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Design as the Bridge Between Theory and Practice*

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It has taken over a year to get to this point. Our Mechanical Engineering Department was attempting its first major curriculum change in over 20 years. Under discussion was a proposal to eliminate Thermodynamics II and the Kinematics course, and to institute a design course in the junior year, while reducing total credits by 6. Still to come was the even more controversial issue of integrating active learning into our lecture-dominated courses without increasing the teaching load or spending more money. It had been a year of contentious meetings, followed by passionate e-mail salvos with **bold highlights** *for emphasis. Mirroring the recent presidential election, there were three camps: two with unshakeable beliefs on either side of the theory/practice divide, and a third group who just wanted the other two to go away so they could get back to their research. When it was time for the final vote on the "Midstone" design course, comments included: How can you teach design if students don't know the fundamentals of xxx . . .? Design is too touchy-feely. This course is not worth 3 credits; can't we do it in one or two? Not technical enough, too much business stuff, you can't teach common sense, we are watering down the curriculum, etc.*

This paper presents the things I wish I had been quick enough to think of and say at that faculty meeting. The outcome of our curriculum improvement process is presented, including the new Midstone design course. Finally, the following long-term goals for engineering education are sought:

1. *Formal training in education pedagogy, with periodic re-certification, for all college instructors.*
2. *Recruitment and retention of "Professors of Practice"—practitioners from industry.*
3. *A new "Goals for Engineering Education" by ASEE, to guide engineering education in the 21st century. ASEE's previous report is now 50 years old.*

Keywords: design; active learning; curriculum change.

HISTORY OF CURRICULUM CHANGE IN MECHANICAL ENGINEERING AT PENN STATE

The B.Sc. Mechanical Engineering program at Penn State graduates approximately 250 students each year. The 40 full-time equivalent faculty in Mechanical Engineering teach the ME courses and are also expected to be active in research in their area of specialty. Forty percent (40%) of the faculty have direct experience in industry. Approximately 60% of the students in mechanical engineering start at University Park while the others start at one of eighteen branch campus locations. Since required courses in the program must be available at all campus locations, the Penn State curriculum cannot have specialized mechanical engineering courses in the first two years. The B.S.M.E. curriculum contains 137 semester credits. This is one of the highest degree credit requirements for B.S.M.E. degrees around the country.

The Department of Mechanical and Nuclear Engineering (MNE) at Penn State has been heavily involved in curricular improvement, both in the college and in the department. College-level programs such as the NSF-funded Engineering Coalition of Schools for Excellence in Education and Leadership (ECSEL), the Learning Factory, and the Leonhard Center for the Enhancement of Engineering Education have benefited from the involvement of MNE faculty in leadership positions. These organizations have inspired several department-level demonstration projects that have been highly successful. Through these initiatives, cost-effective ways to incorporate active learning into MNE courses have been developed, with demonstrated improvements in student learning. Motivated by a number of factors, including the new ABET Engineering Criteria 2000 (EC2000), student surveys, and feedback from our industry advisory committee, the department is currently working to incorporate and implement these teaching innovations across the curriculum. Although courses and teaching methods are regularly updated and modified, a major change in the B.S.M.E. curriculum has not been made since the mid-1980s.

A formal process was implemented by formulating the curriculum improvement as an engineering design problem [1]. The steps in the process were:

- Identify need
- Define problem
- Generate alternative solutions

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- Analysis and feedback
- Winnow
- Detailed design
- Test and refine
- Implement

Following a design methodology created a structured approach to curricular improvement. This allowed all faculty members to participate in a series of discussions and decisions during the process. Our intent was to try to achieve as much consensus and buy-in as possible in what was expected to be a very contentious process. This turned out to be very true.

