience of students as they learned from their prototypes in a naturalistic (classroom) setting. The specific goal was to explore and begin to describe these experiences.[11, 12, 13] Qualitative methods effectively meet this goal.[11] Further, since little is currently published about student learning from prototypes, an exploratory and descriptive approach seemed best.[11]

Qualitative research employs many methods. A bounded case[12, 14, 15] was chosen for this study where the students and environment of the classroom form the bounds on the case. However, a case study method does not specify how the data is to be coded. Since the data consisted of written learning journals, content analysis was used to code for manifest (or obvious) themes.[11] Further, the student entries described their reasoning within context, which allowed for direct and trustworthy interpretation of the comments.

Mid-semester each student was required to post five learning journal entries. In each entry, students were asked to describe something specific they had learned from an experience in design or teamwork. The students were encouraged to include anecdotes and rationale for their insights. During the final week of the semester each student was required to post three concluding entries. All learning journal entries were used for data in this study.

The students collectively posted 236 entries. Two-thirds of these entries (155) described aspects of design, while the remaining discussed teamwork. Of the design entries, 45 specifically discussed how prototypes affected learning. All journal entries were initially read to identify entries discussing prototypes, and also to gain a general sense of what the students experienced.

The entries discussing prototyping were read multiple times until their content became very familiar. Notes were taken with each reading to identify recurring themes in the data. These themes were organized by two major categories: whether they discussed the physical prototype or the design-proto cycle. During the final reading each entry was logged within subcategories of the major categories.

Results

The learning journal entries paint a very descriptive picture of what the students were learning. The recurring themes are presented below, organized by the natural progression of the double design-proto cycle. Throughout these quotes, the students used the terms "proto," and "prototype" to mean either the physical prototype, the design concept embodied in the prototype, or occasionally the entire design-prototype cycle. The students used the numbers "1" and "2" to identify either which design-prototype cycle they were describing or which physical prototype. In most cases the context makes the student's meaning clear.

Designing is an open-ended process and hence is filled with uncertainty. The students described their uncertainty, or the consequences of uncertainty, in many of the entries. The largest uncertainty was whether each team's chosen concept would work well when implemented.

> *There are so many alternatives when it comes to design that it is difficult to choose the best path to take, especially since it is almost never obvious which path that is.*

> *It can be frustrating if after you design prototype 1 you realize that you should've taken a totally different route.*

> *So, we learned that it is imperative to think through the proto 1 concept before investing in it.*

The nature of design work fundamentally shifted when the first prototypes were assembled. Prior to the prototypes, the design concepts and details were realized in the students' imaginations, sketches, and 3D CAD models. As the prototypes were assembled, those concepts and details could be tested physically. Expectably the prototypes embodied design oversights that the students discovered in testing.

> *Any oversight, even some very minor ones, can result in a useless product.*

> *This goes to show that the things that you forget about come back to bite you in the butt because it's the smaller details toward the end of the project that matter the most….*

The students also discovered deeper problems while testing their prototypes.

> *Is it a problem that happens every time? Is it something that can be fixed with a new part? Or is it a problem with the current design [concept] of the machine?*

I found that an important thing we did…was too deeply analyze the problems of proto 1 and why they occurred.

Since the students were preparing to redesign their products, testing of the first prototype naturally switched into generating and possibly testing improvement ideas.

Utilize proto 1 to make proto 2 better. In order to notice mistakes and concept design flaws in proto 1, it really helps to try your best to fudge the machine as much as you can to get it working.

[In proto 2] all [parts are] fitting together from the outside (as opposed to the inside, a big design flaw on our first proto…) so we can easily change parts.

… this first batch of parts really taught us that we need to anticipate sloppy holes and bends not to spec, and design around these problems.

The student entries above emphasized learning about their *product* they were designing, rather than learning about the *process* of design. This bias was typical of most entries. The students also had reflective thoughts about the design process in general, though fewer.

What I really learned was that something that is made on SolidWorks® isn't always going to come out exactly right from the computer to [the] physical model.

Being able to identify aspects of a design problem that might slip through the cracks before going to prototype or solution implementation is a tremendously handy skill to have….

When the students began the redesign for the second design-proto cycle, they had to choose how much to redesign. Comments about how much to redesign were evident in 20% of the entries. Their second prototype designs could incorporate small changes, be a total redesign, or anywhere in between. Just as uncertainty shadowed their initial design choices, uncertainty shadowed many, but not all, of the teams as they redesigned their products.

