Interdisciplinary Core Mathematics

CRAFTY Curriculum Foundations Project
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Summary

Forty-four engineers, mathematicians, and physical scientists met to examine the future role of undergraduate core mathematics (required courses in the first two years of instruction). The participants, divided into four groups, focused on the following areas:

1. Interdisciplinary Culture
2. Anticipated Advances in Technology
3. Goals and Content of Core Courses
4. Instructional Techniques

Abstracts of the discussions of the individual groups are presented in the Narrative. Then the many findings and recommendations made during the workshop are summarized under the headings: Consensus, Concerns, and Major Curriculum Initiative.

Appended to this report are excerpts from the keynote address, Urgency of Engineering Education Reform, given by Dr. William Wulf, President of the National Academy of Engineers, in which he noted that academia has not kept pace with changes in the professions and is failing to educate students to be technologically literate. With respect to mathematics, he encouraged a curriculum reform that spent less time on continuous, deterministic mathematics and more time on discrete and probabilistic mathematics.

Narrative

The state of our academic environment, in particular the interdisciplinary culture, is of great concern. Barriers between departments and lack of communication between faculty restrict the understanding and development of students. The workshop group recommended breaking down these barriers, establishing partnerships, and improving core mathematics programs to serve partner disciplines in the development of their students. The improvement of the curriculum through interdisciplinary cooperation is important as a first step, yet it still faces numerous roadblocks. We must prepare students for a diversity of careers in a rapidly changing environment. To do this, we need to develop broad reasoning and critical thinking skills that can only be accomplished through interdisciplinary cooperation.

Technology is a driving force in curriculum reform and is also a source of controversy. The ability of technology to provide visualization, numerical solutions and approximations, closed form symbolic solutions, and iterations has shifted curricula from focusing on mechanics and techniques to focusing on setting up problems and interpreting solutions. In short, technology has refocused curricula on the modeling process and away from the solution process. The resulting reduction of calculation skills is the major source of the controversy surrounding the use of technology. Another strong reason for incorporating technology in our core-course presentation is to prepare our students for the technological world into which they will graduate.

Content choices, balancing theory with computation, and the diversity of the students in first year courses lead to fundamental questions concerning the intellectual goals of a mathematics curriculum. Developing students to learn how to learn on their own has become accepted as central to the set of curriculum goals. Although not identical in meaning, the phrases *life long learner*, *learning how to think*, *mental discipline*, and *learning the mathematical thought process*, all seem to be perspectives on learning how to learn. There is no consensus on what to teach, and opinions ranged from maintaining the status quo to replacing calculus with a new program focusing on modeling and inquiry.

Some question why very little mathematics developed in the twentieth century is found in core courses. Others suggest that core content should be influenced by the needs of downstream courses, saying mathematics is basically a process, not a collection of topics. The primary concern for many is not content, but how to develop students to become competent, confident, and creative problem solvers.

In a suggested, yet controversial curriculum, modeling and applications would replace calculus as the umbrella course, yet the curriculum would still include rates of change, accumulation, transformation and approximation. All these concepts and many more would arise from modeling realistic situations rather than from studying specified topics. An important aspect of this projected modeling program is the integration of data analysis, probability, and discrete mathematics with continuous mathematics, since the situations being modeled rarely fall into our artificial curriculum categories. Another important aspect is that a modeling program is inherently interdisciplinary because real-world situations are interdisciplinary.

Student growth should be accounted for in curriculum planning; it is too important to be left to chance. Identified areas for attention are learning how to learn, communication, mathematical sophistication, modeling, technology, connection with other disciplines, and history of mathematics. The meaning of high standards in core courses at West Point has changed from preparation for upper-level mathematics concepts in real analysis to new standards that relate to deeper modeling experiences, open-ended projects, inquiry, and the ability to apply mathematics in interdisciplinary settings.

The workshop participants applauded the shift of focus in courses from teacher-centered to ones being learner-centered with less topical coverage and greater depth in the content. The pedagogical shift involves engaging students in multiple learning activities such as group activities, group projects, discovery work, technology laboratory sessions, writing assignments, and student presentations. The difficulties in performing this pedagogical reform lie in the fact that many student-learning activities take considerable classtime, sometimes require more work for the instructor, and often require a change in assessment methods. The time factor poses the biggest challenge. The undergraduate teaching profession has been reluctant to reduce content in order to make time for student learning activities and has difficulty accepting that learning is a very inefficient process. Somehow, this reluctance must be overcome and the center of gravity of the core program must continue to move.

