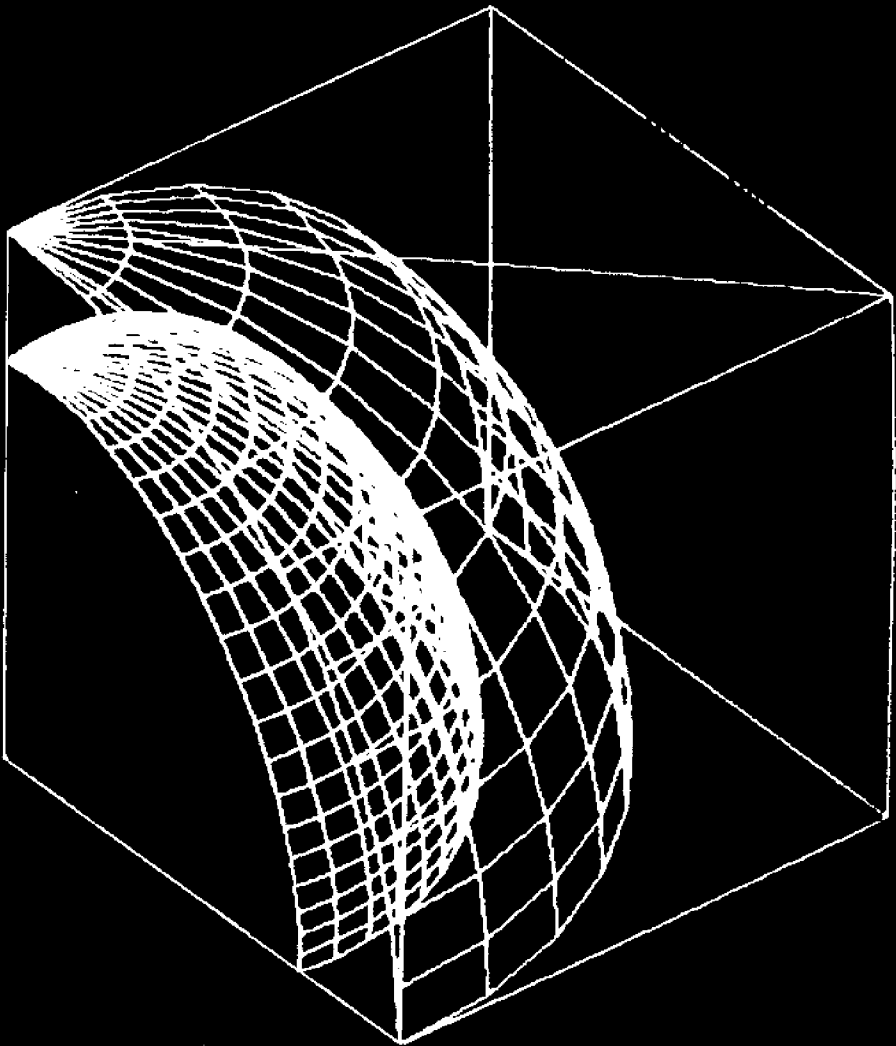8th Annual Robert Bruce
Wallace Lecture

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A National Agenda

The MIT Sea Grant Lecture and
Seminar Series

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The MIT Sea Grant Lecture and
Seminar Series

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Massachusetts Institute
of Technology
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The Robert Bruce Wallace Lecture is presented annually by the MIT Department of Ocean Engineering and is made possible by a gift from Mr. and Mrs. A.H. Chatfield. Robert Bruce Wallace, Mrs. Chatfield's father, was a member of the MIT class of 1898. As president of the American Ship Building Co., he made substantial developments of inland waterway shipping.

This year's Wallace lecturer was Professor Gerald L. Wilson, dean of the MIT School of Engineering. In his lecture, presented here in full, Dean Wilson addressed the need to evaluate how the nation educates its engineers, and touched upon the necessity to graduate engineers who are prepared to be part of interdisciplinary teams.

Dean Wilson's lecture was part of a three-day Sea Grant Lecture/Seminar Series on the Automation in the Design and Manufacture of Large Marine Systems, cosponsored by the MIT Sea Grant College Program, the Department of Ocean Engineering, the Department of Mechanical Engineering, General Electric Co., the Office of Naval Research, and the National Science Foundation.