Through numerous discussions in general faculty meetings and curriculum committee meetings, improvement objectives for the curriculum were formulated. These objectives are:

1. *Improve delivery*—To encourage deeper student learning by:
   a. Integrating theory with practice
   b. Integrating concepts across courses
   c. Requiring fewer courses/semester to increase depth
   d. Enhancing lifelong learning skills
2. *Enhance content* – Increased student exposure to:
   a. New and emerging technologies
   b. Professional skills (societal impact, ethics, team skills, project management, global issues, economic justification)
   c. Computer and numerical skills
   d. Design methodologies and tools

A consistent impediment to any curriculum change can be the entrenched attitudes of faculty. While there are exceptions, faculty in general are not particularly adept or comfortable in team activities. We are trained and encouraged to be independent researchers and grant chasers. We are not trained in education. Teachers at every other level must demonstrate proficiency, must be certified, and must undergo regular re-training to remain current in their profession. A number of strategies were tried to educate the faculty on issues of learning pedagogy. These included:

- Benchmarking of peer institutions
- Bringing in outside speakers from institutions with notable curricula (Phil Schmidt of the University of Texas-Austin; Sherra Kerns of Olin College)
- Informal brown-bag lunches to exchange ideas and promote collegiality
- Circulation of seminal papers from the literature [2–9]

The jury is still out on whether these efforts changed any hearts and minds.

After more than a year of deliberations and heated faculty meetings, it finally came time to make decisions. It became apparent that only proposals which were resource-neutral (in terms of faculty workload and budget) would be considered. Two stages of curriculum revision were proposed:

Stage 1: Curriculum revision

Remove from degree requirements: Kinematics (3 cr), Thermo II (3 cr), Statistics (3 cr)

Modify: Instrumentation (from 3 to 4 credits, adding applied statistics), Senior Capstone Design (from 4 to 3 credits)
Add: Design Methodology (3 credits)
Total credits: 131 (formerly 137)

Stage 2: Curriculum revision—active learning

Following the benchmarked examples of a number of our peer institutions, a number of changes were discussed to more formally integrate active-learning components into the core ME courses to augment our strong lecture format.

In October 2004, by a written ballot of 23 Yes, 18 No, the Stage 1 changes were approved. In March 2005 poll, a majority was opposed to adding active-learning components to the core curriculum in Mechanical Engineering. The results were: 17 Yes, 22 No, 4 Undecided. Despite the best current thinking in engineering education circles, we were not able to convince our colleagues to take this step. Concerns about budget and staff reductions also influenced the decision. Further curricular changes have been put on hold in order to concentrate on successfully implementing the Stage 1 changes. We are all tired and need a break.

THE "MIDSTONE" DESIGN COURSE

One positive outcome has been the approval of what is being termed a Midstone design course—coming between the cornerstone and the capstone courses. Currently, our ME students take two courses in design:

- Cornerstone course—Freshman year introduction to design and graphical communications, common to all engineering disciplines (3 credits)
- Capstone course—An industry project clinic taken in the senior year (4 credits)

The obvious deficiency in this approach (at least to those who believe in the value of design education) is the lack of continuous exposure and practice in design. In the 2–4 years between freshman and senior years, students undertake intense theoretical study, where every problem is well-posed and has only one correct answer. Then in the senior year we expose them to a real, open-ended problem that they cannot look up in their textbooks and we are "shocked" to find that many of them flounder. Currently, the bulk of the senior capstone course is devoted to teaching (re-teaching) material that has been lost or forgotten in the previous two years, and students have limited time to actually work on their project. Capstone course topics include: a structured design process, team skills, project management, prototyping, industrial design, professional communications, ethics, and project economics. Students tend to lock onto the mission, and lose sight of the underlying knowledge and skills that will enable them to complete their next project assignment. The last semester is too late to instill the philosophy that design is a compromise between conflicting technical, social and economic criteria; that there is usually no one best answer; that a practicing engineer seldom has all the information or time necessary to make the proper calculation—Better is the Enemy of Good.

The primary motivation for the midstone design course is to reinforce and expand on the foundation laid in the freshman year and provide a strong foundation for the senior capstone. It will be a required course for all Mechanical Engineering majors and will be taken in the sixth semester. The current text is *Product Design and Development*, by Ulrich and Eppinger. This text focuses on the business aspects of product design. This is supplemented with more discipline-specific engineering material.

Philosophically, this course attempts to strike a balance between the art of design and the science of design. A concurrent approach is used, where theory and application are presented simultaneously, using the design process as the overarching problem-solving method. The problem-solving nature of design provides the motivation for just-in-time learning. When students have a problem that they are trying to solve, they actually want the knowledge, will use it immediately, and are far more likely to be able to transfer that knowledge later to a different application. When technical content is taught without application just because someone else (i.e. the instructor) thinks it is important, students file it away in their mental folder titled: "I can look this stuff up later if I ever need it." This assumption must be tested somewhere in the student's academic career and its limits must be determined. As an old Welsh proverb says: An early stumble saves a later fall. Open-ended design problems provide the test case by which students can begin to develop good judgment and confidence in their abilities as an engineer. Design problems provide an outlet for those rookie mistakes that everyone must make for themselves and get out of their systems.

