Designing a Design Course Sequence:

“Planned Experiences Not Happenstance”

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When asked, many engineering graduates may at first look back fondly on their introductory or capstone design courses. But their next utterances usually point out a number of severe limitations. Typical comments include “it was an isolated experience,” or “the tie to analysis courses did not materialize,” or “there were too many disparate goals--communications, team dynamics, project management, realistic product testing, etc.”

Fundamentally, the design sequence confronts students with too much material too fast. They have not built up the concrete experiences to the level required in the course.
No matter how bright the students or how crafty the faculty presentation, it is unrealistic to expect students to design a smoothly operating, quick, nimble, efficient and profitable machine if they have yet to nail two boards together.

We have documented many experiences with different types of design courses, from contests to dissection experiences to capstone courses, and we understand the benefits and detriments of each. Contests motivate some students to success but block others from ever enjoying practical engineering. Capstone courses bring all disciplines to bear on a single project, but also inhibit core engineering courses from bridging the gap between textbook problems and real applications that overheat, break, vibrate, or run too loud. Dissection courses help students understand how some things work yet can fail to utilize the sophistication of realistic physical modeling. We understand these linkages, yet their implications on contemporary engineering education have not fully materialized.

To improve the modern design-engineering curriculum, we must wrestle with at least five issues:

1. We all learn in the stages of a cycle. Kolb's cyclic model of learning is typically not fulfilled in the structure of most courses. As shown in Figure X, Kolb views learning as a cycle composed of concrete experiences, observation and reflection, conceptualization and theory, and active experimentation. More emphasis on hands-on learning, with a chance to reflect and modify, is critically needed.
2. Studies show that we are all much better at applying knowledge if we learn it in the mode in which we will use it. The "mode" in this case does not necessarily assume a *physical*-working environment, but pertains to the *context* of applying the knowledge. Example contexts might be the application of the engineering fundamentals to the design or redesign of a product. Thus, students should learn in a *contextual* environment that is similar to the one they will experience as a professional engineer. Providing this change to current curriculum should dramatically affect the motivation, retention, and ability to learn on the part of the students. It will also push the working environments in industry to transform and evolve, since the knowledge and technology implemented during problem solving will be state-of-the-art.
3. Open-ended problems are difficult to solve, and many students do not react well to facing them in their first design projects. This reaction occurs not necessarily because the students are intellectually immature, but because they lack the engineering-based physical experiences (mechanical, electrical, etc.) needed for a blank-sheet design. One effective teaching method is to demonstrate by example (or many varied examples), yet we don't do this effectively with a design process. As the first design experience, it is effective to provide a detailed process that the student must strictly follow. We should integrate with this process an incremental development of design methods, physical experiences, and integrated solutions.
4. Design is an iterative process, and the teaching of design should reflect this characteristic. Many design courses progress to achieve a working prototype (or less), and then stop.
5. Design modeling, analysis, and experimentation remain as frontiers for teaching repeatable methods that enhance creativity and innovation. While applied

mathematics and science courses build the students' skills in analysis, a chasm still exists in integrating and bringing the skills to bear on a design problem.

