Learning By Design — What Have We Learned?

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In October, 1997, ECSEL held a workshop in order to assess, and continue to promote, the integration of design throughout the engineering curriculum as a means of renovating engineering education. The workshop was divided into three sessions: A first focused on the use of computers in support of learning by design; the second, on the integration of design into engineering science courses, in particular, courses in mechanics; the third, on industry driven design and manufacturing courses with attention to interdisciplinary projects. Abstracts are presented in an appendix.

This paper is not a "proceedings" of the workshop. Rather it is an attempt to distill out of the different experiences of workshop participants some common themes and to analyze these in as much depth as these few pages permit. Through contrast and comparison of participants reports, I explore the resources required to effect change, the barriers encountered, and the benefits that ensue - to faculty as well as to students. At a still more general level I reflect upon that oft-heard phrase of what we are about — namely, the changing of a culture.

Learning By Design

The appended abstracts describe a diverse set of projects: Some challenge students with "hands-on" confrontation with hardware; others are "paper" exercises. Some are diagnostic activities; others are design tasks. Some promote the use of particular computer tools; others put information processing technology to use but in a transparent way. Even if we restrict attention to those efforts centered on design, looking more closely we find a wide variety of student experiences.

In Theresa Mayer's introductory circuits course at Penn State[1], the syllabus is centered on a series of modular lab exercise which provide students with the background needed to design and build the electronic stages of a compact disk player. In Bill Fourney's pilot section of Statics and Strength of Materials at the University of Maryland, a semester long design project establishes the backbone for the syllabus; the usual topics of the subject are addressed as they are needed in a just-in-time mode. Michel Ghosn at CCNY also includes a semester long design project in an engineering mechanics course[2]; his civil engineering students carry out a first-cut design of a steel-concrete bridge according to AASHTO's standards. Louis Bucciarelli at MIT[3] and Shahram Zanganeh at Howard[4] use short design exercises throughout the semester, again within courses in statics and strength of materials. At Penn State, Nick Salamon in a course "Introductory Strength of Materials" assigns a semester long paper design project[5]; in addition, the students are challenged with short design exercises which, like Bucciarelli and Zanganeh, are constructed from traditional single-answer problems found in the textbook.

Other student design projects engage students outside the regular curriculum: One group at Howard, working with industrial sponsors, designs a solar car intended to compete in an annual, national competition. Another, under the direction of Bob Efimba in Civil Engineering, designs and builds a steel bridge; they too compete with others at the national level. Two student teams at CCNY do interdisciplinary design projects at the capstone level under the direction of faculty from three different engineering departments.

Still other ECSEL educational renovations make “hands-on” activity the core of a course. Vipin Kumar’s Product Dissection course at the University of Washington[6] sets the students down in “The Learning Factory”, a space filled with work benches, tools, and support staff, and leaves them free to disassemble a camera, an engine, a handgun, and a product of their own choosing; their aim is to analyze and understand how these devices function and how they were made. The Learning Factory itself, a collaborative innovation of ECSEL schools Penn State, University of Washington, and the University of Puerto Rico and Sandia National Laboratories funded under the ARPA Technology Reinvestment Program as well as NSF7, provides a broad base for undergraduates and faculty interested in design and manufacturing of industrial products. It’s resources and facilities are not set by a specific manufacturing course but open and flexible to allow a variety of educational uses, e.g., design, dissection, product development.

Product dissection can be coupled with design in the from of redesign: Guangming Zhang, at the University of Maryland, in his industry-driven course, has his students first take apart and analyze the workings of a Black and Decker hand drill, as did Vipin Kumar at the University of Washington, but then the students go on to propose and carry-through a redesign of one component of the device.

This variety of educational projects requires a variety of levels of enabling resources. A design task that encourages or requires students to make use of computer and information processing tools demands that all students have access to comparable machinery. Costs can vary according to software portability, licensing fees, hardware and networking requirements; to what extent students share that cost through fees or purchase of hardware and software, is variable. Setting up and staffing a Learning Factory requires significant commitment of capital expenditures including space which at many of our institutions is at a premium. A circuits course which asks students to progressively build the electronic components of a CD player requires less of an investment. A product dissection course can be run without machine tools and space can be of a more common laboratory variety if the product to dissect is chosen wisely. Coupling with industry brings in resources but also, as Guangming Zhang reports, requires significant investment of faculty (and students’) time and energy in establishing and maintaining the collaboration.

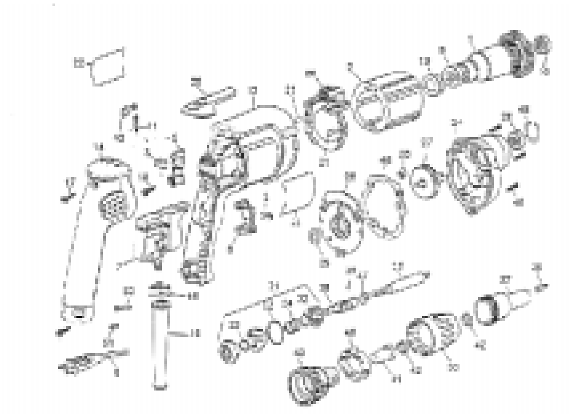
Building a scale model or prototype may require less resources but just as much planning. Certainly the competitive, extracurricular design projects - the solar car, the steel bridge - require funding as well as facilities. Jonathan Allen, the student leader of the solar car design at Howard, reported how fund raising was one thing he learned a great deal about in the course of the project. Faculty also must commit to help students in these projects, often with little formal recognition. Paper design exercises would seem to be the least expensive to sustain, requiring no more than what is already available to us in our current teaching. This mode of integration of design requires the largest institutional investment - in faculty able to plan, manage and evaluate a design task.