COURSE OBJECTIVES—DESIGN METHODOLOGY FOR MECHANICAL ENGINEERS

- Instill the philosophy that real engineering design is often an open-ended, ill-structured process
- Provide students with in-depth practice in design and the use of a structured approach to design
- Develop and practice teamwork, critical thinking, creativity, and independent learning
- Develop and practice communication skills (verbal, written, electronic)
- Reinforce and improve CAD/Solid Modeling skills
- Develop and practice skills in project planning, budget management, resource allocation and scheduling
- Instill a philosophy of professional and ethical behavior
- Provide guidance in applying engineering principles to open-ended problems
- Provide an introductory knowledge of business practices, economic viability, environmental sustainability, and the social consequences of technology

Every class meeting (two hours, twice per week) consists of a brief presentation or workshop (not the "L" word), and a hands-on activity to illustrate that material. Reading assignments from the text are required and are encouraged by brief quizzes. Activities include brainstorming, patent search, case study discussions (DeWalt, and IDEO from Harvard Business School), design of a combi-wrench [10], desert survival team activity, dissection and benchmarking of electric hand drills (including DeWalt), student presentations, and a DFM (design for manufacturability) analysis of a VCR tape. In the first half of the course, case studies and small design activities are employed to illustrate the design process. In the last half, student teams are tasked with a competitive design project, which is described in the next section.

FINAL PROJECT—THE PUMP CHALLENGE

Design and build a system to move water from your tank to your opponent's, while they are simultaneously trying to fill yours. To win the competition, you must cause the other tank to overflow. If neither tank overflows in the allotted time, the winner is the emptier tank.

Constraints

1. Your only source of electrical power is either:
   (a) three AAA 1.5V alkaline batteries or
   (b) one 9V alkaline battery.
2. Maximum weight of complete system (not including tanks or water): 1 kg.
3. The tanks are initially 3/4 filled. The tank dimensions are: $21 \times 33 \times 8$ cm (height, width, depth), width and depth measured at the vertical midpoint.
4. Once put in place and activated, the system must operate without operator input or control.
5. You have a budget of \$50 for purchase of supplies and materials.
6. You must design and build your own water-moving device. Reasonable expenditures for rapid prototyping will be considered, in addition to the \$50 budget. All other items should be COTS (commercial off the shelf).

7. The inlet to your system is 1/8" diameter plastic aquarium tubing 36" in length (supplied).
8. You are not permitted to make any modifications to the tanks or their positions.
9. In its initial state, your system must contain no water or fluid.
10. You are not permitted to modify or in any way interfere with your opponent's system.

Evaluation criteria

- 25% Performance in head-to-head competition.
- 25% Analysis—functional modeling of your system and prediction of performance—this is not a Junkyard Wars, build it and hope project!
- 15% Economic analysis for full-scale production of your system, assuming an annual sales volume of 100,000 units.
- 25% Final report fully documenting the design and the design process followed. The report must allow your design to be reproduced, and should include all analyses, test procedures, drawings and experimental data.
- 10% Weekly progress reports.
- Formative and summative assessment tools are used to gather student feedback for continuous improvement. In the steady state, four sections will be offered each semester with a section size limit of 32 students. To encourage collaboration and sharing of individual best practices, a three-day summer workshop will be held to train faculty in how to teach this course and to collaboratively develop and refine the course content.

FACULTY REACTIONS TO MIDSTONE DESIGN COURSE

At Penn State, the ME department can be divided into two stems: Mechanical Systems—which encompasses Mechanics, Design, Controls, Dynamics; and Thermal Systems—Fluids, Thermodynamics, Heat Transfer, Energy. Reactions to this course have been very polarized, and are highly correlated to these department divisions. Comments included:

- How can you teach design if students don't know the fundamentals of xxx (insert favorite detail here)?
- Design is too touchy-feely.
- This course is not worth three credits; can't we do it in one or two?
- Not technical enough, too much business stuff, you can't teach common sense, we are watering down the curriculum, etc.