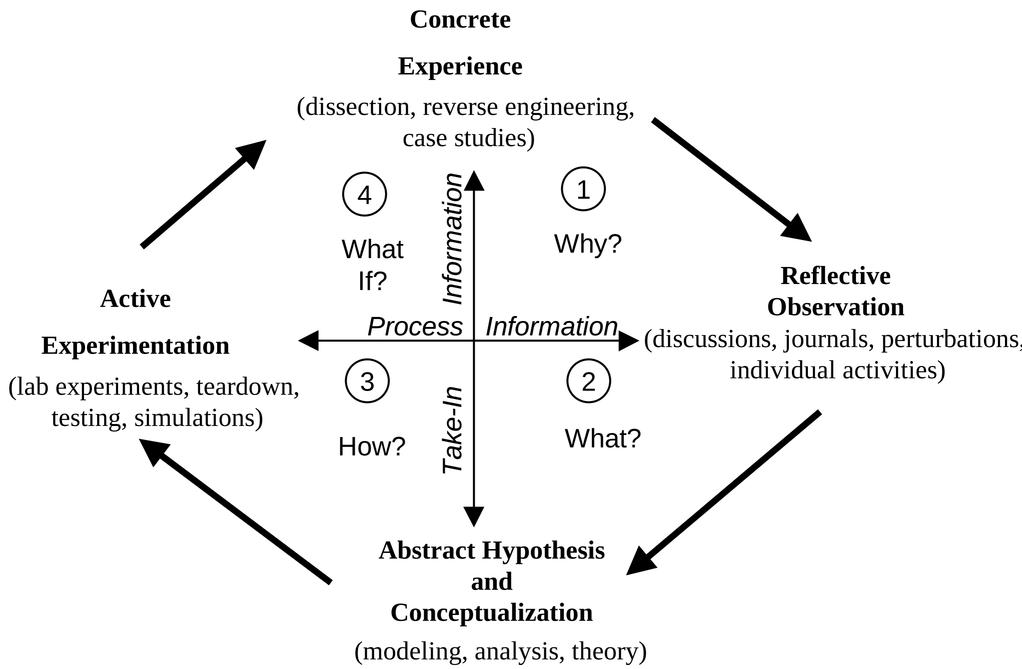

Figure X. Kolb's Model of Learning (Stice, 1987).

The first step in advancing our curricula in engineering schools is to become acquainted with the basic Kolb learning cycle, as depicted in Figure X. This learning cycle has been largely ignored in engineering education, and, in many cases, tossed out as irrelevant in design. To be fair, teachers of engineering analysis have developed an incremental approach, and their curricula have followed portions of the learning cycle, albeit at one extreme. They cover what we call the *model world*, and learning proceeds through the self-contained world of paper models. First students learn basic mathematics in grade school, then algebra in high school, and then calculus. Next, in engineering school, they apply the learned calculus to problems described on paper. Explanations are on paper. Problems are posed on paper. Homework is on paper. Tests are on paper. The problems do increase in intellectually difficulty, with less information provided. However, students are rarely given a *piece of hardware* and told to engineer a fix for it, much less explain the problem with analysis.

The root of the learning-cycle problem is that the concrete experiences provided to students follow no educational trajectory. We run students through the model-world learning cycle, and then toss them into design courses to use this learned material. There they run into a problem: as they design and assemble their prototype, the machine binds, overheats, breaks components, has mismatched systems, etc. And, for the first time, they are faced with the real physical artifact they have to understand and model. But it is not just a subsystem or part of the artifact, “it’s the *whole enchilada*.” Not just one linear bearing binds, for example, but a whole system complete with poor gear ratios, poor mountings, and probably with wrong wiring as well. Or, in another example, the problem is not just one poor heat path on one heat sink on a properly circuited electronics board, but rather a complete motor controller that, in addition to overheating, is not interfaced to a motor correctly on a system with a wrong instrument panel.

Student projects of this type generally run out of time, and the result is junk or an incomplete machine. This product would have no chance of being profitable if anyone attempted to build and sell it. And we accept this situation as a truism. If, alternatively, the machine is well constructed, it is because the students came into the university with the concrete experiences necessary to design and engineer good machines or because of happenstance; it has little to do with what the university curriculum provided.

Incidentally, these machines are the primary outcome from design courses, rather than tests or homework. The engineering faculty examines the poor results, and then, rightfully, questions the material presented in the course. But the design courses are denigrated for the wrong reasons; any poor results are due to the poor (if any) hardware experiences in the analysis courses. On the other hand, the engineering analysis faculty are largely correct to observe that the learning cycle in design courses is incomplete and that the teaching mode remains “learn it by doing it” (with no process or iterations). The entire problem is primarily caused by the lack of an incremental strategy for concrete experiences in the entire engineering curriculum–a curriculum that should, but doesn’t, follow the basic Kolb learning cycle.