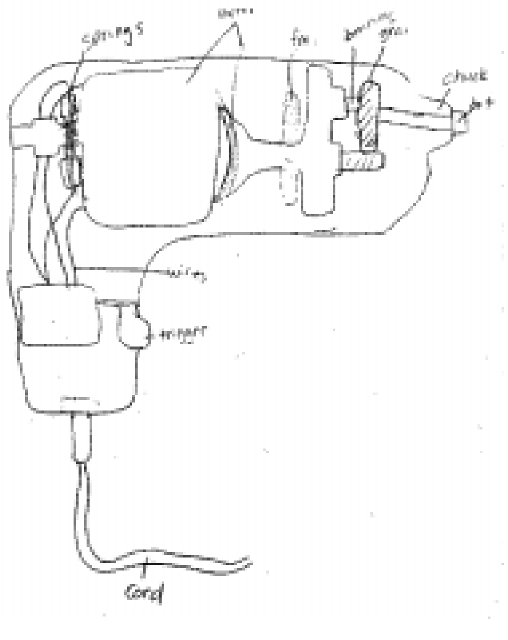
Despite their diversity, all of these efforts have a common characteristic that make them significantly different from traditional teaching modes and offer the potential for leveraging a changing of our culture. They are all *open-ended*.

How is this significant? The argument here is that the reform of engineering undergraduate education is *not* primarily a matter of new laboratory equipment and space, instrumentation and rapid prototyping machinery, nor of computer systems, networks and software — although a good dose of these will be required — but first and foremost it requires a rethinking and redoing of our objectives, and a reform of content — the stuff we teach — and of context, —the way we teach and relate to students. These are tightly coupled. The second part of the argument is that one way to achieve this transformation is through the infusion of open-ended exercises throughout the curriculum.

"Open-endedness"

What do I mean by "open-ended": Product dissection is open-ended in that, although the object is real, "hard", and apparently all there, faculty must constrain the task, suggest, if not prescribe, certain questions to ask, and limit the extent of students' investigations and activities. Consider the power tool of figures 1and 2; although both depict quite similar products, the way Guangming Zhang and his upperclass students of Mechanical Engineering see the object (fig. 1) is different from the way Vipin Kumar and his students see the drill (fig. 2)





These reflect a difference in objectives. Vipin Kumar's objective is to move students to understand how the drill works and something about its fabrication and assembly; an appropriate objective for an introductory course. Guangming Zhang has a more far-reaching objective; he wants his upperclassmen to go beyond understanding of the tool's fundamental workings to explore how it might be made to work better. He limits the context too, however, in that students are asked, not for a redesign of the entire object, but of one component. On the other hand, he stretches the context to include the "real-life experiences" of Black and Decker employees responsible for new product development.

The point is that the same object, lying there on the bench, can be used in different ways in defining *content*, what it is we want students to learn, and in fixing the nature, the *context*, of the student's experience. All of this depends upon our objectives.

Just as significant is the open-ended potential of the experience: When you present a team of students with a hand drill, set out on a work bench in front of them, give them a box of tools, and ask them to figure out how it works, things are liable to get out of control. No matter how well you have planned, or how much experience you have from past years, some students are likely to want to explore beyond the bounds you thought you had set. Now, in contrast to the usual exercises we assign - so tightly constrained by theory and admitting but a single correct response - we can not easily legitimately deny the student's questions and probes. We have, in effect, by laying out the task in terms of a functioning power tool, given students license to creatively explore beyond the constraints we had set. The task of figuring out how it works, just as the task of redesign of one of its components, is open-ended; the multi-facetedness of the drill assures that.

This freedom and flexibility in how we see an object like a hand drill is more apparent when we consider the perspectives and interests of different engineering disciplines. Vipin Kumar and Guangming Zhang are both teaching within a mechanical engineering curriculum. Figures 1 and 2 show the spatial arrangement of physical components. Theresa Mayer's representation of another electro-mechanical device, the CD player her students design and build over the course of a semester, takes the form of a block diagram. No material components here - just boxes with labels "D/A converter Buffered Output", "Amplifier and Level Shifting".... We can imagine what the circuit diagrams would look like for each subsystem. We can also imagine what an electrical engineer's explanation of the workings of a hand drill might be and look like, what questions he or she would ask, what tools and instruments he or she would need, what circuit diagrams he or she would draw and how all of this would differ from the productions of a student of mechanical engineering. So the "open-ness" of the exercise, if presented as a single question - "How does it work?" - is considerably more than we might first imagine when thinking from within the context of a single discipline.

There is still yet another aspect of product dissection, not embodied explicitly in the hardware, that provides an opening to learning about another way technology functions. In the dissection of a handgun, one of the tasks a team of students selected in Vipin Kumar's course, it would not be out of bounds to have students explore why there is no safety lock to prevent accidental firing, say in the hands of children. This might naturally lead to study of the role of codes and regulations in the product development process. From there it is but a small step to exploration of the processes whereby codes are set or of the political interests that drive regulations. The issue need not be so dramatic; a product dissection of a power tool can provoke a similar discussion of occupational health and safety requirements, for example.