Comments such as these illustrate that design as a discipline does not have the stature of engineering science in the eyes of many of our colleagues. Design is a higher-order mental ability, which is part art and part science. It is sometimes chaotic and seldom mathematically elegant. It is a problem-solving mindset that constantly asks several questions:

- What is the real problem?
- What is the best approach? (how to organize and manage the effort)
- I may not get everything I want, but how close can I come? (trade-offs between conflicting objectives, merits versus costs)
- How do I measure success?
- What resources are needed? (time, money, people, new knowledge, raw materials, analytical/computational/experimental tools)
- What are the solution alternatives?
- What has been done before? (previous successes and failures)

This mentality is applicable to virtually any situation where there is a problem and the need for a decision, from the design of a new product, to the choice of a new car.

REFLECTIONS ON ACADEMIA AND CHANGE

By its very nature, academia is not prone to rash or impetuous change. Looking back on the last year, the biggest challenges we faced in improving the Mechanical Engineering curriculum were:

- Lack of consensus on the need for change
- Lack of consensus on what should be in the ME curriculum
- Faculty misconceptions and lack of knowledge about the teaching and learning process
- Lack of incentives and resources to improve undergraduate education

Lack of consensus on the need for change

Despite numerous credible surveys of current students, recent graduates, benchmarking of peer institutions, and input from our industry advisory committee which all point to the need for more active learning and more design skills, several faculty cling to the "if it ain't broke, don't fix it" motto. Today's faculty have been trained in a climate that elevates engineering science and devalues application and anything which cannot be described mathematically. Design is sometimes described as a "soft skill" and is not on the same intellectual plane as, say, compressible fluid flow, or multi-variate calculus. A minority of our faculty have any direct experience in industry. Most went into academic careers directly from graduate school and do not understand the career path that 85% of our students will choose. We are becoming a profession that is taught by non-practitioners.

Recent faculty comments include:

- "What problem are we trying to fix?"
- "Problems in student learning come from lower-level courses (not our courses)."
- "That students do not like a class is not a reason to change."

Lack of consensus as to what constitutes a curriculum in Mechanical Engineering

Mechanical Engineering is a very broad discipline and continues to expand, with new developments in nano-technology and fuel cells, to name just two. We can no longer educate our graduates sufficiently in all of the topics that are traditionally considered ME. We are a diverse department. Each of us has a well-intentioned and firmly held belief as to what should constitute a ME degree. Unfortunately, those beliefs vary widely. Some would argue that compressible flow is essential, while others might go to the matt to defend vibrations of continuous systems. If we were to combine everyone's list of essential topics, we would end up with a six-year curriculum. There is no conceivable way that we can teach students everything they will need to know for the next 30 years of their professional careers. However, we can provide them with a basic core of knowledge on which they can build. Our graduates do need a thorough understanding of some key physical principles. In my opinion, these key principles are Newton's Laws, and the Laws of Thermodynamics. A mechanical engineer should understand the mathematics of these laws as well as their physical meaning, application, social and ethical implications. He or she must also have good judgment, be able to solve problems, and be able to teach themselves all the new skills they will need in the future. We must move beyond thinking of the ME curriculum as a long laundry list of essential and disjointed topics.

- "If I spend more time doing active learning things, I can't cover as much material."

Faculty misconceptions and lack of knowledge about the teaching and learning process

Few faculty have any formal training in education. Those who have no formal training do not even recognize this as a problem, and are not encouraged to improve themselves in this regard. It is virtually impossible to get travel funds to attend an ASEE conference, where they might have heard Rich Felder speak eloquently about learning styles, or Woody Flowers arguing passionately for a more active education. Lecture is the predominant mode by which our faculty have been educated. Most of our professors are where they are today because they learned well and thrived in a lecture environment. This situation would be analogous to giving medical licenses to those people who have survived the most operations.

Unfortunately, most of our students are not as abstract or reflective as we are, and would learn more effectively in more active modes. Dale [11] reports that after two weeks, people generally remember 10% of what they read, 20% of what they hear, 30% of what they see, 50% of what they hear and see, 70% of what they say, and 90% of what they say and do; similar figures are given by Stice [12]. In a large study of Physics courses [13], interactive engagement was found to be superior to traditional teaching methods (passive lecture, recipe labs, algorithmic-problem exams) in promoting conceptual understanding.

