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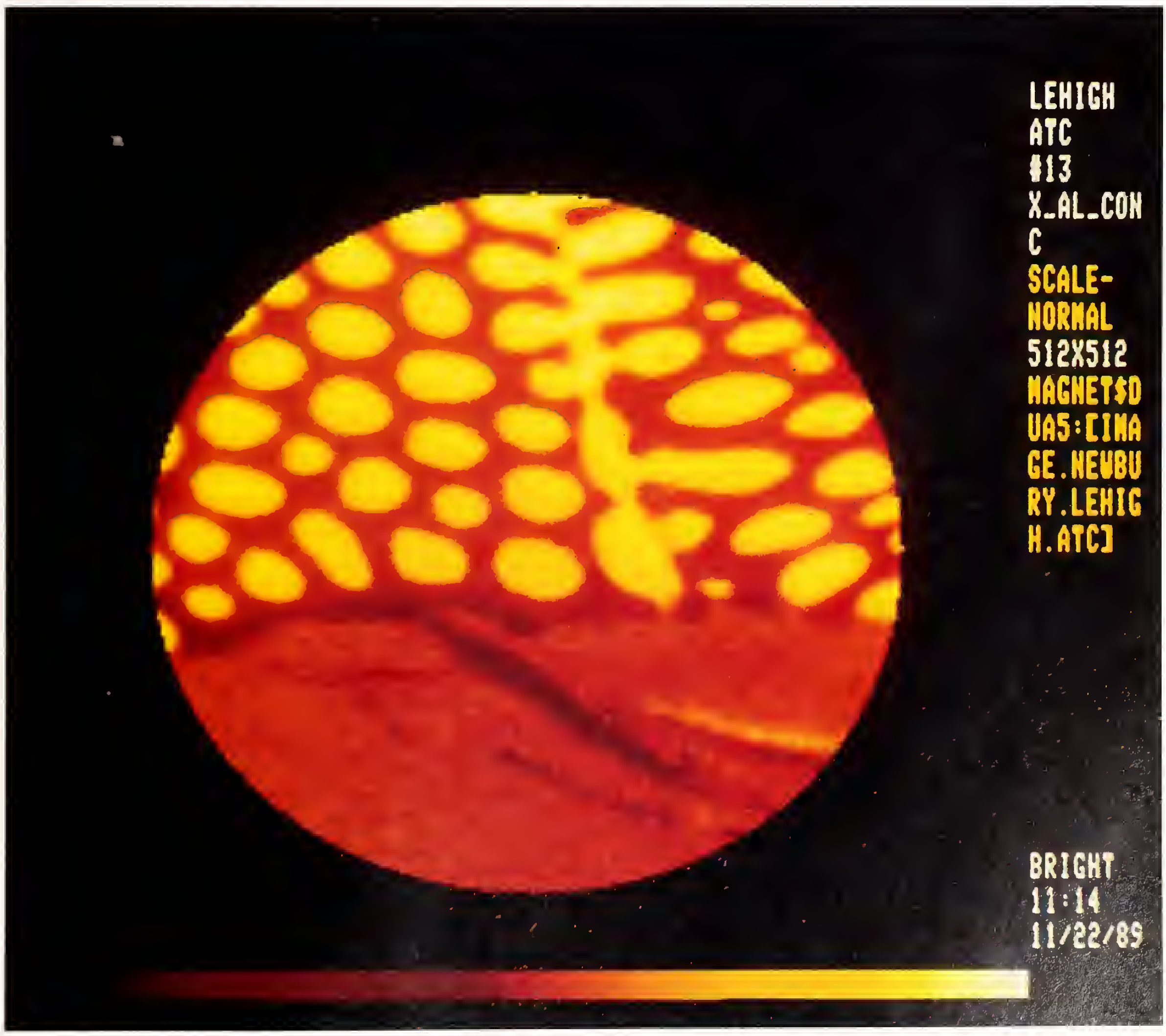
NIST Special Publication 837

Science, Technology, and Competitiveness

Retrospective on a Symposium in Celebration of NIST's 90th Anniversary and the 25th Anniversary of the Gaithersburg Laboratories, November 14–15, 1991



The National Institute of Standards and Technology was established in 1988 by Congress to "assist industry in the development of technology . . . needed to improve product quality, to modernize manufacturing processes, to ensure product reliability . . . and to facilitate rapid commercialization . . . of products based on new scientific discoveries."

NIST, originally founded as the National Bureau of Standards in 1901, works to strengthen U.S. industry's competitiveness; advance science and engineering; and improve public health, safety, and the environment. One of the agency's basic functions is to develop, maintain, and retain custody of the national standards of measurement, and provide the means and methods for comparing standards used in science, engineering, manufacturing, commerce, industry, and education with the standards adopted or recognized by the Federal Government.

As an agency of the U.S. Commerce Department's Technology Administration, NIST conducts basic and applied research in the physical sciences and engineering, and develops measurement techniques, test methods, standards, and related services. The Institute does generic and precompetitive work on new and advanced technologies. NIST's research facilities are located at Gaithersburg, MD 20899, and at Boulder, CO 80303. For more information contact the Public Inquiries Desk, 301-975-3058.

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Retrospective on a Symposium in Celebration of NIST's 90th Anniversary and the 25th Anniversary of the Gaithersburg Laboratories, November 14–15, 1991

G. W. Hixenbaugh, Editor

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ABSTRACT

"Science, Technology, and Competitiveness" was a symposium held in observance of the 90th anniversary of the National Institute of Standards and Technology and the 25th anniversary of NIST's Gaithersburg, MD, laboratories, Since its founding, the mission of NIST has been to strengthen U.S. industry competitiveness, advance science, and improve public health, safety, and the environment. Throughout its existence, and more than any other government science and technology agency, NIST has worked in partnership with industry. At this symposium, distinguished scientists and managers from government, industry, academia, other research institutions, and NIST met to discuss the challenges of today and the future. The conference served as a forum that covered a broad range of issues dealing with competitiveness and government-industry collaborations. The first day's program included sessions on emerging technologies, proprietary vs. non-proprietary research, educating the workforce, and the view from the U.S. Congress. On the second day NIST directors and researchers described some of the latest research at the Institute. Topics included advanced technology; competitiveness; computational geometry; computer performance, fire research; artificial intelligence and robotics; the history of NIST and the future of NIST; optical technology; science education; and surface science.

KEYWORDS

advanced technology; competitiveness; computational geometry; fire research; intelligence; NIST; optics; robotics; surface science.

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*Dr. Kessler served as chairman of the Symposium Program Committee.

THURSDAY, NOVEMBER 14, 1991

Welcome and Introduction to the Symposium

John W. Lyons

Director, National Institute of Standards and Technology (1990-1993)*

Welcome to our 90th anniversary symposium on Science, Technology, and Competitiveness. I'm pleased to see so many friends here. About half our audience is senior staff from NIST and the other half is visitors from various walks of life. We're delighted to have you all here.

We have a distinguished group of speakers scheduled for today—speakers from outside the National Institute of Standards and Technology. Tomorrow we have a program review presented by technical staff speakers from within. We also have some festivities this evening, and I think this audience is distinguished to match our program.

I'd like to thank some people who helped us put this program together. We had a panel of outside advisers headed by Director Emeritus Ernest Ambler, and another program committee composed of NIST managers and staff headed by Karl Kessler. Also, I'd like to thank Mat Heyman, Sara Torrence, and their colleagues who are handling, in the background, all of the arrangements.

A lot has happened to this Institution in the recent past and, I think, a lot more is going to happen in the next few years. So it seemed appropriate for us to stop, take stock, think a little bit about how we got where we are and reflect on how we should comport ourselves as we go forward.

We're further sensitized—at least I and those of us who are involved with the project—by the historical studies we're conducting. We're writing a second volume of history. There is a well-known first volume by Rexmond C. Cochrane called *Measures for Progress*, which a lot of us use as a reference. In fact, I stole a lot of my talk this morning from that history of the first half-century.

It was decided, some little while ago, to write an additional volume that would take us from, roughly, the end of World War II through the infamous battery additive affair and on up to the watershed events of 1988, which I will explain in a minute. That second volume is well along, and I've been reading the drafts, as they come forward, from Dr. Elio Passaglia and his associates.

Many of the issues, as he has found, which were of interest during that period are with us yet again. For example, around 1960, then Director Allen Astin was wrestling with precisely the issues of international competitiveness that we are today and, in fact, he formulated a restructuring of the Commerce Department's Technology and Science Programs that look very similar to what Congress finally undertook to do in 1988. One of the things you learn by being a historian is that there is nothing new under the sun.

This year also marks anniversaries for others. For example, our sister laboratory in Canada, the National Research Council, is this year celebrating its 75th birthday. In June they held a smash. I went up there and attended and participated in that and we'll hear, this evening, some brief remarks from one of our associates at NRC, Canada.

We're also in the midst of the celebration of the 200th birthday of one of the true giants in the history of science and technology, Michael Faraday. You may have seen the recent issue of Chemical and Engineering News [69(38); 1991 September 23] with his picture on the cover, and a very fine issue that was. Almost everybody in our business knows about Faraday, knows about his work in electricity, in chemistry, in electrochemistry; but I'm not sure that everybody is aware of his marvelous efforts to make science interesting and intelligible to the lay public, primarily through lecturing at the Royal Institution.

One of those lecture series was called the "Annual Christmas Lectures Designed for School Boys." A lecture he developed, which I have found particularly interesting and stimulating, was subsequently printed and, more recently, reprinted as the "Chemical History of a Candle." I think it is among the best examples of science writing ever done for the general public. So, happy birthday to NIST, to NRC, and to Michael Faraday, among others.

What I want to do this morning is have the opening speakers set the context for the subsequent speakers. They will all be addressing current events and, I think, looking forward; so I'm going to look back and try to show things in our history, not just NIST history but also our country's history, that brought us to this juncture. I will credit Cochrane's *Measures for Progress* for much of my remarks.

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* Lyons was named director of the U.S. Army Research Laboratory in September 1993.

I'll begin with the Constitution. Article II says, "The Congress shall have power to fix the standard of weights and measures." Note that singular "standard." During the period before the Constitutional Convention, when we lived under the Articles of Confederation, several states had a terrible time with commerce because measures were different in every state. A bushel of apples in New York was not necessarily the same quantity of apples as a bushel in Connecticut. People got very distressed by that, so the Founding Fathers provided for a central system.

However, resistance to Federal intervention was no different—in fact, it was probably stronger in those days than it is today. Nine separate Congressional committees were appointed over the first 25 years, and absolutely nothing happened. So that provision—unlike the Patent Provision which was almost instantly implemented—the Standards Provision was not addressed for a very long time.

Nonetheless, people needed measures. There had been a lot of activity, as you may know, in Europe during this period--particularly in France. In the United States surveyors were having problems, and they finally were the ones who got things moving. Through the Treasury Department's Coast Survey, under the direction of Ferdinand Rudolph Hassler, two standard artifacts were obtained—both of them from England—and the first U.S. standard of length came across in the form of an 82-inch brass bar from which one could select the appropriate 36-inch yard. Hassler also derived an avoirdupois pound from a Troy pound standard that had been made, again, in England somewhat earlier for the U.S. Mint, where these things were important, and he established units for the gallon and the bushel.

In 1836 the first Office of Weights and Measures was set up in the Treasury Department, and Treasury was directed by the Congress to make copies of these standards that Hassler had assembled and disseminate them to the states. However, in no case were their laboratory facilities adequate to support these standards, to measure and track their behavior, and to compare and contrast one from another, as they were in use among the states. So there was considerable variation, and that continued.

Meanwhile, efforts in other parts of the world were developing to get better measurements. The electrical revolution was in full swing when, in 1875, the United States and 16 other countries signed the Treaty of the Meter, which produced an item for cocktail conversation, that is, the United States "adhered" to the Metric System—as the diplomats say—some 120 years ago, and the United States Senate saw fit to ratify that activity in 1878. That treaty established both the meter and the kilogram as a basis for a new international measurement system.

The Coast Survey and the Office of Weights and Measures, in 1893, adopted, as the U.S. Fundamental Standards, the new metric artifacts supplied from the new International Bureau of Weights and Measures established in France. As far as anyone can tell, the two U.S. organizations had no authority to adopt these as government standards; but they did so anyway, which is one way to get things done. So we have a lesson from the 1890's—you just do it.

We have had, then, the metric units as our official standards since 1893. But there still was no laboratory and there was no real force behind these proposed measures so as to realize the practical use of metric units.

Finally, after the Spanish-American War, with exports increasing rapidly—that sounds familiar today—and in the face of formidable efforts by the Germans in the PTR [Physikalisch-Technische Reichsanstalt], the predecessor agency to PTB [Physikalisch-Technische Bundesanstalt] which was established in 1887—so it's considerably older than we are—and also by the English who established the National Physical Laboratory in 1899. The commercial interests had began to fuss for improvement in measures, so the Secretary of the Treasury, a gentlemen named Lyman Gage, led the efforts primarily by bringing to his staff a 40-year-old physicist from the University of Chicago, one Samuel Stratton. Stratton formulated the necessary concepts, drafted the legislation, and made the arguments, and there was considerable support. Congressman James H. Southard of Ohio said, "Never has a bill come with such a number of endorsements." This is a story I find particularly interesting. When arguing about the proposed salary of the director, which had been put forward at $6,000 a year—and of course the Congress cut it subsequently—Secretary Gage justified a relatively high number—it was close to the salary, actually, of a Cabinet officer—by saying, "Almost anybody will do for Secretary of the Treasury, but it takes a high-grade man to be chief of a bureau like this."

As I understand it, the director's salary was set at $5,000 a year. I asked our staff economist to figure out what that would be today and I got, over my computer the other day, the following statement, "Bad news." It said, "Your predecessor in 1900 was even more grossly underpaid than you." And then it went on to say that the equivalent salary today would be of the order of $80-some thousand, however, that would be to manage the efforts of—what was it—10 or 12 people, so presumably there has been some sophistication factor added to this job.

On March 3, 1901, the new laboratory's Organic Act was signed into law by President William McKinley, and you will see a remembrance of that out in the lobby—although some brigand has stolen the pen that the President used. It used to be in the case along with the rest of the artifacts. And we also have, carved in the marble on the wall in the lobby, an appropriate quote from the committee report which says, among other things, that they couldn't think of anything they could do that would be better to serve the interests of industry and others. And the manufacturing sector was, in fact, the first group cited.

The institution was called the National Bureau of Standards. There has been a great clamor around here about the change of our name, in 1988, to NIST. I discovered from reading Cochrane that this is, in fact, the third name change because NBS, so named in 1901, was converted to the Bureau of Standards—the word National was dropped in 1903, the same time as the Department, the new Department of Commerce and Labor was formed—and the word National was not restored until 1934, for some earthshaking reason that I don't understand. So the name has never been inviolate. You can imagine the fun that we would have if our initials were BS today.

There was in the Congress in 1988 an attempt to call us NITS, and some people thought that had something to do with lice, so that was rejected. In the old days they didn't worry about acronyms. So the Bureau of Standards was established before the Department of Commerce and Labor, well before the Department of Commerce which split out in 1913, well before the Naval Research Laboratory, which came into being in the 20's, the National Institutes of Health in the 30's and the so-called "National Laboratories" in the 1940's.

Because of that the charter of the institution was very broad and included helping scientists, industry, and all levels of government, providing broad services tied loosely to measurements and standards. You've all heard the quote, "To a man with a hammer, everything looks like a nail." To a man with this kind of a mission, everything looks like a standards job. So we've managed to justify a very broad series of programs.

The Bureau, over the years, found itself in the midst of the development of aircraft, radio, materials of all sorts, computers, and every other kind of technology. The degree to which the laboratory moved into applied areas varied, depending on the state of the art and the private sector, the condition of the civilian economy and the military security, and the presence of other Federal mission laboratories.

Always, the Bureau remained strong in the underlying sciences of physics, chemistry, and mathematics, interwoven as they were, and are, with measurement and standards problems. Thus a culture, based on doing good science, grew up but was always accompanied by a willingness to pitch in to technology issues when the need arose.

This cyclic movement into and out of technology was never more apparent than in the two World Wars, when the Bureau went on an emergency basis, and became totally immersed in military technologies. After World War II the movement was away from technology, and there was a long period of dedication to scientific research which ran, roughly, from Director Edward Condon's tenure well into the post-Sputnik era.