Design exercises offer the same flexibility and freedom, even if they are restricted to conceptual designs and elementary sizing activities. Here it becomes more apparent that there are various degrees of open-endedness. A slight variation of a text-book problem which asks students to vary one parameter is not really open-ended. It leaves little to the imagination of students, allows students and faculty little freedom to shape and negotiate the design task, to develop a strategy for addressing the task, or to take seriously the concerns of other disciplines, including social interests and needs. While it might be labeled a design task, it is design in the very small sense of the word. It is not open-ended in the way this phrase is intended here.

Open-ended means that boundaries around the task we set students are relatively fluid and diffuse. In the truly open-ended design hands-on or product dissection task the student has considerable freedom to experiment with ideas, to try different approaches, and to make use of a variety of resources relative to the way they should behave when challenged with a tightly constrained traditional single-answer exercise. Implicit in the traditional mode is the idea that what is contained in the textbook and lecture notes is all that is needed to solve the assigned problems; a corollary to this is that what is *not* covered in the course is *not* important. This is why curriculum committees spend so much time arguing over what is to be left in what to be left out; why the traditionalist's first question in response to your proposal to integrate design exercises into the engineering mechanics course is "...what are you going to leave out?" Not to say that something is not left out; it is a matter of objectives and priorities. Nick Salamon reports how in order to make room for design in their mechanics course at Penn State, faculty decided to leave out Mohr's circle for strain and energy methods.

In an open exercise, where student initiative is encouraged, indeed, required, what is important to the task is not clear from the start; it is the responsibility of the student, in part, to figure out what is important, what is significant, what can be neglected, what analysis tool to use, how crude a model might give useful results. Deciding what is "left-out", in the sense of not explicitly specified in the initial problem or project statement, is in part the responsibility of the student and must be engaged as part of the exercise. Bill Fourney, in his pilot section, has students formulate a design task, choosing among several possibilities, then he sets the curriculum. What statics and strength of materials content is important and stressed in the course is shaped by the design task. Fourney makes sure he touches all the fundamental bases but the context is different now; science is not the driver.

The distinction between traditional and open-ended exercises is not between hard, rigorous analysis and soft, loose thinking. To deal with an open-ended exercise, with or without hardware, requires rigorous thinking and action but the domain is less narrowly constrained. In provoking and requiring students to exercise judgement, to estimate, to pose and consider alternative solutions and approaches when there is no single answer or approach is not asking them to think loosely. On the contrary, more discipline is required. The student must judge when to stop a trial solution if it doesn't seem to be headed for a payoff. This requires both the discipline of knowing the limitations of theory as well as its scope of application and the discipline of self, i.e., to turn to someone or someplace for help when needed. In our engineering science courses we have *over-disciplined* our students, deadened their willingness (or need) to take the initiative and responsibility for learning.

Changing the Culture

In making open-endedness the major theme of our renovation of undergraduate engineering education, we can promote active student learning, teamwork, better communication skills, multi-disciplinary competencies — all that we now deem essential to preparation for professional practice. It also can be the lever for changing our culture. But what can this mean? What do I mean by "our culture"?

First, I do not mean *culture* in the sense of “high” culture. Rather I mean culture in the sense of ordinary day-to-day tasks, activities, conversation, and thinking as we go about our research, consulting, meeting, emailing, fund-raising, and teaching in and around the university. In this we share core values and norms in the sense of “If I think that *x* is the important point in my discussion (description, test...) of *A*, then my students (colleagues, contractor, dean...) will respond with *y* which then takes me to *z* — and not tell me that there is no such thing as a frictionless pin or claim we shouldn’t be doing a product dissection of hand-guns because they do or do not kill people. We share tacit understandings of what is serious, significant, and worth teaching; what is not useful, unimportant, and laughable; how to speak, to listen; to read an instrument, estimate a magnitude, how much time to spend on a problem, when to stop taking data.

Culture is about how we “see” and frame the “real world”. We talk about making our teaching more relevant to real world practice. But what is *in* the real world, what it *is*, depends upon our beliefs about what is most important and what interests us — in short, upon what we value. As we have already noted, an electrical engineer and a mechanical engineer looking at a CD player or a power drill may not “see” the same thing. The two have different interests.

Yet there are other ingredients of the real world that don’t even enter our field of view. Consider marketing surveys. These are part of the real world too and those responsible for conducting the surveys and drawing out their implications will tell you that they are as essential to the design process as any mechanical or electrical component. But it seems they do not play as significant role in our culture as in that of the business school across campus. They do not interest us as much, we do not value them; market analysis remains someone else’s responsibility to cover and to teach.

The ways we represent and structure the fundamental concepts, principles, and ideas within the courses we teach also reflects values. We stress the power and generality of abstract theory in application to engineering systems. We hold that it is absolutely essential that our students understand the fundamental underlying concepts and principles of the flow of a fluid, the thermodynamic cycle, the behavior of a structure under load. The hierarchy and authority of theory entrains a correspondingly structured context for learning not to mention the organization of faculties into departments with boundaries fixed more or less by disciplinary foci.

Embedded, as we are, in this culture, it is very difficult to see how it could be otherwise. Yet educational experiments can do so, can provoke and prompt reflection on how things might be changed to better our ways of preparing youth for engineering practice (and beyond) if we are open to the possibility. The thesis here is that open-ended exercises can provide leverage for change. Symptomatic of this possibility are the ways in which truly open-ended exercises challenge our traditional ways of teaching, our traditional beliefs, norms and values as sketched above. I draw upon some reports of the workshop.