- "We should not change the way faculty teach."
- "I have beautiful course notes and I don't want to change them",
- "Students don't want to learn. They can't do fundamental things. How can we teach them higher-level material?" (It's their fault, not ours.)

Lack of incentives and resources to improve undergraduate education

The academic reward system is based primarily on independent research and acquiring grants, not on stimulating learning. All universities are being forced to do more (educate more students, with fewer credits) with less financial resources, making research grants critical to financial solvency. In such an environment, lecture is the most attractive teaching method, despite its pedagogical shortcomings. Depending on your point of view, we are either blessed or burdened with a weak management system. Academic management is sometimes described as "herding cats". While this may allow for individual excellence, it also impedes visionary change, group activities, or working for the greater good of the department. Faculty are independent contractors and zealously defend their "academic freedom".

- "We do not have the space, faculty or money to offer more labs."
- "I am rewarded for bringing in research, not for teaching."

In many ways, our curricula are structured to give the illusion of knowledge. Students are given a superficial exposure to a large quantity of topics and are evaluated primarily on recall and basic comprehension. Quantity of content is stressed over depth of understanding. The higher levels of understanding (Bloom's Taxonomy)—application, analysis, synthesis and evaluation—are left to students to develop on their own. Design can be an effective framework for advancing to these higher levels of understanding. If the goal of engineering education is to produce innovators who can transfer fundamental knowledge to new situations, then the true test of mastery is whether knowledge can be used for design.

Based on many years of personal experience and admittedly anecdotal evidence, I would describe the typical education process thus:

1. Superficial exposure—Because they get high marks on well-posed problems, students are led to believe that they understand the basic principles. They believe that they can go back later and look up the details if they ever need them. Because we make them take five or six courses each term, and are obsessed with the quantity of topics that they must know, students do not have the requisite time to truly

master the material and put it into their own words or thoughts.

2. Reality check—When confronted with a real problem (multiple "good" solutions, ill-posed, missing information, multi-disciplinary, etc.), the student realizes that not only do they not know the details, they really do not understand the analysis principles sufficiently to transfer them to a new situation. At this point, they may resort to the build and hope method, with no analysis like that they see on Junkyard Wars. However, if we have done our job right and have trained them to be lifelong learners, they will go on to the next step:
3. Re-education—At this receptive point, students now have the motivation to go back and convert their superficial exposure into personal, memorable, transferable knowledge. The quality that separates the engineer from the "Junkyard Wars" mechanic is the ability to apply appropriate science and analysis tools, tempered with judgment and common sense.

FINAL THOUGHTS

The 1955 Grinter Report on Evaluation of Engineering Education and the post-Sputnik boom in research funding encouraged a curriculum shift toward more mathematics, engineering science and analysis. Since that time, most universities have followed an approach of fundamentals first, then application later, or after employment. This is akin to the now discredited "toss the design over the wall" product design process, where the marketing department developed the concept, tossed it to engineering, who then sent it to manufacturing. Just as concurrent engineering is now the accepted standard in industry, our goal in education should be to concurrently teach the fundamentals, applications, and an intelligent problem-solving approach (i.e. design). In order to design, one must have a firm grasp of engineering fundamentals, but the best way to learn and remember the fundamentals is to use them for design. Design provides the bridge between theory and application.

Finally, the following long-term goals for engineering education are sought:

1. Provide formal training in education pedagogy, with periodic mandatory re-certification, for all college instructors. (Every professor should receive one week of summer salary to attend an annual teaching methods workshop. Every professor should receive travel funds to attend a national conference on Engineering Education at least once every three years.)
2. Recruit, reward and retain "Professors of Practice". The majority of our faculty have no industry experience, yet 85% of our students earn their B.Sc. degree and get industry jobs. We need more practitioners from industry to bring that experience and perspective into our classrooms. Such faculty are generally more comfortable, qualified and effective at teaching design courses.
3. ASEE should produce a new "Goals for Engineering Education", to stimulate and guide engineering education in the 21st century. The last report is now 50 years old. Other recent attempts at this have yielded many platitudes, but little in the form of actionable direction. This report should document the need to augment the lecture-dominant mode by which we were taught, and which we implicitly perpetuate. It should provide hard data justifying the educational value of such innovations as active learning and open-ended design problems.

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