For the last 20 years civilian technologies have placed increasing demands on us, first driven by the consumer and public health and safety concerns of the late 60's and early 70's—highlighted by the creation of OSHA [Occupational Safety and Health Administration], EPA [Environmental Protection Agency], CPSC [Consumer Product Safety Commission], and others. This was followed by the energy crisis and the push for conservation and ultimate energy sources and, finally, the large military buildup of the 80's shifted our technology focus yet again.

But beginning in the middle 70's, another wave of concern began to build that was to have the most profound impact on us. It was a concern about the lagging competitiveness of the U.S. civilian sector in the global market. Anticipating the civilian technology demands on the Bureau would grow rapidly, even as consumerism ebbed, the Bureau reorganized itself in 1978—and Dr. Elio Passaglia tells us that was only the second true reorganization in the history of the institution, the first having come in the middle 60's. The purpose of this restructuring in 1978 was to gain a better grip on the appropriate technologies and, at the same time, drop or refocus other areas.

In the 1980's a plethora of studies on technology and competitiveness was published, many assisted by Bureau experts and others who are in this room today, and Congress, in the middle 80's, began to address competitiveness issues. One result was the Omnibus Trade and Competitiveness Act of 1988. This title constituted a full revision of the Bureau's enabling legislation, the second such since 1901, the first being a substantial modernizing and elaboration enacted in 1950.

The first change in the Omnibus Trade and Competitiveness Act is in our name. The word "Technology" is added, the term "Bureau" is modernized to "Institute," yielding the National Institute of Standards and Technology. A lot of people think it is "Science and Technology." It's not. The word "Standards" is very deliberately kept in the title.

The Act makes clear the importance of economic consideration. The intent of the bill and the first function enumerated is to provide strong support for industry and to bring to fruition, in economic terms, the promise of new and emerging technologies and advances in science. To this end, the Act reauthorized the existing programs and established three new mechanisms to increase the Institute's outreach and collaboration with industry.

First is the Advanced Technology Program, our new series of financial awards to companies, especially consortia of companies, to help them move through the early, high-risk stages of commercialization of new technologies. We have made one set of awards and are in the midst of our second competition.

The second new mechanism is a set of Manufacturing Technology Centers, funded by NIST, to package and move, to small firms, the latest in manufacturing technology. There are now five of these centers, funded by us and matched with funds from non-Federal entities, and there will be more.

Third, we have a small effort to support state efforts to set up technology or industrial extension services. We seek to catalyze the spreading move toward establishing analogs in the states of highly successful agriculture extension services.

In separate legislation in 1987 NIST—then NBS—was given responsibility for managing the annual competition for the Malcolm Baldrige National Quality Award. This has been a great success. We're working very hard to stay up with the exploding interest in quality management in U.S. industry.

And so, here we are at our 90th anniversary in a new posture. We have a thriving laboratory, a new program of grants to industry, a set of centers focused on manufacturing, closely involved in state and local efforts to stimulate technology commercialization, and leading the national movement on quality. All in all, it's a very exciting place to be and I, for one, wouldn't want to be anywhere else.

Technology and Competitiveness

Robert A. Frosch

Vice President, General Motors Research Laboratories

I was engaged several years ago, and have spent some time in the past year, helping to review material for a book which will describe senior technical jobs in the Federal Government and in state governments, to be kind of a glossary of what these jobs are about. In a remarkable number of cases, the description of the job for, let's say, the administrator of NASA or the head of a technical agency said, "This is fundamentally a management job, and while it would be useful for the holder of the job to have some technical competence, it isn't really necessary." I read enough of this so finally I began to make marginal comments that said, "I presume that the description for the Attorney General of the United States says, 'This is principally a management job, and while it would be useful for this person to be a lawyer or have some legal background, it isn't really necessary.' " That, in fact, is part of the absurdity of our times in technological matters and, indeed, provides part of the theme of what I'd like to say.

Let me begin by congratulating NIST, which I still think of as the Bureau of Standards, on its double anniversary and, in fact, on its increasing and new way of carrying out the roles which were assigned to it, from the very beginning, of supporting commerce and industry and technology in the United States through standards and through research and development.

I'm particularly pleased to be here because we are engaged with NIST and with other Federal laboratories in the technology development and the transfer business. This is a new and interesting endeavor.

However, that is not what I principally want to talk about, and I want to start by saying that this is a very personal speech. It's not particularly a General Motors speech; in fact, some of the things I will say will probably horrify my colleagues, and you are at liberty to think of me as an aging curmudgeon who is complaining about the state of the world. But I am, in fact, worried about a number of factors that are increasingly in play and that, in my mind, have to do with our competitive difficulties.

The problem, as it has been stated by many people, is that U.S. business, and the United States generally, is very good at creating science and technology and very bad at commercializing it. It's not that everybody is bad at commercializing it, but, in general, we produce science and technology for other people who are very successful in commercializing, and we come along afterwards not having done very well at it. And that seems to be part of the problem with lots of big industry and lots of small industry in the United States.

We've got dozens of explanations for why this is: the lack of patient capital, the cost of capital, American individualism, n-i-h,—not the place, the phenomenon of "not invented here." All of these are probably pieces of the difficulty, but I would like to talk a little bit about some things that, I believe, are major difficulties but which nobody likes to talk about very much, and which, in fact, everybody understands but the forces of our times don't care to attack.

Recently Lester Thurow of MIT has been talking about a concept which, I think, he identifies with Japan and Germany, that he referred to as "communitarian capitalism." I think of it as "cooperative capitalism." In any case, I think our system can best be described as adversarial capitalism—a system which is supposed to work by everybody fighting everybody else—and that has some virtues, but it also has some serious defects, particularly at a time when we are trying to engender cooperation in the technological and technological implementation areas.

The problem with the forces of adversarialism are twofold: first, they are a terrible waste of money, and I'll come to that a little bit more; and second, they prevent exactly those activities that are required for good development of technology and its transfer.

I'm referring to a list of things which might be put under the heading of bureaucratics—they really have to do with too much administration, or the substitution of administration for thought. They also have to do with the complexity of auditing and what is usually called "accountability." They have to do with the legal climate, and they have to do with the state of business technology. I mean the technology which is used to run the business side of business, not the technology that the business may use.

The state of business technology is terrible. If you were running a laboratory, with the kind of technology that business has available, you wouldn't tolerate it for a moment.

Let me talk a little bit about several of these problems by beginning with the "Federal Anti-Procurement Regulations."

They pose as a procurement system. I'm particularly familiar, of course, with NASA and the Department of Defense—and the DoD is a good example—but, in fact, these regulations are entirely intended to prevent any of the activities that are necessary for good procurement of technology. They also waste money.

The difficulty is they start from the wrong premise. They start from the premise that the correct way to do procurement is through arms-length negotiation. Anyone who has engaged in trying to figure out how to use technology, and what technology to develop to solve a problem, knows that the first thing you do is engage in very intimate discussions over what the problem is, what the solution might be, and what technology is involved. But we have an entire system for procuring technology which is intended to prevent, from the very beginning, exactly those discussions that are necessary for success.

We start with the wrong assumption, and proceed through all sorts of complications, to nearly anything in the procurement discussion except the subject at the center of it, namely, what is the problem to be solved really like and how are we going to solve it?

The whole competitive picture is dogged by this difficulty and turned into a mess by it. And when I say it wastes money, the simplest estimate is that at least 10 to 20 percent of all the dollars that are used by the DoD, for procurement of anything, is wasted on the machinery of procurement. This may be an under-estimate.

This means that we probably have $20 to $50 billion a year spent, not in buying anything, but in going through elaborate, pseudo-administrative and decision measures, filling out forms, and auditing and re-auditing things that the auditors do not understand. That's $20 to $50 billion that has nothing to do with the question of what weapon systems are bought or what space systems are bought, but has to do purely with the manipulation of paper. One could easily have a much more effective and a much more honest system by spending a couple of billion dollars a year on it instead of $20 to $40 billion.

If you do not believe me, consider the fact that the last estimate of the number of people involved in DoD procurement, both in the Defense Department and with contractors, was of the order of nearly half a million people. If you think that is unlikely, figure out how many contractors there are and estimate the minimum number of people involved. Most of those people are doing nothing whatever that is useful except running around auditing each other.

This is not to say that there isn't an audit problem and a theft problem—there is—but there isn't the faintest evidence that this 40-year accretion of administrative nonsense has changed the amount of theft whatsoever. One has to ask, in fact, whether the accountability systems work.

When someone says accountability, my question is, accountable to whom and for what? What it mostly means is not that one is accountable for the results of the work to somebody who understands the work; it means one is accountable for whether Form 437 was signed in triplicate and suitably dated and read by somebody who is not, by training or background, capable of knowing what it is that is behind what it says on Form 437.

We have an audit system which is, by and large, only capable of adding, subtracting, multiplying, and dividing numbers it does not understand. Let's take the case of the great savings and loan debacle. My estimate is that there were at least eight levels, eight layers, of watchers watching watchers who were watching watchers who were watching watchers. Accountants, internal auditors, external auditors, audit committees and boards, bank examiners, regulators, and so on, and I'm not even counting the Congressional staff. The net result of this was an entire industry, through some odd combination of bad management, bad decision making, economic distress and outright fraud, succeeded in losing an unknown number of hundreds of billions of dollars with all these watchers watching it.

We could have saved a good deal of money by having two layers of watchers instead of eight layers of watchers and had exactly the same debacle.

So, I think there is a very serious problem of so much ivy growing on the system that it is almost impossible to do the work. It is as though the productive workers are working for the non-productive workers; the service industries have taken over.

We, in fact, have an industrial policy in the United States and have had an industrial policy from the beginning of the Republic. Parts of it are excellent and parts of it are terrible. I will remind you that the first piece of industrial policy I can think of, aside from the standards policy, is also in the U.S. Constitution—Article I, Section 8—which establishes the patent system as a clear, industrial policy to stimulate invention. We have continued with some policy for the stimulation of research and development. In fact, that has been a very successful policy. We have marvelous research and development.

We've also had a history of industrial policy in the stimulation of agriculture, which worked very neatly and very well. We have had a history of the stimulation of defense and aerospace which also worked very well. In fact, I believe we continue to have an industrial policy. We have an industrial policy which stimulates, through the tax laws and by other means, all forms of financial manipulation provided they do not involve real investment. The moving of money, the borrowing of money, and the buying and selling of symbols and companies are heavily stimulated and subsidized.

We have an industrial policy that deals with litigation. All forms of litigation—and that is an old policy—are heavily subsidized. The law industry is the only industry for which tax money is used to build and staff the factories—they're called courts. Your tax money pays for that. The legal profession doesn't pay for the courts and, in fact, the civil litigants don't pay for the courts. The tax monies pay for the courts—that's an interesting subsidization of an industry. We subsidize by regulatory enforcement all forms of record keeping, accounting and auditing, because we insist upon them.

I know some lawyers and accountants who refer to the 1986 Revision of the Tax Laws as being the "Lawyers and Accountants Welfare Act of 1986." This is not because it changed the tax laws for good or ill—I'm not arguing about that—but because it made enough detailed, generally irrelevant change so that everybody had to rush out and do lots of work again. So we are, in fact, subsidizing industries, specific industries. We draw the line at subsidizing productive industries, or, at least, we say we're not going to do that.

The style of adversarialism not only produces the waste that I described, and the fraud that comes from describing an anti-procurement system as a procurement system, it also violates all the rules that we know about for the generation and implementation of technology. After all, technology is not gadgets or objects; in fact, it isn't even patents. It is in fact knowledge, both the knowledge of the science and the craft that underlie things, and the ability to practice that knowledge. It is seldom transmittable through documents, and the sense in which it can be bought and sold is very weak because it is always created and moved by people, and the conversations among people, so anything that interferes with that is interfering with the essence of the matter.

To pursue this a little further, let me describe it in terms of a hierarchy of technology transfer. There has been a lot of discussion of dual-use technology, that is, technology that is created for a government purpose but used for commercial purposes, and vice versa. Let me just say, in passing, that I have never heard of a single-use technology. I have yet to find one.

The difficulty comes because most of the people who don't know about this business, but are trying to regulate it, think about it in "zeroth" order. This is what I would describe as asking the question, "Can this gun be used to make butter?" The answer is almost always, "No." But if you begin to ask higher-order questions such as, "Can the machine which makes guns make butter?" the answer is probably still, "No." But if you begin to ask, "Can the knowledge and the techniques that are used to make the machine that makes guns be used to make a machine that makes butter?" the answer begins to be, "Well, very likely." And if you go to the next order and ask, "Do the people who understand how to create machines to make guns have a level of understanding that would enable them to make machines that make butter?" the answer is almost certainly, "Yes—in the generalized sense." And if you go one step beyond that and ask, "Does the education and the experience that gives people the understanding that enables them to create machines, and so on," then the answer is, certainly, "Yes." So part of the problem is that we always try to be, in the regulatory sense, very specific and ask questions like, "Can this machine that was created here be used to do something else?" and the answer is, usually, "No."

I like to describe technology transfer—that is, moving the knowledge which underlies real technology—as a process engaged in by consenting adults in the privacy of their laboratories. It cannot be done at arm's length; it has to be done through long and intimate discussion, and anything in the machinery—to come back to that point—that interferes with that, is preventing and not helping.

Regarding business technology: Perhaps you find the difficulty in the Federal context—I know I certainly did in the Department of Defense and in NASA, and I certainly find it inside the business community. I think that the difficulty is a complex of things which include accounting methods and systems, what I think of as the "return on investment mentality"; and the machinery which is used for that; and the general inability of our formal business decision-making systems to take into account things that are not easily quantified in a money sense but have intangible properties, things like knowledge and the capabilities of people.

In the formal sense, accounting systems do not believe in the existence of either people or knowledge. Occasionally they go so far as to put a value on patents held, but not on people and what they understand. So from the very beginning, an attempt to quantify the probable value of engaging in the commercialization of a technology undergoes the difficulty that the key items likely to lead to success are left out of the computation.

The effect of the misorganization of the corporation is ignored, in the formal business decision-making system, most of the time. Thus a single business unit, or even a single project in a single business unit, is likely to have to pay the entire cost of the development of a corporation will benefit from it. At least, that is the normal, formal system.

Some businesses have managed to figure out how to deal with this problem, some businesses have not. I think of this as the "mom and pop" candy store problem. Mom and Pop open a candy store, and they have to take out a mortgage for the store, of course, so for the first guy who walks in and wants to buy a candy bar, the price is $50,000 dollars, because that is what it cost to open the store. That is a normal computation in business logic largely arising, even though everybody knows better, from the formal technology which has been propagated to do the computation. So we have a structural question and a business technology question.

The questions are complicated by the fact that standard accounting methods are incorrect. They may be of some use for the Securities and Exchange Commission, but when they are used as internal cost accounting systems they are flatly wrong, because they are left over from a previous era. They are based on direct labor which has almost nothing to do with the case, these days. There are changes coming in the costing systems, and there are new systems, but the ones that are in use, in most corporations, are guaranteed to deliver incorrect results. So you start, not only by not being able to make the prediction which is asked of you in order to commercialize the technology, you start also from an incorrect subset of assumptions even about the costs that you are already using in the factories that you are running.

So there is this complex of problems, most of which are not on the technological side or the technological commercialization side. They reside in our current dilemma, namely, forced adversarialism in a system which can only thrive by intimate cooperation. The objection that we don't have the money to take a chance on cooperative diversity, which I find difficult to believe when I see the amount of money wasted in the administrative processes that are forcing the adversarialism, is in fact fostered by what I'd call the bad flip-side of democracy. This means that irresponsible politics drives statesmanship out of the marketplace, because we are all vulnerable to the next person who wants to make a speech about how terrible some particular event was and, therefore, wishes to introduce three more layers of "accountability" even though the last six did nothing whatever to prevent the previous problem.

In a sense, we all know what to do and are doing our best to do it. As a corporation, General Motors is heavily engaged with NIST and with other Federal institutions in trying to work together to use the technology that is here and sometimes to inject technology we've developed that will be of use in creating a common national knowledge base and a capability to do better in using what we know and can do. We do it by these direct means with people and systems, but we are very anxious to evade the more complicated systems that lead to irrelevant administrative foolishness.

What is it that we need to do nationally? I have to admit that I don't know, politically, how to carry out my own prescription. Somehow or other, we need some healing process on our adversarial systems and a pruning process on the irrelevant administrative stuff. We need to move from adversarial capitalism to cooperative capitalism, which doesn't mean dismantling competition, but figuring out how to make competition compatible with cooperation in areas that don't bear strongly on the details of competition. We know the outlines of how to do that, but we don't know how to get the underbrush out of the way so we can do that. We need a great deal of simplification of our administrative systems.