Open-endedness - a lever for change.

Consider, for example, the reference to marketing, how we normally ignore its place in engineering practice. When we reach for stronger ties to industry and invite them to participate in the planning and conduct of a *New Product Development* course, as does Professor Zhang at the

University of Maryland, and key engineers from Black and Decker stress the importance of customer needs, of marketing considerations, and describe the “real world”, hard-nosed nature of the constraints they face in this regard, our framing of what is significant in the real world changes. Our vocabulary changes. What was “soft” is now, if not “hard”, at least must be taken as seriously.

Or take our usual acceptance of the hierarchy and authority of segmented disciplines, how they structure the student’s classroom experience and our ways of relating as faculty. In the real world, functioning as an engineer is very much conditioned and constrained by context and that context is ordinarily complex and multi-disciplinary. The tasks engineers face do not appear as well defined, single discipline, problems. The real world is more of a muddle. Professor Yiannis Andreopoulos reports how complex curriculum reform becomes when he attempts to teach an Interdisciplinary Integration of Design course at CCNY. Getting different academic departments to work together becomes a significant design task in itself — a challenge to our ordinary ways of doing business which prompts the thought that changing of our culture might require significant organizational change.

If the organizing theme shifts from theory to application and application in context, then the neatness and compactness, of theory looses its grip. Peter Chang’s proposed revision of syllabus for statics and strength directly confronts this problem. His course is based on a design project; students set goals and milestones then faculty shape their lectures and demonstrations to support the students in their efforts to meet those milestones. Theresa Mayer’s introduction of a semester long project redefines what ought to be included in a circuits course; so too Michel Ghosn’s and Fourney revision of their mechanics courses.

Another problem arises when we recognize the importance of teamwork to engineering practice and form student groups to work on a design project in a manufacturing course, as does Professor Jorgensen at the University of Washington, or in a pilot section of a statics course at the sophomore level as does Professor Fourney and the University of Maryland, our traditional cultural norms about grading are challenged. How do we evaluate the individual student’s work when he or she is a member of a team? How much responsibility for ensuring the harmonious working of the team should we as faculty assume? Who should break up and assign tasks? Here again, once we break away from our traditional moorings, rooted in the notion that it is individual achievement as individual that matters, we confront a challenge to our values. Yiannis Andreopoulos did not dis-aggregate the design. Rather in his interdisciplinary projects he tried to get students to learn about other disciplines on their own.

Problems of evaluation arise with an open-ended exercise even though teamwork may not be the assigned mode. Grading a single-answer quiz is relatively easy compared to evaluating an individual student’s work on an open-ended project or exercise where there is no single answer or even a single approach. A student, in order to get a good grade, must then justify their approach, assumptions, and document their work. The emphasis is on communication skills; it is no longer the responsibility of the grader to check off the answer and read into the student’s work the missing steps. But we, as faculty with our focus on the tightness of theory and unique solutions to the problems we customarily assign, may not be accustomed to such openness. If we ask our students to take more responsibility for learning and nurture as positive a student’s formulation of constraints and the problem, then our traditional ways of evaluating are challenged. The emphasis of evaluating a student’s “portfolio” as allowed in ABET 2000 reflects the possibility and need for change in the way we grade students’ efforts.

One universal problem stands out regarding the use of open-ended exercises: All faculty agreed that the exercises “...take more time”. Peter Ganatos related how student designing their own simulations using Knowledge Revolution’s Working Model in a dynamics course took more time that they at first thought would be required. Leaving aside for the moment the additional time it takes for faculty to deal with these sorts of exercises, this was the universal student response - open-ended, design, hands-on, product dissection exercises — across the board — take more time. Yet there was a curious aspect to their responses when students were asked about work-load. It wasn’t clear how to assess this complaint, indeed, whether it should be considered a complaint at all.

For example, consider the response to Yiannis Andreopoulos’ interdisciplinary design project at CCNY - students reported the design task took more time and effort, a good bit of this expended to learn about matters outside of one’s own discipline, but they would recommend the course to other students. Or Vipin Kumar, who related how his students displayed such enthusiasm during the quarter while reporting at the end how much more time they had to commit; and his course evaluations went way up.

Shahram Zanganeh’s summary of difficulties he encountered in the integration of design exercises into his mechanics course included one bullet which gives a different twist to this complaint:

“Difficulties... 2. Students may get carried away and do not want to stop working on a specific problem”

Is it not surprising that we consider it a *difficulty* if students get actively interested in an assigned problem? Not really since for students to take an active interest in learning is outside the traditional norm of expected behavior! Ordinarily students are expected to do the assigned homework, and not question assumptions, alternatives, or fundamentals; the drive is to get the right answer, and almost always the *single* right answer; expending extra effort in any other way goes unrewarding. Open-ended exercises provoke questions about our expectations of students, our objectives.

The author had a similar perplexing experience at MIT using short open-ended exercises. While I try to constrain the exercise so that students will not spend more than 3 hours outside of recitation, still some actively pursue some one or another feature of the task that interests them and their journal entries appear correspondingly lengthy compared to what most submitted and what was required. Should I give the student extra credit because she did more than I expected? If I do so, am I not penalizing the other students who did a fine job in meeting my expectations? Again, a challenge to prevailing norms of undergraduate engineering education - again, how we evaluate their efforts.