Seminar presentations focused on ways to represent shapes automatically, interrogate designs for performance, and build in tolerances to bridge the gap between idealized designs and fabrication capabilities. Also presented were discussions on methods for modeling fabrication processes, such as welding and cutting, and ways for exploring potential uses of composite materials in marine systems. Complete proceedings of the conference will be published by Hemisphere Publishing Corp. of New York and will be available in late 1989.

Gerald L. Wilson of MIT is dean of the School of Engineering and Vannevar Bush Professor of Engineering. After having received a B.S. and M.S. in Electrical Engineering and a Ph.D. in Mechanical Engineering in 1965, Professor Wilson remained at MIT as a faculty member in the Department of Electrical Engineering and Computer Science, which he headed from 1978 to 1981. He was honored as the Phillip Sporn Professor of Energy Processing from 1971 to 1982, and is a past recipient of the IEEE Power Engineering Educator of the Year Award. He is also a fellow of IEEE, and a member of the National Academy of Engineers.

Professor Wilson has served as a director of MIT's Electric Power Systems Engineering Laboratory, of which he is co-founder. The Laboratory focuses on the application of electromechanics and electromagnetics to practical systems. Professor Wilson's leadership experience at MIT also includes instrumental roles in the development of the School of Engineering's program in electric power engineering education and research, and in the formation of a major microelectronics research facility at MIT.

He has published some 30 publications related to the fields of electromechanics and electric power systems.

Good afternoon. I am delighted to have the opportunity to give the eighth annual Robert Bruce Wallace Lecture. And to address this distinguished gathering.

The subject of my remarks this afternoon is the education of engineers in America—a topic that is certainly of concern to all of us in this room, and one I believe is of vital importance to the nation as well.

MIT President Paul Gray, in the introduction to the Institute's course catalog, writes, "Engineering and science are, by their very nature, humanistic enterprises.

"Scientific inquiry is, at once, a most natural and highly refined expression of the human mind and spirit. It is derived from native curiosity about the nature of our world and about the universe, and it results in speculations and concepts which help to give meaning and order to that world. Engineering and technology are both natural and socially derived enterprises."

Contrast Paul Gray's sentiments with this rigid description, written by management consultant Peter Block: "There is a bit of (the) engineer in all of us—someone who worships facts, laws, rules, equations, and predictability. (Who thinks) if you can't measure it, it doesn't exist."

My subject today is the gulf between those two views of the engineer's role in society—and how we might be able to bridge that gap through the education of our engineers.

I think it's fair to ask what could be wrong with engineering education when we're graduating 70,000 engineers a year who have very little trouble finding jobs. Some of us—MIT, Stanford, and Carnegie, to name a few—charge amazingly high tuitions, but have no difficulty at all filling our dormitories and classrooms.

Yet, much as I would love to stand here and say I believe things are going very well indeed for engineering, I can't.

There are many signs of trouble in our field. Today I would like to address two that particularly concern me, and many of my colleagues.

The first is the difficulty American manufacturing is having building products that are competitive in the world marketplace.

The second is the increasingly adversarial relationship between science and technology on the one hand, and society on the other.

First, let me address American manufacturing.

The issue here is our ability, or lack of it, to integrate the manufacturing process effectively. To develop a product concept; use technology to turn that concept into a product that can be manufactured, distributed, sold and serviced at an acceptable cost; and ensure that the product will reliably meet some market need.

Not so long ago, American manufacturing was the only game in town. So what if our cars were too big for European or Asian streets? We built to the specifications of our *own* culture, our *own* standards, our *own* guidelines for quality and performance. We didn't worry much about how long it took to develop new products, either, because customers had no choice but to wait for them.

Today, the rules have changed. And we are painfully playing catch-up.

Admittedly, manufacturing is a far more complex process today than it once was. Yet the Japanese in recent years have made it look almost easy. They have become masters, not so much at developing technology, as at integrating technology into the hundreds of overlapping steps involved in bringing a product to market, while maintaining quality that is the envy of the world.

What's more, they have managed to keep their costs down and slash development cycles at the same time! Those of us who remember what "made in Japan" meant in the 1950s can only marvel at what they have achieved.

A few years ago, Xerox discovered that its Japanese competitors were developing new copier models twice as fast as Xerox, and at half the cost. Xerox still hasn't closed the gap. The Big Three American auto makers have all formed task forces to cut their development cycles, from almost five years to nearer the Japanese three and a half. And Honeywell, I've read, has reduced its development time for new thermostats from four years to twelve months.

The problem of American manufacturing capability is not limited to the high tech and automotive industries. It also affects our infrastructure—the investments made by cities, states and the federal government on tunnels, dams, highways, bridges and communication systems.