To work on this fundamental problem in engineering education, consensus amongst the entire faculty must be nurtured and focused on advancing curricula with hands-on trajectories. Systemic problems require system-wide fixes. Our own universities are by no means complete in fixing the problem, and we continue to think and rethink possible advancements. Nonetheless, we present some evidence and developments on possible change to the curriculum to address this serious problem.

DEBUGGING A STIRLING ENGINE

At MIT, the first hands-on course is not a “design course”; it is a manufacturing and analysis course, developed and taught in a partnership between a fluids engineering faculty member Douglas Hart and a design faculty member Kevin Otto. In this first required course, students fabricate parts, assemble, and debug a working miniature Stirling engine. In the process, the students physically experience manufacturing processes. These basic experiences, which are often thought to be common but are not, include working with lathes, milling machines, band saws, hand files, micrometers, sandpaper, oil, steel, brass, and aluminum. Obviously, students experience speeds and feeds, processing limits due to such effects as temperature, and measurement/fabrication part tolerances. But they also experience design concepts such as assembly tolerances, chains, and allowances, and not as mere abstractions. The engine parts form multiple loops, and so must be aligned using the designed-in allowances or they will not assemble together and freely spin. Students also experience different scales of manufacture, from watching large lots rapidly produced on CNC machines with specially built fixtures, to simple jigs which speed drilling on smaller lots, to individual custom hand steps on milling machines.

In this introductory course, it is important that the learning of prototyping skills is isolated from the learning of design skills. The engine design is given to the students complete; they are not asked to design it. Often introductory design courses are also introductory fabrication courses, and there is no attempt at incrementing these concrete experiences. In the MIT course, properly sized components, properly spaced fasteners, proper drawings, and all other aspects of the engine design are provided and explained to the students, who observe and then experience them first hand. Further, because they must build their engine off the drawings, they find out what is needed in good drawings. The course instructors developed the detailed design of this particular engine to make it compatible with the school facilities, and so can explain why materials and geometry were chosen.

Interestingly, the students are required not only to assemble but also to analyze their engine. How much power does it produce at the shaft? How much power goes in? How much is a Watt? How can we make it go faster? How much faster? What if…? These questions are based on their concrete experience and provide incredible motivation to learn difficult concepts such as energy and entropy. Tools that assist the students in their analyses include MATBLAB, XESS, and solid modelers, such as PROEngineer and Solid Works.

Following on this introductory course, the students are ready to begin a design course. We strongly believe, though, that this first design course should not require the student to create a completely original machine. Rather, the course will be much more effective if it presents a *redesign* project. A good project is one in which the device already works at some level; it then requires original thinking to develop improvements.

IN REVERSE

At the University of Texas at Austin, the introductory design course uses a reverse engineering and redesign methodology. This approach allows us not only to increase the percentage of course time spent on “hands-on” experiences, but also to iterate - requiring submissions in later reports that are revisions of work done in earlier assignments.

The first project allows the students to choose an industrial product to reverse engineer (that is, tear it apart and analyze it to understand it). Each team of students is encouraged to pick a commercial product that interests them--whether it be a device that they use regularly but which never performs to their satisfaction, or simply a device they have always been intrigued by but never had the opportunity or time to investigate. The important thing is that they *want* to reverse engineer the product.

Once the team has chosen a product, they are required to perform several design tasks. They must examine the product, and develop a statement of global need or *function* (black box). An initial black box model, relating input energies, materials, and information to the corresponding outputs of the product, provides the team with a clear statement of this global function without knowledge of how the product works internally. They must then use the product over its operating range, interview other users of the product and present a summary of their most common likes, dislikes, and suggestions for improvements. They must develop a process description for using the product, and compare the product to its competition. Finally, they must predict how they think the product works. For example, if a team’s product is a power screwdriver, they might predict that the transmission consists of epicyclic gear train arranged in a certain way. Ultimately, we have them create a predicted function model and a list of predicted components and physical principles. Through this initial process and interaction with a real product, students are given the context of professional designers, bridging the gap between the classroom and the office.