A similar paradox becomes apparent with the project centered activities at Howard - the solar car and steel bridge projects. In one video clip we see a student reporting how he learned more from his bridge project than any course he had taken. Yet do we reward the student with academic credit? If so, it is ordinarily not of the mainstream type. Clearly we have a tension with traditional values occasioned by the introduction of an open ended exercises.

One particular technical challenge of our present predicament needs addressing. We have witnessed an explosive and dramatic change in the tools available to us to do our work. How does this challenge us? How do we make effective use of this technology? How does it fit with open-ended learning?

Computers in support of Learning By Design.

We have already noted the problem of providing students with the resources to make effective use of computer and information processing technology. The problem of equitable access is real. But there is another problem due to the instability in the quality and capabilities of all of this machinery. This is due to the rapid pace of development as measured by processor speed, memory capacity at every decreasing unit cost (or so it appears), and the reach of local and global networks. The technology never seems to stand still long enough to entice engineering faculties as a whole to invest time and energy into adopting and developing a piece of this technology for teaching purposes.   The question of what hardware, what software ought we as a body invest in and require of our students seems to be unanswerable in this context.

Despite these problems, we are testing the waters, experimenting with web-based interaction, student use of powerful computational tools and simulations, even group interaction over a network. And just as efforts to introduce open ended exercises provoke challenges to our traditional ways of teaching, so too here we find questions arise that require a new way of framing what it is we are about.

Several participants at the workshop reported how quick students were to make use of the web, if given the slightest encouragement. With license to roam beyond the traditional bounds of the textbook and lecture notes, they, on their own, will search out data and/or information that might be of use in their product dissection task, conceptual design exercise in an engineering science course, or more detail design and prototype building in a capstone design course. The web becomes a giant database; it can be a place where students independently meet one face of the real world infrastructure of engineering practice. But again we confront a challenging to our traditional norms for we are used to being in full control of course content. If students, using this resource can learn something we don’t know, we become uneasy. It is not just that it may call for additional effort on our part to validate the information found (the quality of web based materials is an open question) we, in a sense, have lost control. The web challenges our authority or at least can put it to the test if we encourage its use.

This same hazard (from our traditional perspective) appears when we introduce students to computational tools that can model systems having sophisticated properties and many degrees of freedom. When Oral Buyukozturk in a design course within civil engineering has one student group design, making use of off-the-shelf software, a composite structure for a building sited in Boston, another group design the same building but for San Francisco and a third for Puerto Rico, he must orient students to the proper use of the tool. While making sure they are left with the freedom to conjecture and evaluate alternate designs, he must, at the same time, be prepared to limit their explorations and remain on guard to critique their misuse of the tool. This mix of new found freedoms and new forms of constraint call into question the one-way transmission of knowledge model of engineering education.

Peter Ganatos in his computer based dynamic simulations shows students how a mechanical system can sometimes go unstable. But how much time should he take explaining the nature of the underlying numerical instability to students? How to ensure they learn to distinguish an instability in the physical system from that due to a hidden numerical method? This kind of question ordinarily does not arise at the sophomore level; as such it can provoke further questions about what ought to be in the syllabus. Content and context are intertwined.

Modern information technology also allows for group work, and group work at a distance, in an asynchronous mode. John Weller at Univ. of Washington[8], puts the work of last-years' students up on the web and encourages current students to see how they fabricated, assembled and tested a Stirling engine in an introduction to manufacturing course. (www.me.washington.edu/~me304). Contrast this policy with the traditional concern about students "copying" homework solutions from their living groups unofficial archives. Open-ended projects, if truly open-ended, make copying fruitless.

Shahram Zangehan reported on his experiences using Mathcad with students in a Statics, Strength of Materials course. Students could do as much as they liked using this tool, even using the graphics tools to draw a kinematic diagram, an isolation of the system or free body diagram. Nick Salamon of Penn State, also involved with the use of a design project in his course, critiqued this use, claiming drawing an isolation of a system requires thinking while drawing - suggesting that there is a symbiotic relationship between thinking and sketching. Shahram responded by reporting that students develop a facility using the tool so that they indeed can spend their time thinking about the physics of the problem not burdened by thinking about how to operate the tool. Is this possible? Are they learning the same fundamentals but in a different way? What of the old are they not learning? What new fundamentals are they learning?

Even what appears as a straight-forward application of the computer as a drawing and visualization aide can prompt similar questions. Diana Johnson and Erik Rebeck, two student instructors at the University of Maryland led off the workshop describing how they introduce freshmen to Pro/Engineer. Their students in short order are able on their own to use this powerful tool to their advantage. More than a CAD drawing tool, they report how the underlying feature-based strategy of Pro/Engineer replicates thinking on the shop floor re machining operations, assembly, and the like. Resonances with object oriented programing are also apparent. Students are learning more than how to use a computer to draw. They are developing a new way of framing and thinking which goes hand-in-hand with mastery of the tool.

All of this is meant to illustrate that the challenge of making effective use of computer tools and information processing technology is a challenge to our traditional ways of thinking about what is important to teach and how best to engage students. If we think only in traditional terms, if we seek to use this technology as a way of improving our teaching efficiency (putting a syllabus on the web, simulating the behavior of the simplest systems...) without changing the content of what we teach, without loosening the constraints and opening up the boundaries of the student experience, adhering to the transmission of knowledge mode, we are not likely to realize the potential of this technology. The concerns about student understanding what is going on inside the black box are real and important to be addressed. But we short change ourselves if we don't explore, test, encourage student use of computer and information processing technology in creative ways.