And, it involves the reliability and serviceability of everything we build.

There have been dozens of studies of quality and productivity in American manufacturing—or the lack thereof. What they "prove" is not clear.

Some believe the answer lies in technology—in computer-integrated manufacturing, perhaps, which would link all the myriad entities involved in manufacturing in such a way as to solve the problems of cost, quality, and time to develop.

Some say we need a commitment from the federal government to manufacturing productivity. Some think we need to revive our national will to excel, as we did after Sputnik. Some blame the high cost of capital, or the unions, or Wall Street, with its fanatical emphasis on short-term, quarter-by-quarter profitability.

I don't discount any of these factors. But I also place a large measure of the responsibility for the lack of American manufacturing competitiveness on poor engineering—in the definition, design, production, and delivery of products. And if it's true that our engineering is poor, then part of the blame must lie with the way we educate our engineers.

Engineering is the process of using the fruits of science and technology for the development of products and systems that benefit society.

Today, in spite of the boom in the intellectual content to be taught, we still do an effective job of teaching engineers science and technology.

But our failure as a nation to develop competitive, smart, well-engineered, reliable, and easy-to-manufacture products does not lie with any failure of our technology. After all, Europeans and Asians are still coming here to learn technology—and then delivering it back to us in the form of new products!

Our failure is in developing engineers who are too narrow in their understanding. Engineers, who, in Peter Block's words, "worship facts, rules, equations and predictability;" who are strong on analytical skills; who rate high on individual achievement—but who are not prepared or inclined to be members of multi-disciplinary teams. Let alone to lead them, as I believe they should.

The result of this failure in the way we educate engineers is the perpetuation of the American way of manufacturing: the "throw it over the wall" syndrome.

We all know how that works. The design engineer, working in almost monastic isolation, designs a leading-edge product, or piece of a product. The design is then passed along to manufacturing, where manufacturing engineers, an underpaid and underappreciated lot now seeing the product for the first time, build prototypes of it and attempt to make it manufacturable.

At this point, the integration that should have been part of the process all along begins—and so do back engineering, reverse engineering, engineering change orders, modifications, and delays.

Eventually, the much-altered product is manufactured. And finally, it's shipped to the sales force, who must explain it to customers and hope they're impressed enough to buy it.

The problem isn't so much with any of the individual steps. It's that they *are* "individual steps." We have treated engineering as merely one cog in the wheel. And we are paying the price.

Some estimates say up to 40 percent of quality problems in American manufactured goods are actually design problems. Clearly, to have better products, we need better and earlier involvement by all parties concerned in their development—particularly engineers.

Engineers were not meant to be merely analyzers working in isolation. They were meant to be synthesizers, organizers, integrators, and above all, builders.

What that means is that those of us who educate engineers must prepare them for that broader role—whether it be in industry, in designing a public highway system, or even in that last bastion of individual achievement, the research laboratory—where today, most of the work is done not by individuals, but by teams.

There are American companies that have gone beyond the "throw-it-over-the-wall" stage—the auto makers being conspicuous among them.

In my view, Ford leads the way. And although Ford has one of the most advanced CAD/CAM networks in the world, that's not the secret of its success. New human systems are.

Ten years ago, Ford was an egregious example of all that was wrong with old-line American manufacturing. It was highly centralized, highly autocratic, and virtually lacking in cross-functional integration. Workers not only had extremely narrow job categories, they were discouraged from ever looking beyond them.

But the late '70s brought a day of reckoning for the U.S. auto industry, and for Ford. In its wake came new management and fresh thinking. Workers began to be asked what they thought of the company's products and methodology. And management not only listened to their suggestions, they actually implemented many of them.

Just how major the change was becomes clear when one examines the "Team Taurus" project: a radical, "clean-sheet" design that literally revolutionized the way Ford produces cars. Lee Iacocca may have called the Taurus "streamlined potato," but that project turned Ford upside down. It proved what can be done when the emphasis is on quality, teamwork, and the smart use of resources, both human and technological.

GM and Chrysler have made some of the same changes, and in many ways have made great progress. So have some other industries.

But although "quality" and "working smarter" have become the new manufacturing buzzwords, engineers are not in the vanguard of the revolution.

The second major failure that can be attributed to the way we educate our young engineers, I believe, manifests itself in the feeling of mistrust so many Americans have about science and technology.

In France and Japan, nuclear energy plants are commonplace and accepted by the public. In the United States, people point to Three Mile Island and Chernobyl, and accuse the government and the utility companies of lying to them. Look 50 miles to the north, at Seabrook.