Without regard to whether the outlines and the schemes of a Clean Air Act are a good idea or a bad idea, it is inconceivable that a statute that runs multi-hundreds of pages and will be served by regulations which interpret it in multi-thousands of pages, can in fact make any sense or work at all. This is clearly not possible, and frankly I don't believe it is the intention. I am cynical enough to believe that the intention is to make it sufficiently complicated so there is plenty of irrelevant work to be done.

We need much more free and open communication on technology matters and, I think, we're beginning to get it. I'm afraid that somebody is going to notice it and come around and say, "See what those people are doing, and tell them to stop because it is insufficiently accountable to somebody who doesn't understand what it is that they are doing."

I think we do need some shifting towards an industrial policy which, at least, worries about what are the real technological directions that will make some sense. We need stimulating technological directions—I don't think that's picking competitors. What are the important subjects that are worth trying to stimulate, and what are the important competencies and technical skills, that are important to stimulate? I think we know how to do that, or at least some of us think we know how to do that, and I think it needs some doing.

Emerging Technologies

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I'd like to talk about the environment for research, particularly industrial research, and about emerging technologies, but also about the environment for research, competitiveness, and technology.

Let me begin by talking a bit about dinosaurs. Sometimes, every now and then, I get this very keen feeling: I'm leaving my office, I'm going down the elevator out of my building, and I'm standing with a bunch of business people on the elevator—you can tell the business people because they're wearing vests—and they're talking about business things, financial stuff, and in the back of the elevator is a bunch of technical people, and you can tell the technical people because they don't have vests and are probably not wearing ties and they're in the back of the elevator—and I see that the business people are ignoring me. I can see the technical people sort of look at me, and I know that they recognize me. I don't know them, but they know who I am. And I get this feeling that I should say, "Don't look at me—I'm a dinosaur. Don't aspire to be like me, because my generation is the last of the scientists, the last of the scientific executives, and we are passing out of this because the world is changing."

I get up in the morning and I can just feel the world creaking underneath me—things are stretching and changing, and there are noises out there, like ice breaking up in the river or something. Things are happening out there, and they're not good for people like me.

I was going through my viewgraphs the other day and I came upon an old one from 1984. I know it was 1984 because that was the year of divestiture, and this viewgraph was given to me by somebody at that time. It has dinosaurs on it, in keeping with my beginning theme. But here is this meeting—it's from "The Far Side" by Gary Larson. "The picture is pretty bleak, gentleman. The world's environment is changing, the mammals are taking over, and we all have a brain about the size of a walnut."

Actually, this viewgraph should be marked at the bottom, "AT&T Proprietary." Well, that's kind of my theme.

The world is changing and, maybe, it's not good for a lot of us, not just for me but for a lot of people here and in the scientific and technical fields. I want to read to you a paragraph from a book I recently read that has to do with dinosaurs. It is Jurassic Park, by Michael Crichton, and I don't mean this to be a recommendation for the book. It is a fictional account of a company that clones dinosaurs from DNA that they find—well, it's complicated, but suffice it to say they recreate dinosaurs from the preserved DNA. In the introduction Crichton talks about the change in biotechnology as commercialization took over. It used to be something that scientists sat around and discussed in scientific splendor, and in academic kind of research; but then Genetech got started and the whole world changed. It got commercialized, and we rediscovered it.

In the past, pure scientists took a snobbish view of business. They saw the pursuit of money as intellectually uninteresting, suited only to shopkeepers and to do research for industry. Even the prestigious Bell or IBM labs were only for those who couldn't get university appointments. The attitude of pure scientists was fundamentally critical toward the work of applied scientists and to industry in general.

Their long-standing antagonism kept university scientists free of contaminating industry ties, and whenever debate arose about technological matters, disinterested scientists were available to discuss the issues at the highest levels. But that is no longer true.

"Today there are very few molecular biologists and very few research institutions without commercial affiliations. The old days are gone. Genetic research continues at a more furious pace than ever. But it is done in secret and in haste and for profit. (These are some of the points I'm going to echo as we go along.) It's done in secret, in haste and for profit."

These are the pressures on the world today. Produce money from this research. Keep the intellectual property secret and do it ever, ever faster.

I want to go through a number of factors in this environment for industrial research. Many of these topics have nothing to do with technology at all. They have to do with this creaking, this breaking up of the world about us—and we're all concerned with competitiveness. It's one of the things afoot out there that matters a great deal to all of us, because if we're not competitive, we're not going to be around, we're not going to do research. Somewhere, somebody has to be competitive.

We had a meeting and we appointed a new board of the National Research Council on engineering education, and at a meeting earlier this year various professional associations came to speak to us about competitiveness. All of them hammered at competitiveness, but I remember particularly Eric Sumner, the President of the IEEE, who said, "That is the one thing the schools have got to do. They've got to produce people who can be competitive."

We could ask, "Well, how do we do this? How do we make students come out who can compete?"

And he would answer, "I don't care, but you've got to do it."

And other people would say, "Well, maybe it's not the fault of the universities. Maybe we've got the greatest university system in the world."

And he would say, "I don't care, but you've got to produce people that can be competitive, and you can't be the greatest university system in the world if your people aren't competitive."

Well, the finger-pointing about who is responsible for this mess that we all find ourselves in goes on and on. Last week I did an interview for Fortune Magazine. People do interviews all the time, and occasionally some article will misquote you terribly, or whatever, but it's not a big deal. But the publisher of Fortune had asked this reporter to ask me what we can do to be competitive. I get asked this a lot. I'm sure many people in the audience do also. The thing that always occurs to me first is, why ask me? I'm scared. If you're asking me, we're all in trouble.

But I told him that we "techies" get together all the time and talk about competitiveness. We get around tables here in Washington, principally, and other places and talk about, how can we be competitive?

I told the reporter, "We all agree on only one thing, and that is, it's not our fault." That we can agree on. But there's a flip side to that, too. The flip side is that we're not helping. The problem is that many people, in this country, feel that no matter what else we screw up, technology will save us. You know, our brilliant technology and science can triumph over everything else. But it can't. We're not doing it.

So, I really feel that the factors for competitiveness—and I'm going to put some things up here on a couple viewgraphs, but I'm not even going to talk about them—I mean, these are the kinds of things we talk about all the time as being outside of our control and they're happening in the world out there, nothing to do with us, but they're the reason for the problems in competitiveness. And the list goes on.

Another problem is that every year the list changes because, we think, now we understand it. Last year we didn't understand it. This year we do, and here is the reason, now. It used to be factories or whatever, then it was culture, and it keeps changing.

You notice that I specifically didn't put "technology" itself on the list, but I put "access to technology," because unfortunately a lot of business people now have the attitude that, "Hey, you can buy this stuff." And that portends great difficulties for us.

As a matter of fact, Bob Frosch mentioned Lester Thoreau, who was a Dean at the Sloan School and MIT. I used to look at people like that as causing many of our troubles, but now I think that people like that are really trying to understand and do something about them. I was on a program a week or two ago with Thoreau, and he gave a very incisive analysis of the problems of competitiveness. He said that, historically, competitiveness had four basic parameters about it. They are what made nations competitive as opposed to other nations. They are your natural resources, the capital that you have access to, the technology that you have access to, and the skills of the labor force.

And Thoreau showed how all the leading economic nations had these in the past—particularly after the second World War—the United States had all of these attributes and we became the leading economic power in the world.

But he said now the world has changed and that natural resources don't matter any more. Only three percent of the workforce makes a living from natural resources. As an example he pointed to the Japanese, who have the best steel industry in the world but no natural resources for steel making.

Actually, it's the capital. Capital, with the information age, moves around the world with electronic speeds. It really doesn't matter so much where you are any more. And unfortunately we have to face a fact. The same thing has become true of technology. It is everywhere. We just don't have a lock on technology, and we have to learn to live in a new world where we don't have a lock on it. According to Thoreau, technology moves around, so it's no longer a matter of where the factories are. Now the one thing that doesn't move is the skills of the workforce. Unfortunately, we're not so good there. For example, he points out that it takes twice as long to train U.S. people as it does to train German workers. Now, we're not talking about the people in this room—we're talking about the people on the factory floor. He pointed out that Motorola decided to build a 64-megabyte DRAMs [dynamic random access memory] in Japan, where the cost of labor is higher—in this particular place in Japan—than it is in the United States, but Japan has a better-educated workforce that's going to be able to do this. So now, education and the basic skills of the workforce, he said, make up the one parameter that a nation can hang on to, and unfortunately we're not doing so well about that.

I made up a list of forces about us, creakings and happening out there in the world. I divided them up into various categories. Today I'm going to spend most of the time on business forces, and I'm going to echo some of the things that Bob Frosch said, because I feel the same frustration from where I am.

I'm not taking a macroscopic view of the world. I'm looking at the world from my window in industrial research and seeing the things that influence me.

The first, and the only, world force that I'm going to talk about is something I have already mentioned. About 7 or 8 years ago I was on a brainstorming panel for Walt Disney, and the question was what could they do with some land that the corporation had down in Florida. The corporation had already built Disney World, and had just finished Epcot; it had other land and wanted to know what to do with it, but that's beside the point—it had experts from different walks of life on this panel. We spent a week just talking about it. Most of us, that is, spent a week.

One person who was listed on the panel was a futurist—he writes best-selling books on trends of the future, big trends. But he is so busy he flies from place to place like some bee that can't tarry very long, so although the rest of us spent a week there he could only come for dinner.

Maybe his wasn't as high a consulting fee. He flew in on a plane, rushed to the limo, had dinner, and then got up to run back out to his limo, getting to the next place. But before he ran off the chairman at Disney, Michael Eisner, asked him, "Well, before you leave, could you just give us one word of advice about the future?"

And he stood up and he said, "Globalization," and then he ran out to the airplane.

Globalization. When I come to work in the mornings at Bell Labs, I feel that I'm walking in the footsteps of the giants who went before me. People who invented the transistor, solar cell, lasers, radio astronomy, big bang—they're all about me, these fossils, left over from prehistoric times. And I wonder, what is my generation doing like that? And what can we do? And is the world so different that we can't do those things anymore, and, in fact, even if we did them they wouldn't matter?

The fact is that in those days Bell Labs, and a few places like it, were unique. Whatever we did was the best and the greatest, by definition. And whatever we did, we could exploit it, because there wasn't anybody else around to exploit it. But that expertise is now, whether we like it or not, spread throughout the world. There are many, many technologically capable places, and there is no uniqueness to this anymore, and we're all striving to come to grips with this.

What does that mean, now, for intellectual property, exchange of information, how we fund research, how research even matters. Hard, basic questions. There are many places that, on a moment's notice, can duplicate or adapt or even originate, instead of your facility. Now what difference does only your own technology make in that kind of world?

Let's look at some of these business forces. I have a list of items—and I'll talk about some of these. I'll even forget the privatization, deregulation issue. It made a big difference in my life, but I still get asked how divestiture has changed AT&T. I can't answer that—because it's only one of many things happening, and I can't isolate what difference it makes.

Around the world, of course, everyone is taking our example, and all the world's telecommunications are privatizing and people are saying, now, let the market decide these things. There's a story about Mark Fowler, the former Commissioner of the Federal Communications Commission, who was supposedly asked, at some dinner, his name, and he said, "Let the market decide."

One of the questions that we wrestle with is, what things is the market good at deciding? What things is the market good at promoting? A question that I come down to is, does the market promote research? Or does it force it out? If we're going to rely totally on market forces, how does that work? I don't think people really know the answer to that.

Anybody working in the research business has to be ever cognizant of the short-term focus of the people in the United States—the financial planners, the business people. They care about the next quarterly return and almost nothing beyond it. They're compelled to go into the short term, and that is antithetical to research.

I don't blame these businessmen. They're good, well-meaning, intelligent people. They're caught in a system. If they don't have a good performance in the next quarter the analysts will down-write their stock. They won't be able to raise capital. It's not useful to point your fingers at the business people, but as Bob Frosch said, the business technology is not right for a lot of things. It compels us to push everything to short term and forces out our research.

I don't want to take over the bean counters. They're running the world. This is the substitution of numbers for thought and insight and wisdom. But that's happening, inevitably, in the American system.

Bob mentioned business units and the organizational structure. This is one of those profound changes in my life. AT&T, like most companies, got divided up into business units, and the key word is accountability. We're divided into about 20 of these, each with its own bottom line. The problem is that research cuts across all of those, and now they're all arguing, who's going to pay for this research? And what are they getting out of it?

The present accounting system that breaks up companies into accountable lines of business, all of which are being forced to the short term, is a very difficult system from an interface standpoint. At AT&T I have 20 different customers, all of them tearing me apart—all of them trying to figure out, well, I'm paying X dollars for research and what am I getting?

Now, research is an investment. We used to take research on faith as good, obviously good, but now everything is being turned into business science. The director of a business unit says, "Explain this investment to me again. Why am I going to put these dollars into research?

And you explain, "Well, we've done these studies, and research pays off manyfold."

And the director says, "Well, that's good. When does it pay off?"

"Well, in 20 years, or something like that."

And he asks, "Who does it pay off to?"

And you say, "Well, not necessarily to you."

And he says, "Well, let me get this straight. Now, this is going to cost me a lot of dollars, it's going to pay off 20 years in the future and not necessarily to me. Why should I invest in research?"

We researchers don't have very clear arguments as to why the business units should do this. I think it is a question, somewhat, of getting our own house in order, but we're not economists. We may not even understand this process.

The next bullet here is "Needs versus research capability." One of the creakings going on, in this world out there—and I'm going to cover some of the technological forces in a little bit—is needs of business are changing very rapidly, and they are changing toward things like software, systems kinds of work, and we say, "Well, would you like a new transistor?" We've geared up large research institutions that are focused on physical devices. We are good at making transistors, inventing little widgets like that.

And the customers say, "Well, that's not what we want to invest in anymore. Our problems are big systems problems, software and virtual kinds of things." So there is a mismatch right now in the world on that.

Research is costing more and more. It's exceeding inflation. We're having to cut back on the head count of researchers every year just to stay at the constant inflation rate. As research moves closer to these frontiers of time and space, frequency—things like that—the cost just runs away from us.

I've already mentioned protection of intellectual property. The business people are running the U.S. corporate world right now. The technology people used to run these companies. Scientists and engineers used to be at the top of our giant corporations that deal with technology. And I sort of feel that we failed.

There is a reason that business people have taken over. I don't think we scientists and engineers did a good job in the last decade on that and the business people are saying, "We don't need very good integrated kinds of things; we can buy this here and that there and, if we need research, we can get it over there in Europe or buy this in Japan. We can solve these problems. There are business solutions to these problems. You engineers don't have to solve these problems. We can solve them from a business standpoint."

I'm going to skip over the push toward consortia and things like that.

The scariest business force of all is this last one, that there is a doubt building up, that maybe technology isn't the answer. We're coming from a place where technology was the answer in the United States. You know, it was up there at the pinnacle and there are a lot of people starting to doubt it. Maybe it doesn't even matter. And that is the scariest one of all. It's so scary I'm not going to go into it.

Things are changing in technology, too. The world is getting ever more complex and we need methods of handling complexity, and our traditional research and technology have not been very good at doing that. I've already commented on the world going toward software and large systems, and unfortunately the physical things are the things that the traditional apparatus of research is good at. The physical limits are so near that the cost and the difficultly of approaching them—things like electronic device limits are great barriers. It's getting very hard to push up into those frontiers.

There has been a collapse of the time scale. In the old world, back when those great things were done, there was time to do research and then transfer the research to development and then to transfer the development to the factory. There isn't time any more. You can't do research and then transfer. It's too late. You've got to all these things at the same time—concurrent engineering.

That collapse in time scale is affecting us very greatly. Already one of the most profound happenings is in exploratory development. I feel it is almost totally eliminated. It's gone. It's even a bad word now.

You know, the way we're really working now—not only just AT&T, I'm speaking for IBM and other places—is you have to have researchers teamed up with people from development in the factory who are doing the thing simultaneously.

And if you even talk about technology transfer I feel you've already lost. If you think you have to transfer something, it's too late. It must be done ahead of time, and it must be done simultaneously, so the old system, the serial system, is gone. I think it is difficult for NIST and government laboratories to deal with this kind of a world where things don't get transferred.