The challenges we face in putting this technology to effective use are threefold according to Nick Salamon of Penn State: We must (1) seek ways to transform and present the theory and fundamentals of our subject matter so that our teaching might put computers to use in ways that take advantage of their power; we must (2) continue to improve on software so that the learning curve students (and we) confront is compatible with the time we have available and the software truly aides students in understanding the fundamental concepts and principles of our subject matter; finally we must (3) strike the right balance, the right mix of computer power and pencil-and-paper thinking.

What have we Learned?

ECSEL remains convinced of the value of open-ended projects and designs, project centered, hands-on learning as a means for the renovation of undergraduate engineering education — throughout the curriculum. The most common and encouraging result of our experiences has been reports of transformation of the classroom or laboratory ambience from passive stares and/or feverish note-taking to active student participation taking things apart, arguing over constraints and specifications, explaining themselves to their teammates, sketching, experimenting, modeling, reporting. We have learned that students will take a more active role in learning if given the opportunity.

And this is not just the “good” students. In fact, once the students sense that the field is open, that their ideas and insights or even faulty intuitions will be listened to (and corrected if the latter), then *all* students are more inclined to participate in the task at hand. This too we have learned.

We have also learned that the use of open-ended,...etc exercises often reveal much more about what the student has *not* learned than what traditional exercises reveal. If the student is required to take the initiative in the formulation of an exercises, develop a strategy for dissecting a product, construct a spreadsheet for testing the effects of varying a parameter, then a wider range of student abilities are put to the test. The inability to sketch a free body diagram, lack of understanding of hardware, failure to keep track of dimensions and units, mindless acceptance of results which are off by a factor of 100, inability to organize their work or explain it to others, all of this comes to the surface.

This points to one of the major problems encountered in the use of such exercises. Evaluation of the students efforts takes more time and attention. If there is no single answer or appropriate method, then evaluation of the student’s process becomes all important. Note also, to say there is more than one answer or method does not mean that some responses are not better than others and some, even many, may be plainly wrong.

We have learned that students take to the use of computers and information technology without fear, for the most part. They are, as Neal Willoughby stated, a “push button” generation. But this raises problems too. Considerable discussion about the challenges of incorporating this technology into our teaching surfaced at different points in our workshop as has already been noted.

We have learned that a good part of this cultural change we are about is redefining our role as educators. It no longer suffices to be the authoritarian lecturer, font of all knowledge and our students the sink. Vipin Kumar reported how, the first time teaching his product dissection course, he was filled with anxiety, concerned that he wouldn't be able to answer every student's question. Only after mid way through the quarter did this loosen - he realized he didn't need to know everything, indeed, no one could know everything about the system. But he could guide students effectively. In ECSEL we speak of moving from teacher, as lecturer and source of knowledge, to educator as "coach" who guides and advises, provokes the right kinds of questions, still in the lead, out front, but in a different way.

We have learned that evaluating the effects of the changes we have made is not easy. Peter Chang reported that he could discern little significant difference in the way his students perform in the next (traditional) course. Vipin Kumar reported the enthusiasm of his students but could not fully specify what they had learned. Michel Ghosn reported that his students seemed to perform better in subsequent courses when compared to transfer students who had studied strength of materials at some institution other than CCNY.

Data on retention due to the freshmen design courses is more positive and convincing. And at higher levels, although the open-ended courses are more work, students tell other students to enroll. On the other hand, Theresa Mayer reported how one student discovered that electrical engineering was not for him after taking the project centered circuits course. But why isn't that a successful outcome? Again a paradox, a challenge to traditional thinking. Retention can be a bad thing if it strings students along to believe that engineering is solving single answer problems and excelling on the final exam.

Indeed the whole push to evaluate efforts aimed at the reform of engineering education in traditional "scientific" language is, to my way of thinking, misguided. If our purpose is to change the culture of engineering education then we ought not to use traditional measures of student success, i.e., success on the next closed book, single answer exam, as a measure of change in culture. We need new measures of student performance. It's a chicken and egg problem. As necessary as science is to engineering practice, it ought not, can not, be the basis for evaluation of educational innovation if we deem that requires a change of culture.

Appendix - Workshop Abstracts

SESSION I Technology in support of Learning By Design

Learning by Design & Pro/ENGINEER
Diana Johnson, Erik Rebeck, Mechanical Engineering, University of Maryland

Teaching industrial CAD/CAM software systems to accomplish "Learning by Design" represents a unique approach to improve and enhance the effectiveness of undergraduate engineering education in preparing our students for life-long productive careers. Experience gained from teaching Pro/Engineer, a leading computer-aided design system used by industry, in design-oriented courses has given the freshman students an early start in developing their career skills.

Computer-Animated Teaching Software for Engineering Dynamics and Mechanical Vibration
Peter Ganatos and Benjamin Liaw, Mechanical Engineering, CCNY

Beginning in Fall 1994, we have introduced computer-animated modules in our undergraduate Dynamics course intended to help the students visualize and obtain a better understanding of important concepts. Working Model, commercially available from Knowledge Revolution, San Mateo CA, is menu driven and allows the user to create mechanical systems on the screen with a mouse. Several illustrative modules have been developed covering a variety of topics. Students were also given specific topics and asked to develop their own modules. We describe selected modules, students' reactions, and dissemination efforts.