Nine instructional methods/issues were analyzed and recommended as valuable instructional techniques in core mathematics programs: Questioning/Discussion, Problem Solving, Use of Technology, Exploration and Discovery, Multiple Representation, Writing, Multiple Assessment Instruments, Control of Section Size, and Use of Group work.

Consensus

Workshop participants achieved consensus on the following desired attributes of an undergraduate mathematics curriculum, especially when significant interdisciplinary connections are involved.

1. More *modeling* should be incorporated into the curriculum.

   Modeling was viewed by each of the subgroups as an effective means of addressing their issues. The Interdisciplinary group saw modeling as representing the best approach to breaking down current barriers to interdisciplinary cooperation. Technology is seen as moving curricula toward the modeling process and away from the solution process. Although in agreement on increasing the emphasis on modeling to prepare students to become competent, confident, and creative problem solvers, the members of the Goals and Content group differed on the extent. The Instruction group viewed modeling as an effective way to address their multiple learning issues.

2. There should be a greater emphasis on *problem solving* in the sense of modeling real-world problems rather than in the sense of exercises.
3. The curriculum needs to emphasize *learning how to learn*.

   Although not identical in meaning the frequently heard phrases: *life long learner*, *learning to think*, *mental discipline*, and *learning the mathematical thought process* all offered perspectives on learning how to learn.
4. Instructors must make *effective use of technology*, particularly for visualization, discovery, and insight as well as computation. Students must be prepared for the technological world into which they will graduate. The terms *effective use* and *appropriate technology* need to be better defined.
5. There should be a pedagogical shift from teacher-centered instruction to *learner-centered instruction*. Topical coverage can be reduced, with remaining material developed to greater depth.
6. There is great value in the use of *multiple learning activities:* projects, discovery work, writing, presentations, calculator/computer laboratory sessions.
7. *Process* is more important than *content*.

Concerns

Workshop participants identified the following problems and issues which need to be confronted when revising an undergraduate mathematics curriculum, especially if significant interdisciplinary connections are desired.

1. The present state of interdisciplinary cooperation and interaction needs improvement.

   Barriers between departments and lack of communication between faculty restrict student development. Although there is (theoretical) agreement on the benefits of interdisciplinary cooperation, several barriers exist such as system inertia, fiefs and turfs, publish or perish syndromes focused on narrow results, entrenched attitudes, rigid reward systems, and time. The low intensity of interdisciplinary cooperation has restricted reform efforts in mathematics, physics, and engineering.
2. There can be a loss of calculation skills due to the use of technology.
3. It is not always clear how to use technology effectively.
4. Serious time issues are raised by the recommended curricular and pedagogical revisions.

   Student-learning activities take time away from instructor activities and require more instructor time (developing materials, grading complex projects) and different means of assessment. There can be a major conflict between content coverage and student-learning activities: such activities can be time intensive, reducing the number of topics that can be covered in a course.
5. There is a lack of agreement on content choices and priorities (continuous vs discrete, deterministic vs stochastic, etc.)
6. There is often a conflict between the *math way* (e.g., emphasizing limits as the major *primitive*) and the *science way* (e.g., emphasizing rates of change as the major *primitive*).
7. There is an unfortunate lack of statistics/data analysis in the introductory courses.

Major Curriculum Initiative

Mathematics departments should consider adopting a core sequence of courses focused on inquiry and modeling that interweaves continuous and discrete mathematics. Calculus topics of rates of change, accumulation, transformations, approximations, and others would arise through modeling realistic situations rather than studying specified subjects. Similarly data analysis, statistics, probability, graph theory, matrix algebra and other discrete topics would also arise through modeling realistic situations. The program would more effectively address the goal of developing competent, confident, and creative problem solvers than do the present calculus courses. In addition, the program would be inherently interdisciplinary, as real-world situations are interdisciplinary.

REFERENCES

The entire Proceedings of the workshop, including the 35 submitted position papers, can be found at `www.dean.usma.edu/math/activities/ilap/workshops/1999/default.html`

Additional information and details compiled from the workshop are found in *Changing Core Mathematics*, MAA Notes Volume #61 (Edited by Chris Arney and Don Small). This volume contains a historical description of the evolution of the mathematics curriculum and an expanded description of the major curriculum initiative presented at the workshop.