Regarding standards, our chief architect—which is a whole new position—met with our researchers a year or so ago. I just remember him pointing his finger—people always point their fingers at you when they're telling you something that you don't like. He said, "Whether you like it or not, whether your researchers like it or not, the future systems are being designed by the standards committee."

We don't know how to extract competitive advantage of things which are standardized. Standardization takes away the edge for innovation, and it evens the playing field and gives the edge to the people who can manufacture in large quantity at lowest cost—and I don't need to tell you that we're not the best at that. The process of standardization is a fact in the world at large, and the world can't live without standards. But how does the research system work in a world totally dominated by standards?

Now, there are government forces—but I'm going to move on. I did concentrate, primarily, on the business technology—having the forces out there—which are making things very awkward for us.

Let me talk just a little bit about the "emerging technologies." It's been a passion lately to do lists of critical technologies, and it's interesting because this is the Government's half-tentative step into industrial policy. I was on a committee last year on critical technologies and the report, when it came out, was condemned for two things. It was condemned that it was so weak and wishy-washy, and then it was condemned, by the other side, as smacking of industrial policy.

There are many such lists. I don't think a great deal of insight goes into these things. I think they are an expression of fashion. I really had to study this system of how fashion pervades and the people all know that things are in and things are out, whether or not there is any scientific basis or technological basis for this. These are the "in" things right now. If you make a list a year later they might change. I'm very curious as to what real wisdom there is and how the government can respond to pushing these technologies.

I'm going to break down one category of one of these critical technology lists—the information and communications list. These are things that I mostly have to do with. There is a huge industry here—electronics industry—the biggest in the United States, and scary things are happening. A report from some executive recently stated that by the turn of the century the market forces will support a billion-dollar fabrication line—that's with the 12-inch wafers, gigabyte RAMs [random access memory], DRAMs [dynamic random access memory]—enormous complexity to deal with. Not the complexity accumulating on that chip and dealing with it, but staying in the business as its costs escalate and escalate. It's not even a question so much of the costs as it is the psychology of the costs. I can remember being at poker games where I just had to get out, because somehow—even though the amount of money relative to my salary wasn't that great—I just couldn't hack it anymore. The psychology of it was so pervasive that I was forced out.

And we all know the story of what's happened in some microelectronics. Now there we are approaching these boundaries. We believe we can get to a 10th micron design rule, and there is so much work—a lot of which NIST will be involved in—to push toward those limits. As you go toward those limits, it is like turning over a rock and all these little things that you never knew were there, crawl out. There are lots of them—electromigration, tunneling and heat dissipation problems—and it's going to take a lot of difficult technology and a lot of expensive technology to keep the United States in this business as we push against those frontiers.

I want to talk about one other thing, the photonics. That's an "in" thing now. There's a lot of push here and in Japan on photonics. It is occurring often these days that we have a choice of doing something, like developing a new switch, electronically or photonically, and we're up against a classic dilemma. The business people are saying, "We cannot ride both horses. We must choose one horse and ride that. So you "techies" tell me which is going to win, and then we'll forget the other." And we're scared, because the Japanese will ride both. We know that. Whichever wins, they will be there. But the business people say, "Hey, we can't afford this. Why can't you do this? This is what we pay you for. Pick one." And we're really paranoid about which way to push.

Now, all of the glitz is with the optics. The marketing people say, "If you have a photonic switch, hey, photonics is 'in,' you can sell that. Electronics, that's the old stuff. It's not going to be a seller." There are a lot of advantages to optical technology. There is enormous bandwidth, many gigahertz of bandwidth, tremendous bandwidth if you want it in communications. By communications I don't mean communication from Washington to New York; I mean communication from transistor to transistor at every level, from chip to chip, from board to board, from module to module. Communications is largely what makes any electronic box work. Optics has the advantage of parallel over electronics, many parallel beams can carry an enormous amount of information. You can have two-dimensional and three-dimensional interconnects.

Optics can switch intrinsically faster than electronics. I'll forget about the impedance transformation, although some people think this is the most important thing, it's a little esoteric. And the long-distance communication has gone optical, because when you do your processing optically you don't have to convert back and forth.

But there is another side. There are disadvantages of optics. This is what "they" say—the electronics people who were not consulted by the photonics people. Optical devices are large, slow, power-hungry, and expensive. That seems to cover it real well. But this is an emerging technology. Somehow people think it can be ridden.

The detractors say that with a million-transistor chip you can achieve enormous functionality and integration level. In the world of electronics you can buy a million transistors, an order of magnitude, for a dollar, a million transistors for a dollar. In optics you can buy one laser for $1,000. This is a factor of 10^9. Economics are working against you. That's very hard to overcome. Photonics might be aesthetic, but by throwing millions of transistors at things, you can do the job unaesthetically but economically.

People say that optics can be intrinsically fast with the existing process, but the ones they have made are really slow, and how long is it going to take them to make faster ones? Parallelism might be offered by optics, but system designers don't know how to use parallelism.

And here is the real problem. There is an army of a million people out there working on silicon. There are handfuls of people working on optics. I always see, in my mind, the army ants marching toward the plantation in South America, eating their way along, crossing the rivers on leaves and on the dead bodies of their companions, but moving ever so slowly to the inevitable. That's what is happening in the world of silicon and electronics. There is an inevitable, irresistible force out there that the world is pushing. If you think you can ride optics, defeating that army of ants with a handful of people, you've got to reconsider.

The people in photonics continually underestimate. They think that army of ants is not moving out there. They see it from a distance and they say, "Hey, forget 'em." Then they look back to one player and they say, "Hey, it crossed the river on me."

This is just a microcosm of the choices that we face and the economical consequences of making these choices, of picking winners. There are these arguments every time to try to pick a winner—and a loser—by definition. And, we're not very good at that.

I feel that the world is changing day by day out there. Although we try to understand the world, my own hypothesis is that the world changes faster than our rate of understanding, and we will never understand what is happening out there. I don't say that it's useless to try, but I wouldn't count on understanding. Just as this year we think we understand competitiveness issues, I assure you that, if you hold this meeting next year, people will be talking differently. So the progress of learning what's happening is not commensurate with the rate at which things happen.

There are very scary business forces which are products of our system in the United States. That's not the fault, particularly, of the business schools or the people themselves, but rather of our whole social and economical system in the United States.

I have to play a role within that system of industrial research, and playing that role is getting increasingly difficult. I would just like to optimize what I'm doing, to try to understand where the levers are. Where is the leverage in technology? And what can we do, as technologists, to promote that competitiveness?

It's certainly a timely issue for this symposium. Let me, again, congratulate NIST on its birthday.

Gaining New Ground

Bobby R. Inman
Chairman, Executive Committee
Science Applications International Corporation

In reflecting last night on the wonderful occasion of the 90th anniversary of an organization I watched through the years and worked with as the National Bureau of Standards, and then have seen, in the most recent years, emerge as the National Institute of Standards and Technology, and knowing I was coming back to a place that I have visited before, in a number of different roles, I decided to seize the occasion to talk, hopefully in an upbeat way, about what Government has done, can do, ought to do, and in many of these areas can constructively do.

But, I need to spend a little time putting a context together for my views. How do I come to look at these problems related to competitiveness and, indeed, to technology?

I am a historian by education, not a scientist, not a mathematician. I spent a lot of my adult life more like a butterfly keeper trying to shepherd scientists and mathematicians as they go about doing very useful work, particularly in my years at the National Security Agency.

Coming in 1982 to the private sector, after 30 years of looking at the outside world from a lens that showed military and political competition, I found myself drawn to a joint research venture that was organized solely because of competition from the Japanese.

We persuaded first 10, then 12, then finally 21 corporations that they could not individually compete successfully against a large effort, then billed as a fifth-generation effort by the Japanese. Well, the reality was that the fifth-generation effort didn't turn out as projected, and Microelectronics and Computer Technology Corporation has traveled a lot of routes that were not initially projected.

But that led me to spend a lot of time, over the intervening 8 years, looking at how this country competes in an international marketplace and particularly how that international marketplace is changing.

Go back to 1960. The United States was looking at a world changing dramatically. Our allies, whose economies had been shattered, were recovering. Our former adversaries, whose economies we had helped recover, were beginning to make great success. And from a public policy sense we began to worry about how were we going to compete. Our answer, in 1960, was to create a structure to guarantee the free flow of goods and services between nations.

We helped put in place the GATT [General Agreement on Tariffs and Trade] structure and were the leading impetus and, even with some backsliding on occasion, the greatest practitioner of opening markets. This was far different from the historical background of barriers. We diverted off to protect a given industry on time frames, but the whole motivation was a structure to open up a changing international marketplace. We made no parallel efforts to change how we did things in what was entirely a domestic marketplace. I say "entirely." That's not quite fair. Three percent of our gross national product in 1960 came from international trade.

Fast-forward 30 years. We are now in a 5-year effort to keep alive the GATT process with the Uruguay round, which now has to be the longest running show on the international scene. We are not at all clear that we are going to extract, in the next several months, the kinds of agreements that keep a basic approach of 30 years on track. So that is a large uncertainty about what will occur, how we will go about keeping markets open, furthering dialogue, if GATT collapses.

But it's not a static world that GATT deals with. One of the reasons we've reached the stage of impasse is the reality that in less than 14 months we will have a new European Common Market. Trade barriers will go down. There will be a free flow of goods, services, and people across those 12 countries.

The large debate over the next 14 months in Europe, in which we will have minimal input, will shape how things are going to go forward beginning in 1993. This debate is on the issue of breadth or of depth.

Will all the focus be on building additional institutions? Will you see Brussels as the emerging "Washington" of the Common Market? A move to monetary union, a move on to political union, and a focus on developing those 12 economies and integrating them?

Or will the focus be on breadth, a move not only to bring in the other European countries that have been part of EFTA [European Free Trade Association], but also to reach out to Eastern Europe, to form some relationships with Poland, Hungary, and Czechoslovakia.

These two approaches are in direct conflict. They are not being looked at as complimentary approaches. Indeed one of the issues—the depth approach—would have Brussels put together, at the Common Market headquarters, a defense committee and begin planning even the security of the countries through that structure.

The breadth arrangement would look for broadening NATO and finding other structures. But there is a significant difference in those two arguments. The breadth approach would put a great deal of priority on keeping North America involved in European affairs, and the depth approach wouldn't involve North America except as a marketplace. Europe would go its own way in setting policies.

How that plays out—setting aside even what happens in the Soviet Union in the way of economic development, opportunity and/or chaos—is going to have a significant impact on what this globe looks like, how we compete, and how we organize our competition.

Right now the secretary of state is at a meeting in Seoul, trying to put in place the potential shape of the future Asian economic gathering. Again, the debate here is breadth or depth. The Malaysians have a proposal, on the table, that would essentially exclude the United States from that structure. The Koreans, Japanese, and Taiwanese appear to be supportive of a very different approach that promotes creating a structure that looks to freer flow of goods and services and technology in Asia, but one that clearly looks at this as a Pacific structure that includes the United States as well as Australia and others.

We don't know how that will play out. But the point is that within the next two or three years there will be significant changes that will affect how the countries, that are part of that, look at competing in an international marketplace. And do they look at a structure that addresses a free flow of goods and services, or a structure with restrictions?

What we do know are the areas where growth is likely to occur over the next 10 years. What we can constructively focus on is what the United States does to be able to compete successfully no matter how the international marketplace evolves, whether it evolves in a way that makes it an easy job for us or a tougher one.

There are several motivations for tackling this problem. Some have to do with the functioning of Government, and some have to do with industry. But let me come down to the simplest one—maintaining a standard of living in this country. We have a great many people who tell us that we don't need to worry about all these changes, we just need to adapt to them.

Between 1982 and 1988 this great economy created an aggregate of 8.8 million new jobs—very impressive for any economy. But when you look more closely, the reality is that we created 10.4 million new jobs in what we loosely call the service sector, and we lost 400,000 out of the extractive industries and 1.2 million out of manufacturing. Of the 1.6 million jobs lost, the average weekly wage was $444. Of the 10.4 million jobs created, even with the great push on the upper end by investment bankers, for that whole category the average weekly wage is $272. So for a great many of our citizens who are working—not on welfare—their standard of living declined during a period of very substantial prosperity because of the shift, largely, to nontechnical, nonmanufacturing jobs.

We aren't going to maintain our standard of living in this country unless we compete, very successfully, in the areas where there will be the demand for higher skills. Now you can argue that workers were overpaid, but not by that degree of break, I would argue.

Why haven't we heard more about it? Because the macroeconomists tend to look at household incomes and, you know as well as I do, the 1980's was the decade where there were two working adults in the household. Overall, household income went up while the individual income, or substantial base, declined.

I chaired an effort, under the auspices of the Council on Competitiveness, drawing the brightest researchers we could find from major corporations, major entities, across nine different industrial sectors. It took some effort playing ringmaster to keep them focused on the problem. The problem given this group was to assess what technologies are clearly going to have an impact on those commercial companies' ability to compete over the next 10 years? And then, what ought we do about it?

We found, after we finally got on the problem—and I ruled out of bounds early in the day's discussion about public policy—we reached broad agreement. We found there were great differences in the industrial sectors, ranging from construction with relatively little direct investment in technology to chemical industry with a long history of a level of investment; to biotechnology, telecommunications, software,and computers; and on to areas such as machine tools. We tried to identify which areas cut across many of the industries and which problems were industry-specific.

In fact, we reached a consensus, and I would say that it wasn't just a fashionable group. These people were persuaded, from a look at what their industries were pursuing, that these were the critical technologies for success at an international marketplace over the next 10 years.

Then we set out to try to learn some lesson from it. There weren't any surprises. The bulk of the areas had been defined in other lists, but we took the additional step of trying to understand how we ranked—not just what the lists were but how the United States was doing. Where were we strong? Where were we competitive? Where were we weak? Where were we losing badly, or where had we lost with regard to foreign owned enterprises?

I'm going to dwell here only on the lessons learned, not the individual technologies. The publication we developed, *Gaining New Ground*, is readily available to anyone who wants to pursue it in detail. But the lessons learned, again, shouldn't surprise those of you who spent a lot of time looking at these issues.

Where there was a short time between the research and an actual product, the United States did very well indeed. That's what we're geared toward. Where there was relatively little capital investment necessary, before you came to be successful at a product, the United States did very well. Where there had been sustained funding by Government, for a variety of different reasons, we tended to be doing very well in the technology, whether it was in the aerospace area and our success in that sector; or in biotechnology, when the level of investment came through NIH [National Institutes of Health]; or where, for specific procurement reasons, we had pursued an area of intense interest.

Happily there were also a few areas where industry had sustained the investment. Much of the leadership, which we now have in the material sciences, came specifically from long, dedicated investment by the chemical industry, not waiting for the Government to be the primary investor. But that turned out to be a pretty rare example as one looked across industry at sustained, long-term investment before you saw a product.

There was even an area, to my surprise, where regulation had propelled us into a leadership role: automobile emissions. Suddenly, with Western Europe and the Far East discovering environmental issues, we have a clear, strong technology lead over any other country in emission controls. It will be interesting to see if, in turning to compete, we exploit that effectively in that international marketplace.

We found that where the United States was losing badly or had lost, little or no Government funding or no sustained industry funding jumped out. Where there was a requirement for long, sustained funding before you ever saw a product—none of this came as a great surprise—in some cases the downfall was the clear result of not having a good, strong, viable industrial base for pursuing the marketplace. These were areas where we simply had given up the market and had not pursued, had essentially surrendered the field.

Now in looking at all of those we produced a report which asked, what do we need to do? Who needed to act? And how? And the report is unique among private-sector reports produced over the last decade in that it talked about what industry needed to do as well as what the academic community and, particularly, what the Government needed to do. It didn't simply say, here, Government, is a problem—go solve it.

On the other hand, it did not use the catch phrase, "industrial policy" once throughout it. And that was a conscientious decision of the chairman, to say we were going to try to stay out of theology.

In fact, there is at least a 130-year history of strong Government investment and involvement in the creation of science and technology. You can probably even go earlier than my date of 1862 and the Morrill Act which created the Land Grant Colleges and efforts aimed at extension services to transfer state-of-the-art technology to agriculture and to try to help manufacturing, and the National Academy of Sciences—chartered in the same year by a republican administration, in the middle of a conflict.