Computer Tools for Structural Analysis and Design in Civil Engineering
Oral Buyukozturk, Civil Engineering, MIT

Commercially available software for structural analysis and design is not well suited for undergraduate use as the learning curve is too formidable for the time available in a typical 3 hour course. We have evaluated commonly used commercial software packages and identified some (SAP90, STRUDL, PCI-Build) more suitable, in terms of flexibility and graphic interface, for student use. Documentation has been prepared so students quickly learned how to use the software exploring innovative solutions to open ended design problems. Case studies include: reinforced concrete frame structure (MIT Biology Building), a prestressed concrete bridge, a steel office building, a steel crane structure, and other special structures (CITGO sign in Boston).

MATLAB, ANSYS and SPSS for open-ended teaching in Static/Dynamics
Neal Willoughby, Morgan State

A major goal is to prepare students for their senior projects, and ultimately for engineering practice, utilizing state of the art computer and information processing tools to perform “real-world” design.

SESSION II **Learning by Design in Engineering Mechanics and More.**

Integration of Design in Engineering Mechanics Courses - A practical Approach
Shahram Zanganeh, Robert E. Efimba, P.E., Howard University

We present a practical approach to emphasize design concepts in engineering mechanics courses. We do this via simple open-ended problems and team design projects. We discuss the advantages and difficulties associated with open-ended problems and team design projects. We use Mathcad to facilitate the transition from traditional teaching methods to a fully integrated computer approach. We present examples to illustrate the advantages of using Mathcad and how this supports the integration of design. We discuss the required resources for implementation and dissemination.

*Designing With Computers In Mechanics Courses*s
Robert E. Efimba, P.E, Shahram Zanganeh, Civil Engineering, Howard University

Building on the infusion of design in the freshman year through the ECSEL-sponsored Introduction to Engineering course at Howard, a two-pronged approach is used to sustain and promote learning by design throughout the four-year engineering curricula in mechanics and other courses. Other efforts, including computer-based assignments, field trips to local construction sites, and the AISC National Student Steel Bridge Design and Construction competition, are used to engage and captivate student interest through learning by design. We show a brief AISC video of the 1997 AISC competition, with comments on Howard's participation and remarkable achievements.

Learning By-design CE 332 - Mechanics Of Deformable Bodies At CCNY
Michel Ghosn, Civil Engineering, CCNY

CE 332 at CCNY is designed to teach undergraduate students of the Civil Engineering Department the basics of mechanics and strength of materials. Over the last three years elements of learning-by-design have been introduced into the course. - experimental investigations, writing of engineering reports, development of computer programs to assist in analysis, structural analysis package (e.g. SAP 90). This year, these elements are being linked together into one major “design project” - the design of a composite steel-concrete bridge following AASHTO's standard specifications. Evaluation of the efficacy of “learning by design” is under preparation by comparing the grades of students who passed CE 332 to those of students who took this course outside the CCNY CE department. Preliminary results to be presented.

Progress Towards A Project-driven Combined Statics/mechanics Of Materials Course.
Peter Chang, Bill Fourney, Ken Kiger University of Maryland

The College of Engineering at the University of Maryland is currently in the early stages of redesigning its statics and mechanics of materials curriculum into a combined year-long course centered around a group design project. The intention is to move students to take responsibility for learning the technical content required by the project and to enhance the strong links between statics and strength of materials, traditionally taught as two different courses.

Mechanics Reform in Introductory Strength of Materials
N.J. Salamon, F. Costanzo, R.S. Engel, A. Segall and G.L. Gray, Penn State

Our objective is to stimulate learning engineering mechanics through realistic application of theory via engineering design and the use of computers. While our efforts impact all mechanics courses, we focus here on the introduction of design into the traditional, lecture format, introductory strength of materials course. The new syllabus dedicates six classes to design and includes a sequence of paced milestones that students must pass to complete the design project. The project is worked on by teams of 3 to 4 students over an eight-week period. Numerous other lectures include design content by “inverting” example and homework problems from analysis - with geometry given - to design for geometry - with performance given. Room for new material was made by combining related topics, revising the delivery of existing topics and dropping two topics (Mohr's circle for strain and energy methods).

Learning By Design In Circuits And Electronics
Theresa S. Mayer.Electrical Engineering, Penn State

A four-credit hour, sophomore-level core course, “Circuits and Devices” (EE 210) has been revised to provide an integrated, design-oriented approach by combining lecture material and lab experiments. A series of modular labs has been developed to give students the background needed to design and construct the electronic stages of a simple compact disk (CD) player during the final weeks of the course. Each week, a new circuit concept, is introduced in lecture and lab by relating it to a functional block in the CD player. Modules used in the final design include analog voltage amplifiers and buffers, a volume control circuit, a volume display circuit using light emitting diodes (LEDs), a 115 V power supply using a filtered half-wave rectifier, and a push-pull power amplifier. The four-credit sequel course, “Electronic Circuit Design” (EE 310) is also being revised with an emphasis on design in lecture and laboratory to enhance student understanding and motivation, and hence the learning of the subject matter.