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APPENDIX: The Urgency of Engineering Education Reform

Exerpts from the Keynote Address by William Wulf, President of the National Academy of Engineering

I want to talk about engineering education and what I sense is the real urgency of engineering education reform. I think we ought to be seeing a watershed change in engineering education—it is not happening. I am very impatient about it and I hope I can communicate to you why I feel impatient about it. A lot has been written on the subject. There were a whole series of reports done in the 1994–1995 timeframe. There was one done by NSF, there was one done by the National Research Council; and there was one done by the Dean's Council of ASEE (American Society for Engineering Education). All of them called for a fairly dramatic reform.

I have three introductory remarks to make before engaging in talking specifically about what I think needs to be done. First, a caveat, I am going to paint with a very broad brush. I fully appreciate that if you go to any engineering school you are likely to find some innovative things happening. What is not happening is the center of gravity moving in any substantive way. That is my concern.

Second, I have a particular view of what an engineer does that colors the way that I think about these things. I want to contrast it with science for a moment. Science is fundamentally analytic. Its concern is with the understanding of nature—understanding what "is". Engineering is fundamentally synthetic. It is concerned with creating what "can be". That difference in approach is profound. My favorite operational definition of what an engineer does is "design under constraint". Given a problem an engineer designs a solution, but not any old solution will do. You have to satisfy a set of constraints—and I will argue in a minute that that set of constraints is getting much more complicated. You have to worry about, first of all, functionality—solving the problem—but then you've got size, cost, weight, heat dissipation, and on and on—I will talk about this more later. If you really want to get my ire up, say that engineering is just applied science. Engineering is not just applied science. Engineering is philosophically at its core very different. It is fundamentally creative rather than explanatory. To be sure, our understanding of nature is one of the constraints that an engineer works under. In my personal experience in the company I founded and ran, it turns out that nature is almost never the limiting constraint. Our understanding of nature is seldom the hardest constraint that you work with.

The third caveat, and maybe this is the most important one—engineering is changing. Indeed it's that change that underlies my sense of urgency in the need for engineering education to change. I believe that the way that we will practice engineering and the way that the students we are teaching today will practice engineering are profoundly different from the way that I practiced engineering or my father practiced engineering. The problem with trying to describe to you what that change is about is rather like standing too close to a mosaic. I have said, sometimes there are monumental events that kind of cast a sharp knife edge between the way things were and the way things are now. World War II strikes me that way. Before World War II there was no federal funding of research at universities. After World War II we built this wonderful mechanism for funding research. The role of women in society dramatically changes across that boundary. In fact, engineering education changes dramatically across that boundary. The notion of the engineering-science model of engineering education comes about because of, frankly, the failure of engineers to contribute as much as scientists did to the war effort.

I don't think we are in that kind of a change. I don't see that monumental event. It seems to me that this is much more like the Industrial Revolution. You know, we talk about the Industrial Revolution now as though it was an event. The fact is, it smeared out over almost 100 years and it is contemporaneous with a whole bunch of profound changes in society. This is when you get the rise of democracy; this is the rise of rationalism; and there was another great change in university education. The introduction of liberal or secular education comes about at exactly the same time. If you were there at the time, you could not have predicted what the world would look like at the end of that time. I think we are in that kind of change.

So I am going to be describing bits of this mosaic to you as opposed to "I'll tell you what engineering practice is going to be 20 years from now"—I haven't the foggiest idea. I can just tell you there are these forces that are, I think, dramatically changing things. I see at least six pieces to this mosaic of change that I want to talk about today. First, I said engineering is designing under constraint. So I want to talk about: The complexity of the design space which I think is exploding. The complexity of the constraint set which is also exploding. I want to talk about what I will call "the fallacy of the possibility of precision". Then I want to talk about a couple of social changes in engineering. The expanding role of engineers in industry, the globalization of engineering, and then note that the pace of change is in itself a change.

Let me talk about the complexity of the design space. When I say design space, what I mean is, for each decision that an engineer makes: How big will this thing be? How heavy will it be? How much power consumption can I allow this thing to have? For each such decision, you want to think of that as a dimension in a design space and each option that the engineer has as a point along that dimension. So each point in that space is a potential solution to the problem that you are trying to solve. It may be a good solution, or it may not be a good solution, but it is a potential solution.