Our view is that there are many areas that have to be approached where industry must lead. But Government does create the environment in a great many ways. And that environment either encourages us to compete effectively or discourages us. You can come up quickly with your own list of things we must do to compete effectively, but there is a point we came back to, time and again. Technology must be seen as only one part of a series of areas that must all be addressed—none are options—readily available capital at competitive rates, a skilled and motivated work force—and I know Erich is going to deal with that in the afternoon—a strong base of science and technology and the supporting infrastructure. In all of those Government leads with its policies, with its investment, with its regulation. Four others that are very critically important to the world we now find ourselves in are quality, innovation, productivity, and safety. Industry has to not only provide the lead, they also have to be dedicated to the outcome.

There are two areas we didn't reach agreement on that sort of hang out there as issues. One of those we gently label as "the cost of doing business," otherwise known as the litigious society. We got into a lot of debates in the task force, simply couldn't come to agreement, because there were such strongly divergent views on how to approach it.

The one thing, though, that we kept coming back to, which is anecdotal, is that our prime competitors in Asia—the Japanese—have six engineers on the factory floor for every one we have, focusing on direct application of the technology and the product.

We, on the other hand, have 10 lawyers for every one they have, addressing the problems of doing business in this country, in a process we've put together to orchestrate and regulate a domestic economy, not looking at and not really adapting to change, as we help lead the world toward integrating an international marketplace.

Time doesn't permit dwelling on that whole range of issues. I've got proposals for all of them. One of the sad problems I find, as I talk to would-be candidates on both sides of the political aisle, is that, somewhere about the time their eyes glaze over, they say it's too complex. The problems aren't articulated in a way that the public can come to comprehend them in the arena that is available to us. And what that means is 90-second sound bites, advertisements, of the way political support is generated for public policy issues.

But let me zero in, for a very few minutes, on the Government role in successfully competing at the international marketplace. You will find that I come back, in a great many instances, to areas that are directly relevant to issues of technology and its application.

First and foremost, the Government creates and maintains the environment for successful competition. Government invests, regulates, and sets the internal trading rules. But, particularly, Government sets the international trading rules, and enforces them. And that's a critical part, ultimately, of how the process works. Primarily, the Federal Government is responsible for providing fair and equitable access to markets. That can't be done by industry. It can't be done by state and local governments.

For the issue of cost of capital and its availability, the Government can play a significant role in reducing inflationary pressures. Now we've seen that occur here, for a period of time, with a recession. Recessions do, indeed, reduce inflationary pressures. But as the recession ends, if we haven't solved some of the other problems, the inflationary pressures will come back. And the critical issue here is the budget deficit.

There are a whole series of infrastructure issues—fire, police, regulatory processes that produce telecommunications, and health—where Government has a significant role. The latest election has told us that it's going to be a much bigger role going forward. Let me suggest, as an example, competitiveness. It is directly relevant to the issue of skilled work force; it is directly aimed at the preschool and the role the Federal Government plays successfully with Head Start.

But then let me turn more specifically to issues for which there are already Government policies and have been for a great many years. The problem isn't that we don't have policies. It is that they aren't coherent, and frequently they aren't funded. Demonstration of the uses of technology, a long-acknowledged Government role. Demonstration of uses of technology and teaching skills. Government investment in facilities, in equipment, particularly for research at universities. Grants for graduate students. This has moved up very near the top of my priority list.

I look at the graying hair of much of the talent that has led us to where we are, and recognize what a large portion of that pool of talent got their Ph.D's on grants from the Office of Naval Research, or one of its counterparts, or the National Science Foundation. Then I look at what has happened since '68 and become determined that we have to find every valve we can to turn on to substantially increase the number of grants for graduate studies across the board if we, in fact, are going to be competing out in the century. We have to have the fresh talent to lead, and talent is going to be in increasingly short supply.

Regarding direct investment in science, we have a different problem. As we increasingly move toward megaprojects that, indeed, capture the public imagination, and therefore build a constituency for funding, what is the risk of crowding out funding for the small science that may more quickly emerge into technology directly relevant in the next 10 years of competition? It's clear we have investment, but we don't have an effective policy mechanism that looks at trading off those issues in the Executive Branch nor in the Congress as they come to address them. We need investment not only in the creation of science but also in the creation of technology, and in the implementation of technology.

Tax policy has, over the history of the Republic, demonstrably been a way that we have turned from Government to produce results in the private sector that are in our interest. Clearly, for encouraging competition in the international marketplace, for accelerating the introduction of technology, there are tax policy opportunities. But we're essentially paralyzed, and the catch phrase is fairness—tax fairness. The only real issue is equitability of the tax code and, therefore, we should use the vehicles of permanent R&D tax credits which have worked and would work now to accelerate the process. Currently, investment tax credits are granted only because of special pleading, and only for short time frames.

Procurement policies also play a very major role. Go back to the 1950's, a time of substantial vibrancy, success—albeit the international competitors were not yet at their peak of performance. A major source of funding for advancing technology and facilitating its move to the commercial marketplace was the defense procurement process of 4 to 5 years.

Then in the 1960's, worried about the military-industrial complex, we set out to change all that, and we created a procurement process of 12 to 13 years. It's now extraordinarily rare when you find commercial activity initiating and flowing out of defense-funded research. We have turned the whole process upside down from the point of view of contributing to our ability to compete in an international marketplace.

Clearly, that's something that can be changed. But three years ago, just at a point when we almost had some momentum for this, along came a scandal we know popularly as "ill wind"—corporate corruption and illegal activity driven by greed. That blocked the most promising prospect since the early 1960's to totally redress the military procurement process and get the focus on speed, timeliness, trade-off of cost for product, and a move away from military specs. It may be another 10 years before we get a chance again. Lost opportunity.

Let me look at two last areas on the Government side. The first is procurement policies and how they affect small businesses. How do we think about, as we implement those policies, facilitating, encouraging small businesses to aim at applying their confidence and the innovation which is still found there on problems that are directly relevant to competing at the international marketplace? Not an easy issue. We tried, at the beginning of the 1980's, legislation for trading companies. It didn't work. Sears World Trade made an effort. Maybe it wasn't long enough, but in any case the effort did not work as compared with the great Japanese success with that approach.

The other is the need to look at regulation in a different light. I'm not proposing the absence of regulation, simply dropping regulation. We saw what can happen there with the savings and loan industry. But how do you create the collaborative dialogue, between industry and Government, looking for the solutions that will, indeed, provide protection and safety—for the environment as well as for individuals—in a way that lets us make progress? The adversarial approach that still prevails will not produce the kind of progress that is essential for competition.

Industry, first and foremost, has to decide to compete at the reality of an international marketplace. Too many of the companies that I watch at close hand still operate as though they're working only at a larger, sheltered, tightly regulated domestic marketplace. The best commercial practice has to be The goal. This is not another lecture on Japanese business practices but, rather, a statement that the goal for U.S. industry has to be the best commercial practices, wherever they're found. This drives, particularly, at the issue of time-to-market for new technology.

Second, industry must design to deal with change as opposed to avoiding change. If you look at competitive results you will find that a great deal of the Japanese industrial success is geared toward going to market with a product to get market share and then, over the next two years, introduce change two or three times, or maybe four. And at the end result you not only have a solid market share but also a very profitable product out of it, rather than an attitude that says avoid change. If it runs up your cost, you can't deal with it.

Regarding longer time horizons, one last shot at a public policy issue, I suggest a look at the pension funds and a change to the tax rules. For any asset held by a pension fund for less than three years, tag it for an 85- or 90-percent tax on capital gains. For any asset held longer than three years, tax at about a 10-percent level on capital gains. You would change dramatically the orientation of investment of huge pools of money, and attitudes of corporate executives would shift very rapidly toward what's going to attract the money and that's going to produce results over several years, not just the next quarter.

In the academic sector, also, we must go back to "Gaining New Ground." The science base we have in American universities is one of our precious assets. No other country has an asset like it. We want to be very careful that we don't destroy that. This was a subject of intense debate and argument within the task force. So, we begin any recommendation by conditioning, protecting the base that is there.

But clearly we need, from the academic community, a sharper focus on producing graduates with relevant capabilities, to make sure they are staying plugged in. We must track and modify the curricula to reflect what is actually happening in industry so graduates can compete and can see, coming down the road, new challenges. And we need much more effort to push technology out of the university laboratories, not just out of the industrial laboratories, toward use.

One final area that did not end up in the report at all was the role of the National Laboratories. I was somewhat surprised, having spent 30 years of my life in Government service, to find the depth of animosity in at least some of the industrial research sectors toward Government laboratories. A lot of problems from the past have surfaced in that animosity.

But the reality, in front of us, is that there are great investments in infrastructure and great investments in people in those laboratories. At a time when we're looking to reduce the size of Government, not create new organizations, finding the mechanisms to more effectively tap those resources is critically important. We can't just waste these resources on many irrelevant issues, but we haven't yet found the right vehicles.

I've been visiting some of the laboratories to see how the current legislation is working, and what I find is a bureaucratic review process, for any proposal to work with industry, that takes 6 months, 9 months, a year. In that time—considering time horizons—in most cases, industry will have lost its interest. So this is a critical problem that we don't yet have right.

As we look at technology and competitiveness out through the century, and certainly well into the next, there is a great resource base there we must find ways to tap.

On this 90th anniversary, a hearty congratulations, John, and thank you for an opportunity to hammer, once more, on themes that I care a lot about.

(*Editor's Note: This presentation was transcribed from an extemporaneous speech*.)

View from Commerce

Robert M. White
Under Secretary for Technology
Department of Commerce

It's a pleasure to be here. What I'd like to try to do today is give you some kind of perspective on where not only the Technology Administration but the Department of Commerce and, I think, the administration, as a whole, stands on the issue of technology policy.

If there is one point on which we can all agree, it is that the deployment and the use of technology really has become the primary driver for competitiveness. That is true as never before, and it's now starting to penetrate the American consciousness.

Technology provides the essential means for creating and producing products and services at competitive costs with high value added. I think we've learned the hard way that developing global, competitive, high-valued products and services takes more than just ideas and knowledge about technology.

I often quote President Bush who said, "If America is to maintain and strengthen its competitive position we must continue not only to create new technologies but also to learn to more effectively translate those technologies into commercial products."

I doubt that anyone in this room will take issue with this view of the challenge that we face and what is required to succeed. But, undoubtedly, many of you in this room, and certainly those that you read in the papers, have very different opinions on the proper roles of the Government and the private sector. What I'd like to do is spell out a little of what I, and I think the administration, believe is the proper role for the Government and the parts of the Technology Administration, in particular.

First, what is the role of the Government—Federal Government, or state government for that matter, although that is somewhat different? It is the belief of this administration that it's the competitive market forces—and we all recognize that those are not perfect in any way, as opposed to the Government which is also, we certainly know, not very perfect, that largely determine the best allocation of our technology resources. Nevertheless, we think that the Government can and, in fact, must play an important role in both complementing and supplementing those market forces. That means the Government must foster, in particular, a stable environment and one that is conducive both to innovation and to investment.

The Government must fight unnecessary barriers that keep the market from functioning efficiently, and in many cases that may mean taking down or not erecting barriers in the first place.

The Government also has a role in supporting the development of generic technologies, and that's a relatively new concept. I think these are technologies that promise benefits that are very widespread, that underpin a number of industries and that are very complex and expensive, too much so that any one company, or even an industry, could afford to invest in. So, that's the role of Government.

What about the role of industry—the private sector? The private sector's principal role is to identify and put technologies to use in commercial products and services. In particular it is up to the private sector to support the research and development that is relevant to industry and to develop the knowledge needed to support that industry. In other words, industry must also adopt a long-term point of view.

Second, industry must identify and aggressively pursue potential commercial applications of technology, whether they are developed by the private industry or the Government or universities and, particularly, whether they're developed here or abroad. So, in other words, industry must become a better scavenger for technology.

It's also the responsibility of the private sector to focus on improving the manufacturing process and to improve continuously the skills and abilities of the private sector work force. Well, that's a tall order for industry.

Now we come, in particular, to the Technology Administration, of which NIST is a very important part. I think the primary mission that Congress has assigned to the Technology Administration is to support and strengthen the competitiveness of U.S. industry through the effective use of technology.

As with any Government mission statement, that is much easier said than done. It's also important to keep in mind that we're talking here about technology, which is only one aspect of competitiveness, and about the economic situation that we find ourselves in. In fact, some people may say it is not the most important element, but I certainly feel that it is a very necessary element.

We must also keep in mind that technology has many facets, and any one of the proposals or projects I'm going to describe for you here, by itself, may look like a Band-Aid, but together they will form a tourniquet.

Or perhaps more positively expressed in terms of tennis, to be a world-class tennis player you have to have a good serve, you have to be able to lob, you have to be able to volley, you have to have a good backhand, good forehand, and so forth. So what I will be talking about are many programs that all support this technology mission.

So, how are we going to accomplish this mission? And, in particular, what are we doing to help industry? First of all, we're linking up with both our customers and our partners, which includes everyone in this room. That means we must work with industry, the financial community, trade and professional associations, academia, Congress and other parts of the Federal Government. We must also connect with state and local governments, labor, and the international science and technology community. Well, that's a pretty tall order for what is, in fact, a relatively small organization.

Let me set out for you our five specific goals that help guide us in meeting this mission of supporting and strengthening the competitiveness of U.S. industry. These are, in fact, the five goals that appear in the White House Office of Science and Technology Policy's Major Technology Policy Document that was issued last year.

First is the translation of technology into timely, cost-competitive, high-quality manufactured products.

Second is a quality work force that is educated and trained and flexible in adapting to technological and competitive change.

Third, a financial environment that is conducive to long-term investment in technology.

Fourth, an efficient technology infrastructure, especially that relates to the transfer of information.

And finally, a legal and regulatory environment that provides stability for innovation.

Major Technology Goals

- Translation of technology into manufactured products
- Educated and trained work force
- Financial environment that supports technology investment
- Efficient technology infrastructure
- Legal and regulatory stability for innovation

Of course, we can't be all things to all customers. That means we have to concentrate on our strengths and work with our partners to meet these goals. So let me now sketch out for you a variety of programs that we have underway to support these goals.

First, and probably foremost, is our goal of translating technology into timely, cost-competitive, high-quality manufactured products. We know that traditional management and manufacturing practices are not designed to meet the market challenges of today and tomorrow. New methods, like concurrent engineering, just-in-time production, total quality management, flexible manufacturing, closer producer-supplier relationships—all can be harnessed to dramatically improve our competitiveness.

But U.S. industry has been slow to adopt these methods. Industry also has not taken full advantage of the new forms of cooperation between, and among, companies and other institutions. Nor have we, as a rule, vigorously sought out technology that is, or might be, available from external sources whether foreign or domestic. And so, our role in the Technology Administration is designed to speed industry's move to these new methods which will make or break any company or any economy in the years ahead.

How are we going to do that? We have a number of ways of doing that: promoting Government-industry partnerships, developing and promoting the use of improved methods and practices in manufacturing, promoting better use of Federal technology by the private sector, and improving U.S. access to and use of foreign commercial technology.

First, let's look at promoting Government and industry partnerships. If there is one area in which we are seeing a culture change, I think this is it. We now have what I've been calling in a lot of my speeches the "Three C's"—cofunding, coordination and collaboration—between Government and industry.

Government-Industry Partnerships

- Cofunding
- Coordination
- Collaboration

I will single out only a few of Commerce's contributions. In our Advanced Technology Program, Government is serving as a financial partner with U.S. industry, supporting industry's development of those generic technologies that I mentioned.

Our first 11 ATP Grants were awarded this past spring, through NIST, for projects that involved 16 small and 16 large companies. NIST recently finished tallying the proposals for the next round of ATP awards to be made this spring. We received 271 proposals for a total of $20 million to $25 million.

I'm happy to say that this program enjoys a broad base of support. One clear sign is that the Congress, with Chairman [Hon. George] Brown's active involvement, recently appropriated $47 million for the program this year. That's up from $36 million last year and five times the amount that was initially allocated for the program. While that's not a lot of money by Washington standards, by any means, this program is already having an impact on the behavior of U.S. industry. In the first round, we know that several consortia were formed particularly to submit proposals, and now some of those successful competitors are working together because of our grants.

Any analysis of our manufacturing infrastructure must conclude that our small and mid-sized companies tend to be way behind the curve when it comes to adopting modern manufacturing technologies. Our Manufacturing Technology Centers, which also have received strong Congressional backing, are building into a network of regional centers which serve as brokers and clearing houses for manufacturing technology. They help companies gain experience with different technologies such as sensors, computer-aided design and manufacturing, and quality control in intelligent machines.

NIST manages this program with Manufacturing Technology Centers in New York, Ohio, South Carolina, Kansas, and Michigan, and we will expect to solicit for new centers soon. These centers are another example of this principle of cofunding.