Integration of Design In Statics and Strength of Materials
Larry Bucciarelli, MIT

I describe the effectiveness of using six short “paper” design exercises in teaching statics and strength of materials to sophomores in civil engineering. The design exercises are open ended. Their purpose is not to teach design per se but to move students to appropriate the concepts and principles of the subject by putting them to use. Students keep a journal (written in ink, no erasures) to document their approach. I encourage students to use the web for data and other concepts, a spreadsheet for evaluating sensitivity to parameters, matlab, the two dimensional, truss and frame matrix analysis tools I have developed. I describe how use of open-ended exercises, together with emphasis on process, reveals student misunderstandings that would go undetected in a traditional course.

SESSION III **Industry Driven Design**

Interdisciplinary Integration of Design at CCNY - A Progress Report.
Yiannis Andreopoulos, Mechanical, Irv. Rinard, Chemical, and Vasil Diyamandogolu, Civil Engineering, CCNY

Three faculty from three departments and ten undergraduate students are participating in this experiment in the integration of multidisciplinary design into the three departments' curricula. Two design projects have been undertaken as part of already existing senior design courses. The first project focused on the design of a chemical miniplant for the environmentally safe production of hydrogen cyanide. The second focused on the design of chlorine disinfection systems for domestic wastewater treatment. Although the experiment is still in its initial stage, already we recognize significant administrative and managerial barriers inherent in our approach due, in large part, to constraints and conditions imposed by existing curricula. While all students found the workload twice as heavy as students in the regular design projects, most still would recommend the interdisciplinary design experience to other students.

Teaching New Product Development through -a Product Engineering Approach
P. Cunniff, J. Dally, L. Schmidt, and G. Zhang, Mechanical Engineering, University of Maryland

We describe experiences gained in teaching a new course aimed at providing junior-level undergraduate engineering students with the fundamentals needed in developing new products. Through a partnership arrangement with Black &Decker, a new product is introduced to the class. Engineers from B&D present a series of lectures on some their real-life experiences developing the product. The students work as teams to complete assigned course projects related to the new product development. We have received an extremely positive response from the participating students.

I*ndustrial Support for Design of Composite Materials*
Mairead Stackpole, Materials Science, University of Washington

HUSVT - an Experiential Approach to Engineering Education
Lucius Walker, Jonathan Tucker, Howard University

Interdisciplinary, industry driven design, has been explored at Howard through our efforts to enter Sunrayce 97. While not meeting the competition deadline, the project provided a wide range of valuable educational experiences to an interdisciplinary team of faculty and students from engineering, architecture, fine arts, business and communications and introduced students, through first hand experience working with industry, to the challenges and complexities of project management, scheduling, costing and fund raising.

Product Dissection: How Things Work
Vipin Kumar, University of Washington

A new course and laboratory was developed in Spring of 1997. The students, all sophomores, dissected a mechanical pencil, a hand drill, and a lawn-mower engine. In addition, they carried out a three week project in which an item of the students own interest was dissected.The course was enhanced by participation from UW's Center for Instructional Research who encouraged working effectively in groups. Students creativity and enthusiasm exceeded all the instructor's expectations.

Sterling Engine As A Project In Manufacturing Course
Vipin Kumar, John Weller University of Washington

The Learning-by design concept was extended to the introductory manufacturing course by introducing a quarter-long fabricate-and-assemble project.The usual set of laboratories and demonstrations were suspended. Each section of 14 students produced and assembled one engine consisting of 30 components.The project provided opportunity to incorporate teamwork, project management, and a feel for the relationship between tolerances, fit, and function.

Industry-Based Projects in Academia - What Works and What Doesn't
John Lamancusa, Penn State, Jens Jorgensen, U. Washington

In June of 1994, three universities and a national laboratory (Penn State, the University of Washington, the University of Puerto Rico-Mayaguez, Sandia Labs) formed a partnership, under the auspices of the Technology Reinvestment Program (TRP) of the Advanced Research Projects Agency (ARPA). This partnership - (MEEP) Manufacturing Engineering Education Partnership - focused on injecting a stronger manufacturing emphasis into the engineering curriculum, with a strong industry connection. Now after three years, each of the three universities have in place formal minors and options in design and manufacturing as well as new laboratories known as Learning Factories

The Learning Factory
Jens Jorgensen, U. Washington, John Lamancusa, Penn State

The goal of the Learning Factory is to provide a new engineering educational experience that balances engineering science and engineering practice and emphasizes the interdependency of design and manufacturing through integration of a practice-based curriculum and advanced manufacturing facilities. The key element in this approach is the combination of curriculum revitalization with coordinated opportunities for application and hands-on experience, thereby erasing the traditional boundaries between lecture and laboratory, academic and industrial practice. We describe results of the first year of the MEEP partnership's operations.

Program In Products Realization

Jens Jorgensen, U. Washington, John Lamancusa, Penn State

As part of (MEEP), design and manufacturing courses have been restructured into a sequence leading to a Program in Products Realization (PPR)for undergraduates. The purpose is to provide a broad based, interdisciplinary program for students interested in the design and manufacturing of industrial products. Although each school has taken a slightly different approach to the implementation, the students at the three schools experience design and manufacturing activities each semester (or quarter) in residence. The program bridges the gap between engineering science and practice, and allows students to work in teams on real industrial problems. The implementation of the program has required restructuring of existing courses, the addition of new resources, and makes full use of the Learning Factories at each of the institutions. We describes new program at each of the institutions, the resources required and operational experiences to date.

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