Let me just illustrate with three examples why I say the design space is getting much more complicated. The examples are: materials, information technology, and systems—and I am not going to say here anything that you don't already know. My father was an engineer. He was a mechanical engineer. He designed machines for a company that made cookies. I can remember growing up and going to his plant and just being amazed at how you could get very flaky crackers, for example, to be mass-produced at a horrendous pace. I mean they just came flying out of this literally 300 ft long oven. But, for my father there was a little book on a shelf, a little thin book, of the materials that he had as an option to design with. There were a half a dozen different kinds of steel, there were a few kinds of bronze, plastic was not in his vocabulary, fibers were not in his vocabulary, composite materials were not something he considered.

Well, now we are talking about designer materials, which give an engineer the ability to say "these are the properties that I want the material to have" and at least potentially the possibility of producing that material for that subject. Literally, that thin book has become an infinite set of options. The notion of biomaterials (you know we talk about biotechnology a lot in terms of medical applications), but do you know what the slipperiest stuff in the world is? The stuff with the lowest coefficient of friction known to man? It is the stuff at the end of your bones. There is no man-made material as slippery as your joints. We are going to be talking about growing materials. One of my colleagues at Virginia is into making smart materials and it is almost scary. He talks about materials that understand their role in a structure, sense the environment, and adapt their properties to better fulfill their role. Materials in which electrical properties and small forces can be exploited to build structures that are very much lighter and do in fact adapt to their environment with very small changes.

My second example is Information Technology: Everybody knows Moore's Law? Two times the number of transistors on a per unit area every 18 months. The fact is you can have intelligence imbedded in everything. There will not be a product produced 20 years from now that doesn't have some degree of intelligence. Have you ever played this game of how many electric motors you have in your house? You know, as we went through the transition from watermills to steam engines, in both cases plants had these great big shafts down the middle of the plant and hung belts off of them to run all the machinery. The first use of electric motors was simply to replace steam engines that ran the shaft. Then slowly every tool got its own electric motor, and now, of course, we just embed an electric motor in everything. The typical home has hundreds or thousands of electric motors. I was standing in the shower one day wondering how many computers I had in my bathroom. I know of at least two and I probably don't know of some others. Because its the cheap way to imbed control into a product.

One of the projects I was working on in Virginia before I took on this job dealt with bridge construction. Building a bridge is expensive. Inspecting a bridge is even more expensive. The rebar and the concrete slowly corrode. Concrete cracks and water seeps in onto the rebar. So you have to inspect the bridge to make sure the concrete is still doing its thing. We were designing a chip that contained a corrosion sensor, a microprocessor, and a small radio transceiver. Objective—make it cheap enough that you can put a shovel-full in every load of concrete and simply drive a truck across the bridge with a radio transmitter that asks the bridge whether it is corroded or not.

Everything is going to have intelligence imbedded in it—everything. If you start thinking of combining IT with MIMS, the potential is absolutely incredible and I haven't even started talking about nano-technology yet.

The third thing I want to mention with respect to complexity is systems. Simply; the number of components per product has been going up exponentially and we are starting to hit that point of the curve where it really, really is going to go up fast. That is going to imply more and more kinds of engineering expertise to produce any single product. So, the bottom line is that the design space, the number of options that an engineer has, is just going through the roof.

Design under constraint—the design space is going up—I want to argue that the complexity of the constraint set is going up equally and rapidly. My father had primarily two constraints to work under—functionality and cost—one of those was a fixed point—the machine had to work, so he was designing against one free variable. This is particularly true when you are building great big machines. It doesn't matter whether the thing weighs 200 lbs or 400 lbs except to the extent that weight represents additional cost. Well, if you look at our society now, the constraint set includes safety, reliability, manufacturability or remanufacturability, repairability, maintainability, a whole set of ecological concerns that didn't exist before, ergonomic concerns that didn't exist before, human interface considerations that we never thought about before, and many, many more things.

It is not only that the list of constraints is huge: the optimization function isn't clear. For my Dad, fixed point functionality—drive the cost as low as you can—easy optimization function. Not at all clear what the optimization function is for things like ecological concerns. We have time after time found that driving down the knocks in automobile emissions does not necessarily minimize pollution in places like the Los Angeles basin. It is a much more complicated chemical process. Not only that, but you don't even know how to measure some of these things. What are the units of ergonomics suitability? Oh, and by the way, the public seems to believe that some things are absolutes. No degree of environmental impact is acceptable. There is no lower bound on what the public is willing to accept.