Let's look at the last goal, briefly. One of the most difficult policy issues that we've had to grapple with involves proposals for joint U.S. research projects with our overseas competitors. Japan's Intelligent Manufacturing Systems Proposal is a case in point. We've been working closely with the private sector to develop a national response, not an individual company-to-company response, to Japan's proposal for collaborative R&D in advanced manufacturing. At the same time, we are striving to promote, within U.S. firms, the capability for domestic deployment of this technology.

Well, I'm personally also involved in another program, that's not on this list, to foster Government industry collaboration. This is an effort, under an interagency process, to inventory critical technology—R&D activities—across the whole Federal Government and share those results with the private sector and establish feedback on the appropriateness of that investment. One example of this will be the review of all the manufacturing R&D that is going on in the Federal Government that will be presented in NASA's 2001 conference in San Jose in early December.

We're at NIST, so I feel no need to go into any detail about the laboratory's important manufacturing and automation research. Suffice it to say that NIST manufacturing research and services are vital in helping companies to incorporate advanced measurement, processes, quality control, and sensor technology into their manufacturing environments. And NIST has dozens of examples of success stories, cases where manufacturing technology work in the laboratories here have paid off handsomely for U.S. firms, not to mention the U.S. Navy and other Government agencies that they are involved with.

Just two days ago, at an exposition in Phoenix, I announced a national initiative to spur the development and use of technologies and techniques for exchanging digital product data. This product data exchange commits industry and Government, including Commerce, Defense, NASA, and the Department of Energy, to work together to computerize our whole manufacturing enterprise. The development of PDES, Product Data Exchange using STEP [Standard for Exchange of Product Model Data], as the technology initiative is called, will allow manufacturers to achieve the open, global exchange of digital data about different products, something that we feel will remake manufacturing in the 21st century.

One of the most encouraging signs of the times is the way in which our Malcolm Baldridge National Quality Award has taken hold. We now have, literally, thousands of companies using the guidelines from this award program to improve the quality of their products and services. First presented in 1988, the award has become a standard for quality achievement. The three 1991 winners—relatively small electronic firms—and the nine other firms prior to that—provide shining examples for improving the methods and practices of all American companies.

Occasionally, in addition to all the good things you hear about the Baldridge Award, you also hear occasionally some criticism. But I think the real issue is—and it relates to this whole issue of the involvement of Government in this technological competitiveness issue—would the U.S. Government be better off if the Government had not, or would U.S. industry be better off if the Federal Government had not, exercised leadership in introducing the Baldridge Award?

American manufacturers are missing out in a very basic way when it comes to how they measure things, and converting to the metric system is not really a choice our manufacturers should be pondering in 1991. It's a choice that they should have already made, because the rest of our trading partners did it a long time ago. At Commerce, we are putting a high priority on achieving that goal. First, we are trying to practice what we preach and carry out a law—that, again, Chairman Brown helped to author—for Federal agencies, to make the switch to metric by the end of next year when procuring billions of dollars' worth of goods.

Let's talk a little about promoting the better utilization of Federal technology by the private sector. With the huge Federal science and technology investment, on the order of $72 billion a year, we have a tremendous national resource which can, and must, be put to better use.

At Commerce, we are emphasizing outreach to industry by sponsoring conferences to highlight Federal technologies which do have commercial application, and we're promoting industry-Federal laboratory partnership through Cooperative Research and Development Agreements, CRADA's. NIST alone has signed nearly 160 of these CRADA's in the past 3 years.

We're also making an effort to upgrade the private sector's use of the wealth of information available through the National Technical Information Service, NTIS, which serves as a clearing house for disseminating the results of Federal research.

One of our greatest shortcomings in this country has been our lack of attention to the wealth of technology being developed abroad, and that is why we must reach far more companies with our Japanese Technology Program, which makes technical information from Japan available to U.S. firms.

International standards are another area deserving far greater attention by our manufacturers. NIST has established a variety of new services to assist U.S. manufacturers and exporters in addressing standards-related issues. In fact, Commerce Secretary Robert A. Mosbacher clearly understands and appreciates the importance of international standards. He has been a tremendous supporter for U.S. industry in discussions and initiatives to open up the process for setting and implementing standards, particularly in Europe.

Let's talk briefly about the quality work force that has to be educated, trained, and made flexible. You can debate all you want about the accuracy of international comparisons which show American students at the bottom of the list when it comes to math and science education. The fact remains that too many Americans lack the knowledge and skills to manage and perform the demanding jobs of a fast-paced, technology-based economy. Businesses complain loudly about the poor quality of new work force entrants. Unless dramatic changes take place, the majority of those entering the work force in the future will be even less skilled. This is an area that we, at Commerce, have not specifically been charged with addressing, and frankly, it has not been an important part of our efforts to date. Still the issue is growing in importance, and we do have programs that attack this problem, if only in a limited way.

I want to single out, again, our NIST hosts for their ambitious education efforts, both here and in Boulder, in ventures that reach out to elementary school students all the way to "post-docs" and rely heavily on volunteers. NIST is setting an education example for our other Federal laboratories.

I'll say a little about the financial environment. It's difficult and maybe impossible to point to any new and emerging technology that doesn't require financing over extended periods of time with little, if any, short-term return. That doesn't sit well with investors, who want near-term payback, and that obviously is a significant obstacle to improving U.S. competitiveness. Most analysts and policy makers attribute this short-term focus to the cost and patience of capital. But there are other important explanations that too often get short shrift from the finance and accounting professions. These include outmoded accounting methods and investment analysis techniques, as well as the legal and traditional separation between U.S. finance institutions and manufacturing enterprises.

In the Technology Administration, we have two ways to help create a financial environment that is conducive to long-term investment and technology. We're doing that by identifying and advocating policy options to increase the availability of long-term capital for technology investments. We're attacking this problem, in part, by hosting a series of round tables and by networking with our customers. We've also been working with the financing, accounting, and manufacturing communities to develop accounting and investments analyses methods that better reflect the benefits of investing in new product and manufacturing process technologies.

Let's talk a little about the infrastructure. Recognizing the importance of the technological infrastructure, we've carved out special assignments that relate to the measurement, control, and market transaction activities that make for modern commerce. Industry under-invests in this infrastructure since the benefits cannot be captured directly by their investments. Government assistance here often comes in the forms of standards. Today's short technology life cycles increase the importance of providing the technical bases for standards in critical technologies, and it makes timeliness not just a virtue but a necessity.

Other nations in the world marketplace are providing their industries with timely, systematic, and competitive technical information. We need to do the same. That's way we provide measurements and measurement techniques, reference data and materials; the bread and butter of NIST for the past 9 decades. It also explains why we, through the National Technical Information Service, serve as a central source for technical information and services.

Finally, let me say something very briefly about some of the activities in the legal and regulatory area. It doesn't take any special genius to know that Government regulation and policies make a big difference in determining the time and costs needed to bring a product to market. Regulation is also a major factor influencing investment decisions for new technologies. It can, literally, make or break any hopes for commercializing a new technology.

Our foreign partners, meanwhile, have their own policies and regulations that may give them an unfair advantage. For example, wouldn't it help our balance of trade, our job situation, and our tax base if we had the, roughly, $50 billion that we lose each year to those who infringe on our own intellectual property? At the Technology Administration we're providing the technology perspective to establish a legal and regulatory framework conducive to rapid technology development and commercialization. Too many policy decisions have been made in the past without the benefit of this technology perspective, and that is why we're providing information and advocating certain positions in a whole host of different Government forms.

Once again, winding up with NIST, we are providing both industry and Government with a means for achieving more equitable regulation. We do that by offering the technical measurement support which underpins Government regulation of important areas of public health and safety. These include building and fire codes, medical testing methods and standards, and environment measurements and analyses. The sheer complexity an diversity of Government regulation continues to put great pressures on the relatively invisible, but critical, scientific and technical measurement base upon which regulation rests. NIST laboratory work helps to make sure that that base is sturdy and even.

I've set out what I think is a fair description of the relative roles of industry and Government and have sketched for you the role of the Technology Administration. Our technology policy today looks much like it did many years ago, but there is a difference, an important difference. That is obvious by looking at the way in which we are implementing these policies. The implementation has changed substantially and for the better. We launched new efforts and are making new headway in cooperation, cofunding and coordination. The results are not as dramatic as we would like. Programs such as the Baldrige Award are the exception rather than the rule. They usually take much more time to take hold and show results. Our Advanced Technology Program, our Manufacturing Technology Centers, our shared flexible teaching factories, are off to good starts. Our efforts to coordinate a U.S. response to proposed international joint R&D programs are making a difference.

But cooperation and coordination are not easy to come by in a society that is steeped in the tradition of individualism, and that is perhaps the greatest challenge that awaits us as we move down the decade of the 1990's.

View From the Congress

Honorable George Brown
Chairman, Committee on Science, Space, and Technology
U.S. House of Representatives

I am one of those who count myself as being very fond of NIST and all of its programs and having a very great deal of respect for them. I also compliment Dr. White on his exceptionally good presentation of the programs of the Department of Commerce. They are strong. They are evolving. They are effective. And I'm still going to criticize them for not going as far and as fast as I would like.

On the other hand, it is legitimate to criticize the Congress on occasion for being unrealistic and expecting more than is deliverable, and I welcome that kind of criticism also.

But, frankly, I'm going to make a point here that this country, and maybe the entire global economy, is going through a stage which a noted sociologist of science once referred to as a paradigm shift, and it's going to make demands on us which I don't think we can thoroughly anticipate in terms of changing the way in which we look at the world today.

I will not assert that this is the view of all members of Congress and that, therefore, it falls within the title, or the implication of the title, of my remarks about a "View From the Congress," but it does represent the view of a member of Congress which, I think, perhaps a few others share.

I'm pleased to be a part of a celebration of the 90th anniversary of the National Institute of Standards and Technology and its predecessor, the National Bureau of Standards. This organization has upheld a nearly century-long tradition of leadership and quality performance, and it therefore is a real pleasure for me to participate in it.

The many distinguished speakers on the program, I'm sure, will cover, with great expertise, the many topics of science and technology and competitiveness. I will try to give you a somewhat broader and less detailed framework to look at these things. Some of this may be original but non-expert, and some of it may be redundant. If there is anything original in it I will claim some modest ownership, and if it's too redundant, I apologize in advance.

Competitiveness can neither be discussed nor improved by separating it from our national attitudes and our social environment. There is probably a broad familiarity, in this audience, with the ongoing Congressional debate on science, technology, and competitiveness. What I hope to explore is why we have spent more than 15 years discussing and dissecting our competitiveness problems and why we are still unclear as to the nature of the solutions.

To a large degree the focus of much of my work in the Congress, for many years, has been trying to establish a long-range or a strategic viewpoint on problem solving for the future. I have not necessarily won much support or sympathy or, perhaps, even friends for this position. Nevertheless, it is my nature to think in these more global and strategic terms than in parochial and tactical terms. This sometimes gets me into trouble politically, and I have to apologize for this lapse from politically correct thinking on occasion.

Every nation or culture has an internal image or vision of itself. That depiction, as a positive force, shapes the society's expectations, its goals, and much of its ability to reach those goals. As broad economic and social changes occur, over decades and centuries, every nation's position in the global context also evolves and shifts. If these changes influence national understanding and attitudes, they are a productive force. They help shape the society's ability to develop realistic goals and pragmatic mechanisms to achieve them. History, however, provides us with many examples of countries, and even empires, whose concepts of global reality stopped at the moment of their own historical prominence.

In 1986, the writer-historian Paul Kennedy wrote in his text, *The Rise and Fall of Great Powers*, "So far as the international system is concerned, wealth and power, or economic strength and military strength, are always relative and should be seen as such. Since they are relative and since all societies are subject to the inexorable tendency to change, then the international balances can never be still, and it is a folly of statesmanship to assume that they ever would be."

Kennedy uses the British as one example. The geographical size, population and natural resources of the British Isles would indicate that it should possess 3 or 4 percent, perhaps, of the world's wealth and power, all other things being equal. We know, of course, that all other things are never equal. Thus, an unusual set of historical and technological circumstances allowed the British to far exceed their 3 percent to 4 percent of world wealth and power. At one time in British history that percentage probably rose to 25 percent of global wealth and power.

Kennedy goes on to suggest that since those uncommonly favorable circumstances disappeared for the British, their country has been returning to its more natural position within the community of nations.

Now, through a set of equally unusual circumstances, the United States experienced a period of extraordinary historical and technical advantage culminating in 1945. At that time our share of world wealth, productivity, reached about 40 percent. Two situations allowed us to achieve this extreme prominence. America had a vast manufacturing capability intact after the war, while at the same time the economies of the other major industrial nations were in a state of virtual collapse. This uncommon advantage persisted for only slightly more than 2 decades for the United States. In our own imagination, however, it has persisted until very recently.

The danger for us has not been that other nations are now strong economic competitors; rather the danger has been that our concept of global reality became fixed at the point of our post-war preeminence 45 years ago. This has been a powerful obstruction to tackling our competitiveness problems in a strategic and pragmatic fashion.

I'm not in any way suggesting that the United States is no longer a significant world power. Far from it. I am suggesting, instead, that we have been unwilling to accept in our own mind these new global shifts and trends. This has inhibited our capacity to seize new opportunities. These trends are not complex or esoteric, but rather unbelievably apparent.

For example, for many years the National Science Foundation has regularly published comparisons of the research and development funding priorities of all the major industrial nations. From them it is simple to discern other countries' priorities and many of their strategic R&D decisions.

From these comparisons we know that, in 1988, fully two-thirds of U.S. Government R&D funds were spent for defense purposes. In comparison, other industrial nations devoted much smaller portions of their government R&D to defense. Japan spent 5 percent, Italy 10 percent. West Germany spent 13 percent. Even the United Kingdom and France, which spent 49 and 38 percent respectively, were both spending significantly less on military R&D than the United States.

And I will not argue the necessity, the political necessity, for that at the time. But what research and development work did we choose to neglect for our disproportionate emphasis on defense? In 1988, the United States spent only 4 percent of its R&D budget on industrial development and energy combined. During that same time Japan, West Germany, and Italy each spent between 22 percent and 29 percent of their R&D budgets on industrial development and energy. Also, in 1988, the European Community member countries spent about one-third of their R&D funding on the advancement of knowledge, while the United States spent about 4 percent in the same category.

These percentages are not unique to the year 1988. They are indicative of a shift in emphasis and planning going on among industrial nations for at least a decade. Although these significant global patterns should have been easily recognizable, we have chosen to ignore or resist their message.

There is a kernel of wisdom from 11th-century China that perhaps sheds some light on this. A Chinese philosopher-poet at that time wrote, "Look at things from the point of view of the things and you will see their true nature. Look at things from your own point of view and you will see only your own feelings." It seems to me that the true nature of things exists in their indisputable facts. Whether or not we choose to ignore those facts depends upon our own personal feelings and motivations.

For America, the Second World War established a continuing Federal commitment to defense technology development. There is no question that this was dictated by world events. However, we have directed our national life primarily from a national military security perspective since then. In the past 20 years the substance of national security has moved, in large part, from the military to the economic arena. Nevertheless, our defense emphasis persists, along with a post-war dogmatism about things as they were. These attitudes have kept us from making decisions based on the true nature of things.

Every one of us here is familiar with a decade, at least, of reports indicating American weakness in many critical technology fields. Each subsequent report has shown another area in which we're losing ground. There is a new report from Japan's Economic Planning Agency entitled, "Technology Forecast for the Year 2010." It lists 22 emerging technologies in which Japan believes it now leads the world and 23 emerging technologies in which it is tied for first place. They don't believe they're second in anything.

At this point such information is not surprising, but unfortunately predictable. Nevertheless, the current Administration has had to design a clumsy, absurd term which you're all familiar with, "precompetitive generic enabling technology," in order to provide any Federal support for civilian technology development. It's surely difficult to build a major technology strategy on such subtlety and semantics. That's why I say we need a paradigm shift.

I will not recite the history of Congressional efforts over the past 15 years to encourage a more aggressive Federal role in helping U.S. industry remain competitive in the global marketplace, including the advanced technology marketplace. I will not even contend that all of these Congressional efforts were necessarily the best course to follow. But these efforts did lead to the development of the Advanced Technology Program in the Department of Commerce, and I'm extremely proud of that. That was incorporated, of course, in the 1988 Trade Bill, one of the few good things that President Reagan ever did, for those of you who may be Democrats.