Some of this is our own fault.

We build nuclear power plants, neglecting to design a viable plan for processing the spent fuel, and without making the effort to understand why the public fears nuclear energy. We build chemical plants, ignorant of the effects of the downstream effluents on the water supply and on wildlife, and ignorant of the interrelationship between the plants and the local infrastructure.

As engineers, and as engineering educators, we bear some blame for those failures. Too often, we have worn blinders, concentrating on all the technological issues that fascinate us so, while disdaining the social and economic factors to work.

"Scientists" and "humanists" have been adversaries for generations, neither side understanding the concerns of the other; each blaming the other for what goes wrong. The results have been tragic.

A garbage barge plies up and down the coast, looking for some place to dispose of its load. Syringes and blood bags wash up on our beaches. Poisoned dolphins beach themselves to die.

For 30 years, we've been adding to the amount of CO_2 in our atmosphere by continuing to burn fossil fuels. This hot summer, we started reading seriously alarmed articles in the popular press on the greenhouse effect.

We fight about building a secondary treatment facility in Boston Harbor, when in fact every time it rains, water overflows the city's antiquated sewer/storm drain system and bypasses even the two *primary* treatment plants.

Waste disposal has us all but stymied. We simply don't know what to do with the trash we produce—from the soaps and plastics under our kitchen sinks to our chemical and nuclear wastes.

Decades after the introduction of polymer trash bags, we realize that because the material does not degrade, it's harmful to the environment. It really would not have taken a lot of foresight to figure that out sooner. Why didn't we? Whose responsibility is it to anticipate such problems?

These issues are not going to go away. Nor are the new issues that arise alongside them likely to be any simpler.

I think the only solution, if there is one, lies with our educational system. We must have a better-informed citizenry, with a clearer understanding of technology. And we must teach engineers how to lead that education process.

That means the teaching of engineering must be revitalized. We must build on the foundation of all the many things we are already doing right. But we must change our emphasis.

Before I describe how I think that ought to be done, let me take a moment to review what we have been doing in engineering education, and why.

After World War II, many American universities took a look at the technologies that had been developed as part of the war effort—microwaves, gun control systems, navigation control systems—and realized that scientists had done most of the innovating, not engineers.

The result was that engineering schools across the country, with MIT conspicuous among the leaders, began to re-emphasize the teaching of basic scientific principles. The fundamentals.

This was not only appropriate; it was a master plan that has served us well. Over the intervening decades, however, several trends have developed that are disturbing.

One is that in re-emphasizing the basics, we have placed so much emphasis on analysis that we have short-changed synthesis. Given an engineering concept, our students are first taught concepts of modeling. Later, they are given computational aids to help them analyze the model and predict the system's performance.

But with more and more emphasis on the abstract, there has been less and less on what Barton Rogers called the "mind and hand"—the theoretician and the designer/builder working in concert.

The laboratory is one of the few opportunities students have to connect what they learn in the classroom with the way the real world behaves—to perform the extrapolation from theory that is an essential part of the design process.

Yet fewer and fewer faculty are teaching laboratories that challenge and develop our students' ability as experimentalists.

The result is that students are not learning to invent—which is sadly ironic, since the prospect of developing and innovating was what drew many of these students to engineering, and to places like MIT, in the first place.

Over the past seven or eight years, the Accreditation Board for Engineering has placed more emphasis on design in undergraduate education.

Yet their approach is that of the bean counter: they add up the number of hours students spend in design, but virtually ignore the quality and content of that design experience.

At MIT and a few other institutions—a very few, I might add—faculty have developed techniques for nurturing students' design skills that mimic the relationship of the apprentice to the master.

For instance, students are required to invent 40 or 50 ways to approach a design problem before they choose the two or three they believe will work best. Computer-aided design tools help them translate their rough ideas into line drawings, which they can then present to others for feedback. Then, continuing the evolutionary process, they use both their intuitive design sense and the tools of analysis to refine one "best" design into a finished concept.

This is a start. But it's only a start.

We need to give students more of these visualization tools. We need to provide them with more opportunities to build and test prototypes of their concepts, and to learn from the feedback process that is so important to design.

These things will require more time from our faculty. But I believe they are essential if we really want to prepare our students to go out into the world and use the creative spirit they had when they arrived at MIT, for the betterment of society.

I would like to cite one more example of the need to rethink the detailed content of our technical subjects.