So the argument I am trying to make to you is the design space has gotten much bigger, the constraint set has gotten much bigger, and it's a different kind of engineering world than it was for my Dad. Not only that, it is not even clear what constitutes the best design.

Now let me talk about the possibility of precision. For my Dad, looking back in particular, I realize he was a very good engineer. But there was absolutely no way that he could *a priori* predict what the exact behavior of his machine would be. I mean, it was just a given that you built a prototype and it might work as intended, but probably it wouldn't. You would probably wind up having to modify some things in it. That was the whole idea of building prototypes. You worked with kind of crude orders of magnitude computation. He had a lot of knowledge of prior machines that he drew on, but basically nobody expected the first thing out of the pocket to work, and in fact if the first one didn't work his boss wasn't upset about that. There wasn't someone standing in line to sue him because of it.

But with modern computation, and better and better models of the physical world, a better and better understanding of the physical world, it is in fact apparently possible to be precise. Everybody talks about the Boeing 777, for example, for which no prototype was built. The first one that was built was the first one that flew and that was because of the modeling that was done ahead of time. At least in principle it appears possible to be precise.

Now I claim that this is kind of a mixed blessing. On the one hand it is nice not to have to build a prototype, but it carries with it an implied responsibility. It is not unreasonable for your boss, your insurer, your customer, the federal regulator, to believe that the first prototype will work as intended. Now what does that mean? That means that in the face of this much more complicated design space, much more complicated constraint set, you as an engineer have an implied responsibility to search all of it, to make sure that the design you come up with is really the global optimum in that space.

Well, I frankly just don't think that is possible. I happen to be a computer guy, as I was introduced. Can I teach a little bit of computer science for a minute? I am going to wave my hands so if I bore you forgive me. You have all seen programming languages. You all know they contain classes of statements. For each one of those classes of statements it is possible *a priori* to specify the following. Suppose you had a logical expression that characterized the state of the system after the execution of the statement. It is possible to mechanically take that logical expression and the statement and produce another logical expression that must have been true in order for the statement to have been executed and to result in the logical expression that follows. If you have an assignment $x = y + z$, then for any property that was true of x after the statement was executed, that same statement must have been true for the expression $y + z$ before the statement was executed. I can do that for every kind of statement in the programming language. What that means is if you can write down a logical expression that describes the state that you want to be true at the end of the execution of a program, I can completely, mechanically, and really quite simply back that statement up, that logical expression, one statement at a time through the program and derive an expression which must be true at the beginning of the execution in order to get the right thing at the end. Well, if that expression at the beginning is a tautology, if it's always true, then I can absolutely guarantee that the program works right. Possibility of precision—it is possible to write programs which absolutely are guaranteed to be correct. Or at least produce the results that you said you wanted.

And yet have you ever encountered a program that was correct? I rather suspect that you haven't. Now, why is that? Well, there are two things—first of all the logical expression that you get at the beginning after doing this backing up is huge and our ability to prove those to be tautologies is not up to the task. But there is something more important than that. Humanly, we are not able to describe what it means to be correct. We are not able to write the expression that you want at the end.

One of my research areas—I've had a crazy research career doing lots of different things—one of them has been computer security. Within the domain of computer security there are things called cryptographic protocols. Cryptographic protocols happen to use cryptographic techniques, but they are intended for situations like—if you have two parties at opposite ends of the communication lines, each party should be able to verify that the party they are talking to at the other end is who they claim they are. I want to be sure that I am talking to you, and you want to be sure you are talking to me. These protocols are often ten-line programs. They are really tiny. They are something you think you can verify. And in fact people have published proofs of the correctness of a number of these protocols which have subsequently been shown to not work. In essence because it is just much harder to describe what constitutes correctness than you might think. So, I find this possibility of precision to be one of the things that may have the most profound effect on the practice of engineering. We are going to be expected to be precise in an environment where it is not at all clear whether that is an achievable goal. .