The efforts also led to the restructuring of the National Bureau of Standards into the new National Institutes of Standards and Technology.

The Advanced Technology Program is basically a mechanism to leverage industrial research for new technologies. The program is designed to fund industry-led consortia or joint venture R&D work for technology relevant to commercial use, and you've heard a very good description of that from Dr. White.

In the first year of the program, it was a program in name only because there was no money either requested or appropriated for it. In succeeding years, growth has been slow, but we hope steady. Each year the Congress has funded the ATP somewhat above the Administration's request, but the money appropriated bears no relation to industry's eagerness to participate. In 1990 the program was funded at $10 million, and there was $125 million in proposals from industry. In '91 the funding was $36 million, and for '92 it will be $47 million, and the 1992 funding is not even one-half of what the industry proposals requested three years ago.

Now, I do not advocate having an ATP budget that would accommodate every possible proposal. However, I do think that efforts to reach our national goal, which is to stimulate industry investment in advanced technology development, should not be inhibited by regressive political attitudes. We are hoping for a significant change in the Administration request for Fiscal Year 1993 to which the Congress can then respond in a favorable way.

And of course I probably should mention that we will have a rather strong initiative contained within the Department of Defense Authorization and Appropriation Bill which is currently in conference and will be coming to a vote—both of these bills—within the next few days. And I support this major initiative. If it is what I expect it to be, it will far exceed what we have in the Department of Commerce.

And while I will support it, and I do not want to disparage the excellent work which DARPA [Defense Advanced Research Projects Agency] is doing, or any of the other technology initiatives in the Department of Defense, because we need them all, but I think it is ironic that this initiative should be coming from the Department of Defense when the need is within our domestic civilian high-technology industrial sector.

We keep putting our eggs in the Defense technology basket when the marketplace has been selling its wares from the civilian basket for the last 20 years. In our long struggle to understand the competitiveness puzzle, we've repeatedly emphasized American inventiveness. We think of ourselves—and we are—a nation of inventors and inventions. Our contributions over the last 35 years alone would earn us a foremost position in the history of modern science and technology.

In historical comparison, that position would rival the status of Chinese invention 500 years ago. The Chinese were unquestionably the world's most innovative people during the medieval period. At a time when much of the world slumbered, there was a flurry of inventive activity in Chinese society. With certainty, we can attribute to them the invention of gunpowder, paper, silk, weaving, clockwork, astronomical instruments, the horizontal loom, the spinning wheel and the water wheel.

Despite this extraordinary contribution, the technology of the modern world is Western. The impact of innovation and invention on the future course of civilization did not occur in the East, but rather in the West. James Burke, in his work *Connections*, explains why this phenomenon came to be. He tells us,

> "In the stable, civilized East the innovations were not permitted to bring about radical social change as they were in the brawling, dynamic West. The chief reason for this may have been the stultifying effects of bureaucracy . . ."
>
> Where have we heard that before?
>
> ". . . which owed its origins to the geographical nature of the country. China is a land of wide plains and major rivers, and early in recorded history the Chinese undertook vast irrigation schemes. The Civil Service, which evolved to run the irrigation schemes was to remain in power for thousands of years, guarding its position and privilege against change."

This rigid social design was an important influence in shaping Chinese expectations. Without any motivation for the individual to use technology to improve his position in the world, the startling Chinese advances were severely controlled by social gridlock. Invention may have emanated from the East, but it was only in the West that it became a major vehicle of change.

It seems to me that the Chinese offer an important case to consider. Americans, as the master inventors of the post-World War II period, are repeatedly chagrined by their inventions becoming Japan's commercial successes. Some historian in the 23rd century will dispassionately point out that the social and political infrastructure of the United States in the late 20th century was a major inhibition to American commercial success. He or she will record that in 1991, in the United States, every 8 seconds of the school day a child dropped out of school; one in five children lived in families with below-poverty-level incomes; every 26 seconds a child ran away from home; approximately 32 million Americans were without any health insurance protection; every 67 seconds a teenager had a baby; the length of the American school year ranked among the shortest in the industrialized nations; every 7 minutes a child was arrested for a drug offense; the American transportation sector was 97 percent dependent on oil for energy, despite the fact that this made this nation severely dependent on imported oil; every 36 minutes a child was killed or injured by a gun; and American students scored at the bottom of the international ranking for science and mathskills. That's what the historians of the future will point to in our society.

There are many more examples, but I think we all understand them. James Burke tells us again,

> "History is not, as we are so often led to believe, a matter of great men and lonely geniuses pointing the way to the future from their ivory towers. At some point, every member of society is involved in the process by which innovation and change come about."

No one would dispute Burke's premise of every member of society being a participant in change and innovation. Every person, however, must be prepared by the society to contribute effectively. We know that children who are hungry or frightened do not learn, workers who are poorly trained do not improve productivity, businesses that ignore quality control management turn out poorly made products, and industries that don't invest in R&D may soon be left behind.

Our science and technology can only contribute to our desired outcomes if the larger structure of our society does not obstruct that from happening. China's constraint was the rigid social organization of its civil service; America's constraint is the sizeable human infrastructure that has been both neglected and negligent, and a self-image focused on our role of past preeminence, rather than on the realities of the world today. Our first-rate science and invention makes us proud, but they make others prosperous.

To reverse this pattern, we need to assess realistically our place in a new global order and to prepare every citizen to lead us in that direction. For the policymaker, this means that the rhetoric of preeminence must be replaced by the realism and the recognition of both strengths and weaknesses. For the CEO, this means replacing the only-if-invented-here attitude with the admission that good ideas are not exclusive to America, they're global. For the teacher, it means replacing rote learning with problem-solving content.

None of these tasks are unreasonable, nor any of our goals unreachable, but science and technology will only help us if we begin to help ourselves.

Education and the American Workforce

Erich Bloch

Distinguished Fellow, Council on Competitiveness

I wouldn't have missed this opportunity to talk to this group this afternoon on the 90th anniversary of NIST—and my congratulations. NIST has been, is, and I am sure will always be, a force in technology in Government and industry and with regard to competitiveness, and I want to congratulate John Lyons and his excellent team and all of you in this particular room, and I offer many happy returns to you personally and to the organization.

I think it's proper and very timely to talk about science, technology, and competitiveness. We are at a very important juncture of our national life. The world is changing, and I want to remind us of this as we go through some of the discussions this afternoon. Just look at the changes this year alone: the Cold War biting the dust, an Iraq war that nobody could have foreseen, a recession that doesn't seem to end. And, by the way, just an indication of how bad the recession is, the American Rifle Association had to lay off two Congressmen.

Well, the question obviously is, why do we find ourselves in the situation that we are in? What are some of the causes and some of the reasons?

It took us a long time to understand that the world we live in is fundamentally changing. Over the past 15 years the United States and other nations throughout the industrial world have faced, and are continuing to face—maybe more so in the future than even in the past—economic, political and technological realignments of unseen proportions. The markets in which we have to sell our products have become international. We no longer have a large domestic market dominated by our own industries. This is true for the new, as well as the established, industries. In this global marketplace technology has become the key to economic growth and the principal source of competitive advantage.

Since World War II, the economy has been transformed into a knowledge-based, into a skill-based, economy. Industries based primarily on knowledge—and just think of biotechnology, think of computers as examples—and fast-moving technologies, are the industries that are fueling this growth and this change. In this new environment competitiveness is determined much less by a nation's natural resources, or low-cost labor, and other classical comparative advantages that were very important in the past, than by the ability to generate, and to access, and to rapidly deploy new knowledge and technical insights and convert them into quality products and processes faster than one's competitors. That is the fundamental law, the new fundamental law, in this competitive world.

If this analysis is correct, then it stands to reason that the investment a country makes in people and education, in research and technology, is really critical to its success. In fact, a high-quality, educated technical workforce is the basis of the knowledge economy and a prerequisite of competitiveness.

We had an impressive lead right after the war. We enjoyed a very big lead as far as our technical workforce was concerned, its quality as well as its size, compared to some of our competitors, and that lead has narrowed significantly as other countries expanded their workforce, educated their population and put money into R&D.

It's kind of interesting. I just came back from a two-day session—and that's really why I was late, because it didn't end until 1:30—of the Council on Competitiveness. Two pollsters, over the last few months, have gone up and down the country and interviewed something like a thousand people in focus groups, and the results that they came back with were disconcerting. The overall conclusion is, of people speaking to these pollsters, the system is broken, the Government is failing us, business is failing us, and education is failing us. And notice the focus on education. These are, by the way, the most prevalent kind of comments that you get out of this particular survey.

The view on education is that we are continuing to lose ground, that we are no longer the best-educated country, that having education is the make or break point to personal well-being, and the United States has not adjusted to the challenges. What these people propose is steps to help our training, tightening educational standards, and putting dollars into education. It's kind of interesting that that comes to the surface in the broad range of discussion that ranges from unemployment, to Japan, to all kinds of other things.

It's encouraging that these people who have been interviewed, and it was a good cross-section of people throughout the country, geographically as well as socially, focus on education, and I would question if that would have been the case 5 or 10 years ago. But I consider that—if you want to see something good in a dismal situation—that's a silver lining.

The education of our children, the education of our workforce, and the education of our population to be technically and scientifically literate, I think, is the highest priority a country can have in this day and age. It's infrastructure, par excellence. We always talk about infrastructure—communication, transportation, and so forth—and I think education is the basis for all of these other infrastructures, specially in today's information technology-based world.

I noticed George Brown quoted the Chinese, and I wanted to quote the Greeks. You might as well see something else. Aristotle, a few thousand years ago said, "All who have meditated on the art of governing mankind have been convinced that the fate of empires depends on the education of youth." I don't think this could be said with more reason today than at any time before. It could be not more true today.

So let me talk about education, and what I would like to do is define education very broadly. I don't just mean K-12 [school grades Kindergarten through 12]. It's the totality of our education problem from K to, well, let me say from K to grave, and I don't want to sound morbid, by the way, when I mention it. But let me break it down and say something about each of these component parts, K-12 first.

Much has been said about it. Many reports have been written. Too many reports. Much, by the way, has been done. You see a lot of things happening. The President has made it his agenda, and rightly so, and I don't want to repeat everything that everybody else has done. You have heard it yourself. I just want to remind us that this is a 20-year kind of process, that the results of this will not be visible in 1 year, or 2 years, or 5 years, and, as you know, both Congress and the Administration deal with 2- and 4-year kinds of time frames, and this doesn't lend itself to this kind of treatment. We'd better stay the course is what I would really want to emphasize.

It should concern us all, if one reads, as I did in The Washington Post the other day, commentary maintaining that we are not as bad as the tests would indicate, as if it matters if we are last or at the low end or the middle of the pack. The point is that we sure are not at the top, and that is what should concern us. So we see some people essentially trying to fix a problem by analyzing the second decimal point of a fairly subjective kind of test in the first place. That's not solving the problem. That's not leading up to a solution.

What's the reason for our poor showing? The reason is the values we put on teaching and on learning, and we are not putting a very high value on either of the two. Family life certainly has a lot to do with it. The priorities in our leisure occupation—TV, sports. Have you heard of books? What I'm implying, I guess, is that we are all at fault for this poor showing we have in this very important area.

The next area that I want to discuss is undergraduate education. Especially in this setting I think it's very appropriate to talk about engineering undergraduate education, but many of the things that I have to say are equally applicable to the sciences or even to the humanities. They all have similar kinds of issues coming at them from similar kinds of directions.

If you talk about undergraduate engineering education, I've got to tell you right from the beginning that I'm not enthused with what I'm seeing these days. We are in the middle of change, and nothing changes more, by the way, than engineering. New knowledge, new tools, new demands are redefining what it means to be an engineer. New areas of research and development are emerging. Many new material areas, robotics, biotechnology, new tools, computers, sophisticated workstations—every day another one—graphics, new analytical software packages, are changing the way we practice engineering and making top-down, complex system design a reality.

Moreover, the problems that engineers are expected to solve are changing. Many modern problems require a multidisciplinary approach, so that while firm grounding in a specific engineering field is necessary, it's no longer sufficient for engineers to have only mastery of a narrow discipline, but that's how we educate them.

Today's engineers need a broader base of knowledge. A practicing engineer today must be a master of one and a jack of all trades. He or she must be able to learn quickly what needs to be known from other engineering specialities, other sciences, in fact from the humanities and the behavioral and social sciences. The demands on American engineers are changing in response to changes in the world. The pace of progress is quickening. The time gap from concept to technology readiness is shrinking, and the transition from prototype design to commercial production is accelerating. You could compare what goes on today with previous developments, but I don't want to spend the time on that.

As we would expect, these changes are affecting the way we practice engineering, and the old approach—the linear, the compartmentalized engineering organization and procedures—focuses much too narrowly on engineering parameters. The new approach takes into account the interplay between product design and manufacturing processes, as well as environmental impacts. Regulatory constraints are entering into the engineering equation, believe it or not, and so are multiple and foreign sites and sources where some of these products either wind up or are being assembled or are being tested.

State-of-the-art engineering requires a systems approach. U.S. industry has been slow to adopt this approach. It takes U.S. firms twice as long and four times as many man-hours to install flexible manufacturing systems, as an example, or, if you have read *The Machine That Changed the World*, the Massachusetts Institute of Technology study of the world automobile industry, it takes us 60 months from the beginning of design to production versus 43 months for our competitors in Japan.

One reason why we are trailing in manufacturing is that engineers are not trained in these new approaches, and only in the last 5 years has manufacturing engineering been reintroduced into college and university curricula. In college, by the way, or subsequently in a company, we are not doing the right training job either, and I believe this is a shortcoming of U.S. industry and the U.S. educational system. I think both of them share the blame for that.

The National Science Foundation, 2 or 3 years ago, had a workshop to look exactly at that problem, and it was interesting what came out of it. There were some observations and some suggestions. Let me just give you a few of these suggestions:

—Greater emphasis on design, on synthesis, in the curriculum, rather than just analysis;

—A standard treatment of engineering science among the various engineering disciplines. Instead of educating the mechanical engineer and the electrical engineer, let's educate an engineer-kind of a novel idea, by the way;

—Greater use of workstation and expert systems;

—More industrial internships; and especially,

—More lab work and experimentation, which really have fallen behind in recent years, especially in some of our better research universities.

It's no surprise, based on that, that our impressive lead in scientific and engineering personnel has disappeared. With half of our population, Japan trains as many engineers each year as the United States. And, by the way, the question is what are they doing with all of these engineers? It always puzzled me, but I think of late I've heard too many stories that they are much more careful in their engineering approach, they use more engineering manpower, they do things more rapidly, they do it with higher quality. And, by the way, what I'm just telling you I heard from a middle manager engineer in one of our prestigious companies who has interfaced with Japan over the last 3 years, transferring a process from Japan to the United States. Interesting. By the way, similar statistics are true in Great Britain and in Germany, as well as in France.

At the same time, we see a drop-off in our engineering enrollment and completion, maybe even more so in completion. The demand for technically qualified labor is increasing. It's increasing all over the place, in the service sector as well as in manufacturing. And in manufacturing it's kind of interesting. With a static population in manufacturing, in terms of percentage of the total population, the engineering component has increased on a percentage basis, which makes essentially the point that we need more, that what we're trying to accomplish in manufacturing is getting more sophisticated, more technology oriented, and as a consequence you need different kind of people.

I said before that at the same time we have this greater demand, the technical degree acquisition at all levels is declining. Science and engineering degrees have been falling off primarily, by the way, because the demographics are changing on us. The 22-year-old population, or the 18-year-old population, is essentially decreasing. The composition of the college-age population is changing. By the year 2020, minorities will constitute almost 50 percent of the student population, and they and women will play a more important role in our talent pool. But all statistics indicate that women and minorities are not participating in engineering as a percent of the population to the extent that the rest of the population participates, and that's an issue that we need to address, and I have tried to address. And we are making, just as with the K-12 education, very slow progress.

Putting all of these factors together, one can conclude with accuracy that there will be an under-production of scientists and engineers, an under-production in terms of what we've produced in the past, and other technical people, in this decade compared to the 1980's. If the country wants to grow in an increasingly technological world, this erosion of our human talent pool can put us at a disadvantage. If our decline in technology leadership is caused by the lack of attraction of our students to sciences and engineering, or if the inverse is true, it's difficult to decide. That the two events are connected, however, is pretty obvious.