Since we had a relatively good proto 1, we didn't end up making any drastic changes to our machine, but just improved on the design we already had.

…it is important for proto 2 to be an improvement on proto 1 and not a complete redesign…we completely changed our escapement design and as a result, proto 2 was not much better than proto 1….

We found some fundamental problems…after trying to test proto 1. Because of this… we scrapped a good portion of our design in favor of something completely different…. The main risk of doing this, of course, is that you are starting from scratch and don't know if it will work as you expect…. We told ourselves that we only had one shot to get this redesign right, so we had to be even more careful than before. It took a lot of time, and every single part on the machine ended up being changed (both for the new design [concept] and for easier manufacturability), but we ended up coming out with a proto 2 *that we were proud of after a few minor tweaks. I learned that sometimes starting over isn't a bad idea.*

The journal entries do not inform *how* each team decided to improve their designs in the second design cycle; the journals only indicated *that* the students attempted to address major design problems. From feedback sessions with the instructor, it appeared that the teams implemented the minimal design changes that would address their prototype's known problems. However, some teams felt their first prototype designs had fundamental conceptual problems and correspondingly their design changes were major.

Though uncertainty shadowed both design cycles, the redesign during the second design-prototype cycle had a different foundation. In the redesign cycle the students based design decisions on experience grounded in assembly and test of the first prototype. In essence, the students could apply what they learned.

We were able to learn from our mistakes in proto 1.

Not only do we have some design flaws that need to be changed for proto 2, but we also need to simplify parts, maybe make more smaller parts to fit together instead of one larger complicated part.

It's amazing how often we've needed to dismantle this machine to make changes, tighten parts, etc. We were not expecting to need to take it apart or adjust parts as often as we are now, so we are taking that into account for proto 2.

The prototypes created in the second design-prototype cycle worked much better than the first prototypes; however they did not work perfectly. As before, these new prototypes uncovered improvement possibilities which some students suggested as appropriate for a third design-proto cycle.

This journal entry is going to be based on mostly proto 2 and what I learned from it to what I would improve for a proto 3.

One improvement we could have made is try to design proto 2 to not be so affected by a surface that is only relatively level.

The improvements that I would have made in proto 3 would mainly focus on simplifying and making the design more compact with less material and less movement.

Discussion

The discussion returns to the three questions posed earlier, each question framing a subsection.

How did the double design-proto cycle affect the learning environment?

The learning environment in this double design-proto cycle can be characterized by expectations, motivations, and the presence of a safety net. The expectations implicitly set by the double cycle were that the first prototype will likely not meet all requirements. This expectation was reinforced in lecture and physically realized with prototypes that did not work as conceived. This expectation could be equally true of a single design-proto cycle, however in a double cycle there is a joint expectation that problems will be designed-out in the second cycle. Many of the student comments explicitly and/or implicitly identified this expectation.

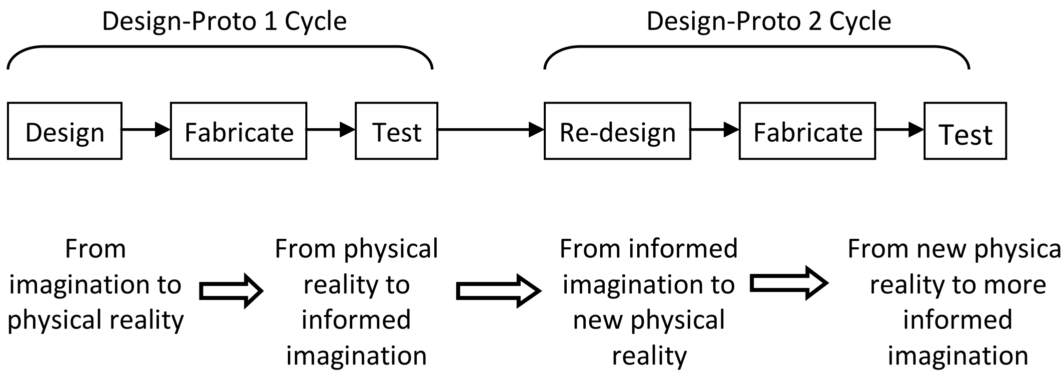
The expectations set by redesign motivated corresponding behaviors. For example, some students reported an increased attention to detail. *Careful* examination of other students' prototypes was a way to find solutions; *careful* review of 3D-CAD models was a way to avoid oversights. Further, students described motivation to seek manufacturability improvements, assemblability improvements, and other design simplifications in the redesign of proto 2.