I would like now to talk about the expanded role of engineers in industry. Everybody has written about or heard and read about teams. About how industrial practice now is very much oriented around marketing people, engineers, financial people, etc., working together on a product. That is an environment in which the engineer we are training today is not equipped to operate. When I first heard about it, I thought it was a passing fad. The more I think about it, the more I realize that that's the way engineers operated through almost all of history. The era of specialization, of having an engineering department that threw designs over a transom, is the anomaly. Now whether the particular management fad of the day on how you do that will persist—no I don't think so. But the notion I think is enduring. Globalization of industry maybe is a special case of a team thing. Lots of people are more expert at this than I am, but it seems to me that this really underscores the fact that the engineer who is trained superbly in a technical sense, but does not understand the cultural and social issues in a very broad sense, in a multicultural way, is really useless.

Another important perspective is the pace of change is itself a change. Just as I came on board for this job, the NAE was concluding a conference about life long learning in engineering and somebody at that conference talked about the half-life of engineering knowledge. How long does it take for half of what an engineer knows to become obsolete? I must admit I quote these numbers all the time without ever verifying them, just because the dramatic effect is worth it. I won't stand behind these numbers, but what was estimated at that conference was that it varies by field from 7.5 down to 2.5 years. It so happens in software engineering:that the claim was half of what you know becomes obsolete in 2.5 years. Frankly, I am a little uncomfortable with that kind of one-dimensional characterization, but the important point is that it has not been part of the engineers culture to feel responsible for their own life long learning and I think that has to change.

There is a bunch of stuff that needs to change: curriculum, pedagogy, (I am particularly sensitive to the issue of diversity), the notion that the baccalaureate is the first professional degree, faculty reward system, the need for formalized lifelong learning, preparation in K through 12 and technological literacy in the general population

Let's talk about the first professional degree. Whether you are talking about medicine, law, business, there is no other profession that treats the baccalaureate as the first professional degree. And I think, frankly, the fact that we do causes all kinds of foolishness. We misrepresent the situation to both the students and potential employers. We seem to be perfectly comfortable with the notion that an employer is going to spend the first couple of years adding to the education of our products before they are useful. It has caused our curriculum to expand to the order of 135 semester hours as compared with 120. And by the way, that problem is going to become truly acute when states like my own, Virginia, actually do what they say they are going to do, namely mandate that the engineering program be a 120-hour program. We are going to lose five courses out of the curriculum. We'll squeeze out the humanities, liberal arts, which I think are becoming central to what an engineer is going to have to be able to do.

You may not know this, but engineering is not a profession. We may like to talk about it being a profession, but in a technical sense the Department of Education defines what is a profession and there are two properties that a profession must have. The first one is at least two years post-baccalaureate. Second, it has to be on "the list". The DOE maintains a list of the professions, and engineering is not on that list. My members are quite offended that they are not considered professionals, but technically they are not.

Curriculum—if you get a bunch of engineers together there is an oath that we all recite. That oath is that what we must do in the baccalaureate is teach "only the fundamentals". "Only the fundamentals"—you hear that recited over and over again because we treat the baccalaureate as the first professional degree. Well, rubber meets the road when you ask what are fundamentals? And then the mechanicals will tell you something quite different from the civils, and neither one of them will recognize, for example, that they sort of agree, because since WWII the fundamentals have included continuous mathematics and physics. That much I think everybody agrees on.

But as I said before engineering is changing. Information technology is going to be imbedded in everything that engineers produce. And discrete mathematics, not continuous mathematics, is the underpinning of information technology. I mentioned biological materials. Biology and chemistry are going to become as fundamental as continuous mathematics and physics. And the fact that engineering is done in this more holistic team-oriented, multinational global context means that there are a whole set of business and cultural issues that are really fundamental to engineering. You can't practice without them.

If you want to continue to say that the baccalaureate is the first professional degree, then you have to agree that some of our cherished current fundamentals aren't any more. Or you have to figure out a way to teach them much more efficiently and effectively. I happen to think that continuous mathematics ought to be done in two semesters, not four, and I think that is possible to do. But I leave that to all of you to figure out how to do.

While I am on the subject of curriculum let me come back to the possibility of precision for just a minute. One of the properties that we see in software systems, and I think you will see in all engineering systems as they become increasingly complicated, are what are called immerging properties. The systems behave as specified but they also have other properties, other behaviors that you did not anticipate. The question is how do you engineer safe, reliable, cost-effective products whose behavior you could not have anticipated ahead of time. It is not that you are a lousy engineer, that you did a bad job, it's that you literally could not have anticipated everything ahead of time. The complexity of the system is such that it is infeasible. I think this is an opportunity for a whole new class of mathematics. Don't ask me what it would be.