Over the last 20 years, a revolution has occurred in such fields as fluid mechanics, structural analysis, and electromagnetics, to name a few. These are all fields requiring extremely sophisticated mathematical analysis and modeling.

The development of the Galerkin method and finite element techniques have led to computer tools that can analyze geometries and configurations well beyond those amenable to closed-form analysis. These tools are now used both in educational institutions and in industry.

The effect has been that engineers are depending less on their understanding and common sense, and more on the gadgetry. Because they don't know how to go back and check the assumptions that went into their model, they have no choice but to accept the computer's findings. As one of my colleagues described it, we have gone from "garbage in/garbage out" to "garbage in/gospel out"!

The use of these computer tools raises bedeviling questions.

For example, there are now sophisticated software systems that can perform differential and integral calculus, as well as relatively complex algebraic manipulations. Does this mean we should stop teaching the calculus to engineering students? Or does it mean we should be teaching it differently than we did 30 years ago?

The answer is not clear. What is clear is that we need a major review and revision of what we are teaching our engineers—and of how we are teaching them.

We need a new breed of engineer—one who can not only deal with organizational, economic, sociological and technical issues simultaneously, but who can lead the multi-disciplinary teams that will be required to solve them.

At MIT, we have taken a number of significant steps toward that goal. Let me describe two recent programs I believe hold particular promise. And then I would like to suggest a more radical change.

The first, which began last June, is called "Leaders for Manufacturing," a new master's program developed and administered jointly by the School of Engineering and the Sloan School of Management, in partnership with almost a dozen world-class manufacturing firms.

"Leaders for Manufacturing" is a landmark research and educational program, aimed squarely at preserving the competitiveness of American manufacturing in the worldwide marketplace. Its purpose is to define that combination of educational experiences that will yield graduates who can be measurably more effective in the definition, design, manufacturing and delivery of high-quality products and systems.

Students enrolled in the two-year program will earn master's degrees in both management and engineering. Their research projects are being carried out both in the classroom and at industrial sites.

The focus is on industrial teamwork—on teaching these talented young people to see engineering and management issues in their total context. We want these students to emerge from the program as agents for change—as industrial revolutionaries, if you will.

Our industrial partners are working intensively with our faculty to define the program's content. Faculty and students from both the management and engineering schools will be working in teams in the industrial setting—working to understand it, and to change it.

Our industrial partners are looking very closely at the education we provide these students. We will be looking very closely at the organizational, technical and cultural environment these partners provide our students.

And all of us are working to replace barriers with bridges; mutual defensiveness with understanding.

To date it has been an exciting and dynamic endeavor.

The other program I would like to describe is aimed at the second major challenge I have discussed today—changing the adversarial relationship between technology, and society at large.

Last spring, the Institute's Hazardous Substances Management Program, part of the Center for Technology Policy and Industrial Development, brought together for a two-day conference 21 people involved in the debate about incineration of hazardous wastes.

Participants from industry, governmental agencies, and environmental and citizen groups took part. The objective was to help the parties to this acrimonious dispute first to define the issues, and then to work toward solution.

What usually happens with issues like these is that scientists and technologists develop a technical solution. Then the scientists present it to the public, and the public immediately becomes alarmed. People say, "We don't need that," or "It's too dangerous," or "You're not telling us the whole truth."

At this conference, participants started out as wary of one another as usual. But by the end of the second day, with the help of an experienced facilitator, they had managed to hammer out an "agenda for action" that provided not only the basis for further discussion, but some points of agreement.

I find that hopeful.

One participant said afterward, "I had not realized that a deeper, more broad-based process of involvement (by all the parties involved) was so important."

I believe such a process of involvement by many parties very *early* in the process is not only important, it's essential if we are to make progress. Continuing contention about these issues wastes time, energy and resources; it erodes trust, and, worst of all, it perpetuates inaction—inaction that threatens every living thing on our planet.

Earlier, I described how students in fields such as fluid mechanics are placing too much trust in automated analytical tools, because they lack the understanding or question the computer's findings.

When the public is confronted with information about arcane technologies such as the ones involving hazardous waste disposal, or nuclear power generation, their response is to reject what they are told, because they mistrust the source of the information—scientists and engineers. The result is often stalemate.

We cannot afford that. Those of us in science and technology have got to learn patience. We've got to listen. We've got to explain more clearly. We probably have to go more than halfway.

Both the programs I have just described are important steps in a long process. But to produce the "new breed" of engineer, I talked of earlier—the one who can be a leader of multi-disciplinary teams—will take nothing less than a redesign of engineering education.