A safety net created by the second cycle complemented the high expectations and corresponding motivations. The first prototypes were not graded; mistakes on them were not final. Rather these mistakes and oversights were the means to learn and perform better on the second round. Some entries described the opportunity to learn from mistakes, many described specific design changes learned from mistakes and oversights, and many described weighing how deep of changes to make to the design during the second cycle. These reflections and actions based on learning from failure would not be part of the learning environment if the means to implement the learning were not available.

How did the double cycle affect learning about the product being designed?

Students certainly learn from their prototypes in any design-proto cycle. In the double cycle, the students began assembly of their first prototype a little after midway through the double cycle which meant the students had a prototype in hand about half the time. One way to consider how this prototype affected the students' learning about their design is to map the flow of ideas in the design work.

When the design cycle began, the students generated conceptual machines, chose a concept, and implemented it to an actual prototype. In essence, the flow of product learning was from imagination to reality. As the prototypes were assembled, the flow of product learning reversed; reality started to correct the imagination. As the redesign began, the flow of product learning reversed again; imagination was again forming the next reality. This flow is diagrammed in the figure below.



Various student journal entries described each of the four flows of information diagrammed above. For example, entries describing uncertainty whether a concept would work frequently noted that the prototypes would tell all. Entries describing problems in the prototype frequently included how redesign would be affected. Entries about proto 2 testing frequently included how to improve the design for proto three. This flow of ideas is similar to Kolb's experiential learning cycle[16] where a concrete experience flows to an abstraction, which flows to a testable experience, which flows back to an abstraction, etc.

What learning opportunities did a double cycle create?

The double cycle facilitated three unique learning opportunities: more certain success on a difficult project, addressing layered design problems, and designing with experience. Students are novice designers and hence apply little product-relevant experience to their designs. In contrast experts apply a wealth of experience to solve problems.[17, 18] In this context, seasoned designers apply a wealth of product relevant experience gained through multiple design-proto cycles. Though the students in no way became experts, they did begin to develop expertise relevant to their own product. Student journal entries contain many examples of redesign based on the knowledge gained from the first design-proto cycle.

Layered problems could be addressed since the students gained modest expertise with their products. For example, assemblability concerns were second tier relative to functional concerns. The students knew that their machines had to work even if they were difficult to assemble. With this motivation the students naturally layered these problems. Though professional designers would typically address manufacturability requirements as they met functional requirements, balancing these divergent concerns easily overtaxed the students' design abilities. However, the students did address second-tier concerns in their second design-proto cycle. This opportunity would not have been open in a single proto-design cycle.

The combination of being able to address layered problems and designing from product relevant experience opened the opportunity for higher student success rates against a difficult design problem. At the beginning of the marble loader project the students told the instructor that, "they had no clue how to create such a machine." They began to cite their unfamiliarity with factory automation equipment and design in general. Had they been aware, they could also have cited their lack of experience at sheet metal design, applying dynamics to real machinery, and a host of other skills. When the first prototypes were assembled, only one of eight functioned reasonably well with minor changes. The other seven required major changes to function at all. However, the students did apply what they learned from these prototypes so that in the second design-proto cycle six of the final eight prototypes worked quite well and the other two prototypes worked with occasional misplacement of marbles.

Conclusions

Design problems are open-ended and usually have multiple possible solutions of varying quality. This open-ended learning context generates a fair amount of uncertainty, which is a challenge for student designers. This uncertainty can be redirected into a positive learning environment by using a double design-proto cycle. In a double cycle students become focused on learning from their prototypes with the intent of designing-out the problems. This focus reinforces conceptual understanding of their own product design, including its shortcomings and possible variations of their original solution. Simply put, the students can apply their modest, but developing, expertise about their own product. Applying their developing expertise allows the students to address layered design problems, where shortcomings that would not be apparent during the first design cycle, or were of second tier importance, can be remedied in the redesign cycle. This safety net of the second cycle allows students to succeed on challenging design projects. Finally, a double cycle provides another aspect of authenticity to a design course. Professional designers learn from prototypes with the intent of redesign for many of these same reasons.

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