As the second part of the project, each team must create a plan for disassembly and then take the product apart. This step is often the most enjoyable and increases the “hands-on” percentage of the reverse engineering methodology. In this part of the project, students should gain a full understanding of how the product works and how it is assembled. They also determine areas for how it might be improved. By the time this first project is completed, each team should be capable of answering the customers’ question “so how are you going to help me?”

During disassembly, students determine the functions of each part and subsystem by removing it and play-operating the product--the *subtract-and-operate method* of functional modeling. They create a bill of materials as well as an exploded view of the product. They must describe how the product actually works (fulfills customer needs). More interestingly, they must also compare the actual workings with the predicted workings as completed earlier in the term. For each part, they describe what it does and then abstract to determine its functionality with a careful eye toward multiple functions being fulfilled by one part and toward the overall product architecture. They must consider how the major flows (e.g., energy, signal, material) interact with the product and how they relate to the detailed functions of the device. A function structure model is then constructed for the product. They conduct research into appropriate standards, map the customer needs to appropriate engineering requirements (i.e., perform a Quality Function Deployment (QFD) through the construction of a House of Quality), and include a qualitative and quantitative ranking of the product with respect to its competitors for each customer need. Finally, they identify ways to improve the product (according to the customer needs) and prioritize which of those opportunities the team plans to pursue.

Next, the second major course project at UT-Austin focuses on developing original design concepts. Giving the students the opportunity to work on a truly original design problem is too valuable an experience to disturb. Student teams use the concrete and structured methods from the first project, in addition to others, such as inventive concept generation methods (C-Sketch and the Theory of Inventive Problem Solving) and Pugh concept selection (Wood and Otto, 1998). The additional methods fill-in the gaps left by the reverse-engineering project. For example, C-Sketch provides a procedure to use drawings (without verbal communications) to express and iterate the development of design concepts.

Having completed an original design, the teams return to their reverse engineering in the third project. Armed with a course of action towards product improvement (as presented at the end of the first project), each team should now be prepared to work to achieve this improvement. “Make it better!” is the subtitle of this project, and the students are encouraged to strive towards making significant improvements in their products--improvements they would be proud to suggest to the product’s manufacturer. Their experience in the first two projects has introduced them to fully developed QFD matrices and functional modeling, so they will now be able to use the materials they have gathered to produce effective redesigns.

The requirements of the third project include determining, concretely, how the teams will achieve the improvement in question (i.e., modeling, prototyping, etc.). They develop alternative concepts for effected subsystems, choose concepts that maximize the improvements, and justify the choice with the analyses from the previous projects. They develop analysis models of effected subsystems, calibrate the models and solve for preferred variables, and then use design-of-experiments methods on the evolved product. They revise bill-of-materials and exploded views as the final result of the course. A final build of an alpha product is not required, because doing effective redesign is enough work for one course. With this three-stage project experience under their belt, students in a subsequent design course will develop and build a working prototype.

The remainder of an ideal design sequence will include courses that are intermediate to the one’s we describe above, but include incremental advancements in the hands-on content. For example, hands-on redesign and construction are included in the machine design and thermal systems courses at UT-Austin. With these intermediate experiences included during each semester of a student’s degree program, the epitome is a capstone design experience during the last semester. The expectation from this final experience is a working machine or system that builds upon solid foundations in engineering fundamentals and hands-on activities.

The main point is to understand and design the sequence of concrete experiences with special attention paid to completing the human learning cycle. A well-designed sequence of incremental concrete experiences allows students to start to “get it” by the time they are seniors. It also truly permits higher learning on more open-ended design projects in the senior year, since students not only have seen and analyzed good design, but they have experienced a well-formulated design process, which follows the well-established learning cycle.

FOR FURTHER READING

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