Ethics has been very important to engineering. Engineers are very much like physicians—first do no harm. We spend a lot of time teaching engineers how to over-design their systems so that they tend to not fail or if they fail, fail safe. How do you cope with the ethics of not knowing what the behavior, what the immerging properties, of a system will be? I don't know.

Let's talk about faculty rewards. And I don't mean the teaching versus research debate. I happen to be one of those people who believes that, most of the time, research and teaching compliment each other. Most of the people who I know who are good researchers are also good teachers. Good people are good. There are the outliers. But I think we have another problem. Remember I said I believe what engineers do is design under constraint. I happen to think that engineering is an incredibly creative activity. Something we don't advertise very well. In my heart, I believe that engineering is one of the most creative of human activities. If you stipulate that for just a minute, can you think of any other creative activity, on campus, where you don't expect the faculty to practice, to perform that creative activity? The Art Department doesn't promote or tenure anybody who doesn't practice their art. Think about the Music Department. Or even think about the other professions like law and medicine. If you go to medical school, you go on grand rounds with the faculty who is practicing his/her profession. Engineering is the only creative activity that I can think of where, in fact, the faculty are actively discouraged from practicing the profession. And what we wound up with—you know the criteria that we apply for promotion tenure in universities is essentially derived from the Science Departments. The criteria are research, publication, getting grants—and you'd better teach pretty well too. But, practicing the profession counts for nothing and probably counts against you because it detracts from other things.

I actually had a Dean who would not let one of my faculty take a sabbatical in industry. His belief was that there was nothing to be learned from industrial experience, and in fact somehow those industrial people were just going to suck out his brains and take out everything he knew. Well, I can tell you, I spent almost ten years of my life in the private sector and one of the most intellectually challenging things I have ever done in my life was delivering product. It is not just that it is hard, it's intellectually challenging. Going back to the curriculum issue for just a moment, I think one of the things that is really wrong is that we have a curriculum being designed by faculty members who are not practicing engineers. I have a great deal of respect for my colleagues at the university. They are wonderful engineering scientists, but very few of them know anything about the practice of engineering,and so they design a curriculum that is an engineering-science curriculum, not an engineering-practice curriculum.

Let me talk about the notion of technological literacy in the general public. Before I took this job, I was a Professor at the University of Virginia. As many of you may know, Virginia was founded by Thomas Jefferson. What you probably don't know is that Jefferson did not die, he participates actively every day in the decision mechanisms of the university. He was very proud of having founded the university. It was one of three things he put on his tombstone. He didn't mention things like being President of the United States. He founded the university because he believed you could not have a democracy without having an educated citizenry.

Well, I think he would be scared today because we have a citizenry that is not only ignorant of technology, it is proud of the fact that it is ignorant of technology. You know, I go to a cocktail party and someone will ask me what I do and I say I teach computer science and they say, "Oh, I don't understand that computer stuff". Can you imagine asking somebody else what they did and they said they were a Professor of English and you say "Oh, nouns and verbs, I can't …." Engineering schools don't offer technological literacy courses for liberal arts majors. Why not? We could pass on knowledge of not just science and math but the process that takes that knowledge of nature and converts it into the things that profoundly change our quality of life. Think about how the average person in 1899 lived. Think about how an average person in 1999 lives. All of the differences are engineer products. In 1899 the average life span was 46. In 1999 the average life span is 76. Not all of that increase is due to modern medicine. It is almost all due to cleaner water and sanitary sewers—public health. Engineering!!

And yet, "Oh, I don't understand that computer stuff and I am proud of the fact that I don't." Every person who has a liberal education ought to be at some level technologically literate and it's our responsibility to provide the opportunity for that to happen. It is no good to point a finger and say "You English professors ought to be technologically literate" if there is no mechanism for them to do that.

I've tried to indicate to you that I think the practice of engineering is going to change tremendously and that therefore the education of engineers needs to change tremendously. I love this quote: Wayne Gretzky, probably the best hockey player that ever lived, talked about the fact that he didn't skate to where the puck was, he skated to where the puck would be. I'm afraid that engineering education is skating to where the puck was.