Today I have attempted to describe some areas I believe need attention:

- Our too-narrow focus on specific engineering disciplines

- Curricula that focus on analysis while short-changing synthesis

- The relationship between what is taught to students in school, and the sophisticated tools that are now available to practicing engineers

- The teaching of laboratories

- The whole area of the way the products of engineering affect society at large

I don't have a silver bullet solution—I wish I did. We engineers don't feel very comfortable dealing with ambiguity or "inexact sciences" and educating young people is certainly one of those!

I am convinced, however, that a large part of the answer lies in broadening our definition of the word "engineer" to mean someone who is pivotal to society. And to revise our goals as educators of engineers to recognize that new definition.

I said earlier I have a "radical" proposal. A radical, you recall, is a root. My proposal is that we abandon the delusion we can produce people ready to undertake a professional engineering career in four years. Or even six.

The job of the engineer is simply too big.

Instead, I propose that we consider the undergraduate education of young engineers as simply a foundation—a launching platform.

I propose that we not only broaden the undergraduate engineering program, but that we design a new graduate curriculum as well, so that they will serve as the "root" of the kind of life-long learning needed by people who are right in the thick of things. People who are involved and committed. Who are leaders.

One of the essential parts of learning a body of knowledge, whether it's engineering or English literature, is to isolate it—to put bounds around it, however arbitrary, so that the learning becomes manageable. Inevitably, the bounds harden.

We need to remove some of the bounds around engineering. And it will not be easy.

In many ways, the American school of engineering is poorly organized to provide the broadening and integration among the disciplines that are needed.

For one thing, students enter engineering through a particular department—one whose boundaries were defined decades ago—so that as they progress through their undergraduate years, their education becomes not increasingly broad, but increasingly narrow.

For another, and this is partly because of the requirements for promotion and tenure, engineering faculty often appear to students to be extreme specialists—people whose intellectual achievements are miles deep, but only meters wide.

This is another sad irony. We have brilliant faculty—people whose contributions are recognized all over the world. They are also masters of synthesis—they must be, to envision new research, and to understand how their work relates to that of others. Many are involved in product development through consulting work. And all are involved in sales when they present their ideas for funding!

Yet, these are activities students see only rarely, and that is too bad. It is wrong for such important role models to be perceived as one-dimensional.

A minute ago, I referred to engineering departments as structures that resist broadening. Several institutions have tried to solve this problem by eliminating departmental boundaries. Not only has this not often worked, I don't think it is a broad enough solution.

Undergraduate engineering students must experience the points of view and intellectual challenges of history. Of language. Of the arts. Of philosophy. They must experience the concerns of the searching human spirit—not in a perfunctory way, as a series of requirements to be gotten out of the way, but as integral to their preparation for life and work in a pluralistic society.

A new graduate curriculum must continue this broad focus, operating in parallel with our present, research-focused programs.

We in academic institutions must work more closely with industry, to learn what we can about present industrial practice, and to be agents for change where change is required. We must modify our criteria for faculty promotion and tenure so as to recognize the skilled synthesizer; the man or woman who can codify methods of dealing with complexity, and the person who can help students understand how technology can *benefit* a beleaguered planet, not add to its woes.

Let me be clear. I am not advocating that we stop expecting students to acquire knowledge of one engineering discipline in depth. What I am advocating is that we stop calling that kind of knowledge "enough." It is not enough.

At MIT, we are not clear yet as to exactly how we should proceed.

We have enormous strengths as an institution—faculty and student body that are internationally renowned; programs based on decades of experience; a deep commitment to engineering and scientific principles. We are blessed with a richness and diversity that are the envy of the world.

But this institution is also renowned for recognizing when there is a need for change—and for its willingness to step out in front.

The "new agenda" I have proposed today would require a considerable shift in our teaching and research environment—one that the School of Engineering could not undertake in isolation, even if everyone were convinced today of the need to undertake it.

It would require a true collaboration with those in the humanities, the arts, and the sciences. It would require discussion and cooperation with our professional organizations. It would require the care, the patience, and the cooperation of all who are affected by the profession of engineering.

But I propose that we begin. After all, we engineers love a tough problem, don't we? Isn't that what the world expects of us? Isn't that where we are at our best?

Paul Gray wrote that engineering and science are humanistic enterprises. And humanism is concerned not with abstractions, but with the concerns of living human beings in a complex world.

In other words, with the very business of engineers.