It's an interesting observation that Congress is trying to figure out if NSF predicted a shortfall of engineers and scientists or not. All NSF ever asserted was that there would be fewer undergraduates in science and technology produced than in previous years as a percent of the population. We are not good at projecting demand, but we can project with very great accuracy, in fact, we can project attainment rates. By the way, it's questionable whether we need all these people. If biotechnology declines, as it has in the last 10 years, and our manufacturing organizations and other companies decline at the rate they have, maybe we won't need any. But that's a poor way of looking at the problem, I would suggest.

Let me switch to what can be done about this undergraduate education. I think a revamping of the curriculum is in order. NSF has funded some experiments in that particular area, not enough of them, but I think it's up to the universities, to the professional societies, to the people in this room, to really address that problem and ask ourselves if we have the right educational standards for the 21st Century, at least as far as engineering is concerned, and I would suggest that we do not.

You know the story at the graduate level. The number of Ph.D. degrees have been declining very rapidly. They have been leveling off, and they are starting to increase somewhat, primarily because of the influx of foreign students, not because of the increased interest of our own students in advanced degrees or in engineering and the sciences at least, and we need not only to understand but also try to remedy that situation. We can't depend strictly on foreign students to help us out in these very vital areas. As possibilities and capabilities increase in other countries, we'll be in a very competitive world for these students.

We need to talk about another area of education, namely the technical non-professional area—the technicians, the laboratory assistants, the manufacturing technicians, those in manufacturing support, and so forth. This is an area that should concern us. We have 3,000 or so 2- and 4-year colleges, vocational schools, community colleges, whatever you want to talk about, very varied kind of institutions. There is not much quality control there. There are some very outstanding schools, there are some very poor ones, there are some in the middle. The educational need for the people that I'm talking about who take this vocational training or pre-professional training, or paraprofessional training, is also changing, just as the needs and the knowledge base for engineers are changing.

Let me describe it by suggesting that the manual dexterity of the past, as an important criterion for deciding who should go into this particular occupation, is no longer quite as important or the sole indicator of talent. Today, a technician has to know statistical analysis; he has to know how to make a software patch, how to read a software program. The intellectual capability of the individual is much more stressed and much more in demand than the manual dexterity of 10 and 20 years ago. But above all, a more in-depth knowledge of more technology, of more of the sciences, is required with the quick-changing technologies that we are facing, and the broad range of these technologies has to be understandable to the individual, and the individual has to be fluent with those.

This paraprofessional group supporting scientists and engineers and technologies has always been neglected, by the way, compared with their colleagues in Europe and especially in Germany, and I think this will be even more of a problem in the future.

By the way, you don't see much of an effort made to bring that group of people to the forefront of knowledge of science by essentially influencing some of these institutions that educate them and where they're being educated. Even companies which at one time had this kind of program have done away with it over the years for all kinds of reasons, good and bad ones.

I need to talk about one more education issue, namely continuing education or lifetime education. This is a requirement that is falling by the wayside. Technology obsolescence occurs at a much faster rate; business is changing, the requirements are changing, the research agenda is changing; people grow older, get older, are longer in the business, no more is 65 legally the end of a career; new tools are coming into use. The computer revolution, by the way, created a generation gap both in business and Government, as well as in academia. We'll have more of these revolutions coming.

What must employers do to keep their professionals at the leading edge? This is really the question. Laying off people is not the answer, obviously, and secondly, it's wasteful of human resources. There are many companies that are doing something about it, but it's primarily reserved for the large companies—the IBM's, the AT&T's, the GE's, et cetera. The midsize and especially the small companies, small companies that have five engineers and maybe a population of 100 employees total, cannot afford to address that particular problem. Here is a chance where some networking among companies could really address that particular issue. It's a chance for industry to solve its own problem.

What I have been trying to do is not just narrowly focus on one part of education such as K-12, but look at the whole span of it, because I believe very strongly that it's the span of education that we need to address and that we can ill afford to fall behind on that.

So, let me summarize. I believe, and I hope you do, that education must be at the top of the nation's agenda, total education, not just one segment of it. It's not today. Who has the responsibility? I would say all of us—parents, the business community, Government, localities, certainly professional societies, business associations. Professional societies are doing a great deal, but they probably could do more in these very important areas, in all facets of it.

How can we compete if our infrastructure is not the most modern—like transportation, communications, medical health and medicine, but above all education? Not only can we not compete; we cannot even, in the long haul, attract foreign investment of banks, of factories, if we don't have the human raw material to be able essentially to function in this new environment. We also will not be able to maintain the excellence of our universities in the end. Both teaching and research depends on educated people. We cannot solely depend on immigration, as I said before.

So much is at stake. In fact, I think our whole future is at stake. And to rectify the situation, I'll repeat again, is a long-term process, and I hope that we all have the fortitude to stay the course.

Introduction of Discussion Panel

John W. Lyons

We're now going to ask the speakers who have been able to stay with us today, of which there are three—Bob Lucky, Bob White and Eric Bloch—if they would move to the table where we have nameplates.

I want at this time to thank all of our speakers. I am very proud that NIST is able to attract such a stellar group of performers. I've heard comments during the day about how much people have enjoyed these talks, and I'm only sorry that we couldn't take your questions when the speakers were at the rostrum. But we'll try to substitute for some of our absent colleagues now by taking a few questions as we wind down the day. So, let me move over there as well.

The floor is open for questions, plants or otherwise.

Discussion Panel

Robert M. White, Robert W. Lucky, Erich Bloch, and John W. Lyons

QUESTION: I'm on the staff of Congress here, but just to be contrary I'm going to ask a political science question. In the 1988 Presidential campaign competitiveness got relatively little attention, including the technology, and I'm wondering what the panel sees, given the changes in the awareness of this issue that has taken place in the last four years, will be the case in the forthcoming campaign?

BLOCH: You know, the word "competitiveness" is a difficult word for people to understand. I think the focus that you will see in the campaign, hopefully that you will see in the campaign, is on jobs, and that stands for competitiveness. You know, if you're not competitive you don't have any jobs. But making that kind of connection is very difficult. I talked before about these focus groups that were interviewed, and that was one of the questions, "What do you think about competitiveness?" Well, there was not much of an answer. But if you said, "What do you think about your possibility of getting a better job, or keeping your job, or whatever it is," everybody had an opinion. So, it's very difficult to make that connection. And I think it behooves us all to make that connection as much as we can so that people will understand what it takes to have jobs,what it takes to be competitive, that it takes technology, that it takes people, that it takes education, and so forth. But if you just confront—I'm afraid—the broad cross-section of our voters, you're not going to get, or not elicit, the answer that you think you should be getting.

LYONS: I think it was Chairman Brown who pointed out that these issues have to be convertible into 90-second TV bytes; and the jobs issue makes it, I guess, standard of living makes it, but the depth of the subject we've been probing today I don't think can make it into 90 seconds.

LUCKY: Ninety seconds is far too long today with the time squeeze. You know, MTV has brought this down to really quick things.

QUESTION: I have a question for Dr. Bloch primarily, but the panel as a whole. It's been mentioned many times I think, by all of you, today that declining educational standards in the technical fields are a real problem and there is no one here who could refute that. I think the thing that troubles me is the implication that declining education is the cause of loss of competitiveness as opposed to the consequence.

I'm in a situation where I've hired many, many technical—or tried to hire—many technical people in business over the last five years and rather than finding that there aren't enough technically qualified people, I've found that there are, in fact, many, many overqualified people, people who are under-employed, in the workforce. And I have a 14-year-old son who is very good in math and science and has every prospect of being a fine engineer, but as a father I have to wonder, as we were told this morning by Dr. Lucky, that maybe we're dinosaurs. Am I doing my son any favor by encouraging him in math and sciences if, in fact, he's not going to be able to be gainfully employed? Would you like to tackle that?

BLOCH: I'll tackle it, since you addressed it to me, but I hope Bob Lucky and Bob White will address it also.

First of all, let me say, your son is 14? Go encourage him, will you? Unless you take a very pessimistic viewpoint of what this country will look like 10 to 15 years from now, mainly that we are an agricultural colony—if that's your viewpoint, don't encourage him. But if we want to be competitive and if we should be competitive, and I hope we make it, and I think we'll make it, then I think engineers and scientists are required. I told you before, it's the biggest growth sector in professional employment over the last 5 to 10 years. That doesn't mean that it has the most people, the most professional people, in it. Point number one.

Point number two is that it's not just in the area of manufacturing, or product design, or Government research, or academic research, but also in the service sector where these backgrounds are required. And, by the way, you hear many times that in 1960 and 1965, Ph.D.'s drove taxicabs in Boston. Every time I go into a taxicab in Boston I ask him if he has a Ph.D., and I haven't found one yet who says yes. If you look at it on a per-year basis, you see all kinds of fluctuations. For instance, 5 to 6 years ago chemical engineers were a drought on the market. Today you can't get enough of them. And so forth. So things vary from year to year. But I have no doubt that if we want to be preeminent in world trade, if we want to have a viable kind of an economy, I think scientists, engineers, technicians are a prerequisite to make that happen.

LUCKY: Well, let me give a different answer. I agree with what Eric said, that the nation needs that. But you personalized this and I think you're right to do that. Does your son have to be one of these people? You see, the nation needs them, but what kind of a message are we giving your son about what it's like to be an engineer? I have a potential son-in-law who is in law school, and he says that the population of people in law school is at an all-time high because of "L.A. Law," you know, the TV show. What are we telling these people about what's important in the world, and who is making the money, and who is it that's being put in all these sound bytes and these images that the kids see? It isn't engineers. I've known a number of very bright people who got engineering degrees, and they said, "Hey, you know, I think I'll go to Wall Street," or something like that, because, let's face it, that's where the bucks are and that's where the power is. Whatever.

BLOCH: Some of them are now in jail.

LUCKY: Well, you take your chances. But I was really struck by the difference between your question and the answer that you were getting. We all agree in the abstract that the nation needs these things, but when it gets down to your son it becomes a different thing, and you look at it differently, and I think you have to take that viewpoint.

WHITE: I think it's important to realize that our economy is becoming more and more technologically based and yet our whole economic process has not kept up with that, and so that the people who are trying to manage the economy are having to deal more and more with a very nebulous, intangible kind of thing, and those people who have a technological background are going to have better intuition and be able to function better in this technological society in the future. And so I think that whether they go on to become active professional engineers or not, I think I would encourage everybody to get a technological background somewhere, somehow.

QUESTION: I think the bottom line is the question, do your technical skills create competitiveness, or does competitiveness engender technical skills?

BLOCH: I don't think that's even debatable. Technology, research, science, whatever you want to point to, is done by people; it's not done by machines, for heaven's sake. So it's not a chicken and egg proposition; it's people that are the basis for it.

By the way, let me mention one thing. I was in Japan a couple of weeks ago talking to some of my former colleagues in JSPS—Japanese Society of Promotion of Science—and they have a similar problem. All of a sudden they can't attract students any longer to science and engineering. Reason: "Three D's." What are they? Well, it turns out that they are dirty, dangerous, and difficult. That's from Japan.

QUESTION: I'm from Montana, and there's a story out there about a miner who came in from the cold winter night to sit in front of the fireplace and said, "You give me heat and I'll give you wood." I have the sense that we're in this kind of mode.

LUCKY: Is it cold out there?

QUESTION: It was when I left. The question comes then, in this education that I think several of you proposed, how do we deal with it, and I guess my query is this. We seek long-term solutions, going back and revamping the whole process, which will take us the next two decades. In the meantime are there other solutions which work? I know that NSF this year, for the first time, is beginning to look at graduate student support, and it hasn't looked at it for the last at least decade, maybe 15 years. This is a good start. I know that there are additional programs from time to time for math teachers from high schools and from short-term institutions, the 2- and 4-year colleges, that they can get into. Is it possible that programs of this kind, where we're looking at remanufacturing the teachers of our youth at various levels, either K-12, or even into the secondary system—is it possible that these teachers can be revamped through a relatively low-cost program that will allow them to be put in the mainstream again from where they've been, across a summer, or across a semester, or something like that?

And I guess my query is, are there any programs along this line as a more instantaneous solution to the long-term problem of not having people trained properly, or at least excited about science?

WHITE: Well, I'll just offer my comment on that. I think that it doesn't have to be a long-term proposition. I think it's an attitudinal kind of thing. Certainly my experience is when youngsters want to learn, or when they're excited or turned on about something, they learn. Say you present a youngster with a computer system that has a big thick book on how to operate it. I'm just amazed at how my son instinctively knows what to do, because he's turned on. I could spend hours reading the book and still not understand what he does. So it's a matter of, I think, building that enthusiasm, and I think that's something that can be done in a relatively short period of time.

QUESTION: But are we doing it? Are there mechanisms that are starting out, are there programs that are being developed, to do this?

WHITE: There are a lot of programs. There is nothing in a coordinated way. I mean there are things here and there. The Federal laboratories are all starting to develop, as I said, volunteer programs. NSF has a program that a large percentage of the employees volunteered to get involved in. I think it's got to be a kind of grass-roots effort like that, of professional people taking an interest in the education of their children, and that will spread.

LUCKY: I was going to say, we do have a fellow who is very active at the National Research Council, Ken Wilson, at Ohio State, and he won a Nobel Prize in computational stuff, but he's taken up this challenge of doing just what you said, teach the teachers, or teach the teachers of the teachers, and that's the way to get the quick leverage. He's become a real apostle of this, that if you want the quick start, there are too many kids out there and you can't go out to all of them, so you go to the teachers and maybe even you go up a couple levels in the hierarchy, the teacher of the teachers. There are programs like that in Ohio that he claims are working and are doing this quick start.

Now, I'm sure there are other things like that. Perhaps you know of them, Eric?

BLOCH: I agree with everything that has been said. You don't have to wait for everything to happen all at the same time. There are many programs that make in-roads at one level or another. Drexel University, for instance, started about 2 years ago to put a new undergraduate engineering program in place in parallel with their existing one so that they could measure the effect of one group against another group. Their program was pretty much what I outlined—a systems approach from day one, not after two years. They teach engineering, teach design, use laboratories, use experimentation, use experience in the industry, and on and on. They are going through that particular program right now, and I think a lot of people are watching what the outcome will be.

There is a start. It takes 4 years before you see the result of it, but 4 years is a relatively short time. And there are many of these programs in continuing education, certainly in K-12, and so forth. But I would still suggest that the basic thing that we have to change might be more long-term than that, and that's the basic culture of the country.

You know, speaking of Bob Lucky's sound bytes, how many sound bytes on engineering or on science or something like that are there? We need some. Forty seconds or 90 seconds. It doesn't make a difference.

QUESTION: I have an observation on the educational process and then a concrete suggestion for something to do about it, and then my question will be why aren't we doing more of the concrete suggestion.

The observation is—and this has to do with our culture—Americans are spoiled. Not just the youth. The workforce is spoiled. If education is hard work and not much fun, Americans won't want to participate in it. So, the off-the-cuff next step would be, well, how do you make education more fun? If you look at the educational process—and I know we've all been through it and we've probably been good soldiers ploughing our way through it—each student functions as a passive recording device, not only of facts, but of derivations, and you may spend 18 years before you get to work on a real problem you can get your teeth into. By then most people are burned out and ready to rest on their laurels and they're not really excited about knowledge.

The only reason anyone would do something like that, be in that kind of process, is because he or she is forced to. It's not any fun, that passive element.

The concrete suggestion is that when people work together as teams, so now there is cooperation, but looking over your shoulder at the competition when you're in this high-stress educational situation, you work as teams on real problems, and it's a lot of fun and you can't stop adults from wanting to work on things when they're in that kind of work situation.

My question is, why isn't that done at a young age—10, 15, 20? Why don't we have little teams of students in college working on patents? That would eliminate our competitiveness problem.

LYONS: Of course we do have some of those. We have these concrete boat competitions and the solar powered vehicle competitions which, in fact, have leavened mightily, I think, the curricula of some engineering programs. The student body and the faculty, and everybody, gets all excited about who is going to win those races. So, I would agree that there is certainly truth to what you say.

QUESTION: I think it's rare, though.

LUCKY: I think you actually have a good point. In fact, I've been sort of worrying lately about why the enrollment in electrical engineering and computer science is going down, and my own theory is that it's not any fun anymore, that in the old days you could build kits and do things, and you can't do any of that stuff anymore. This stuff has become unfun.

LYONS: Unfun?

LUCKY: Yes, exactly. And we're really going to have to work at making it fun. That's sort of a contradiction in terms. But intrinsically this is tough stuff. Mechanical engineering enrollment has gone up, and my theory there is it's just a conservation of numbers. I mean they don't want EE, they don't want computer science, and what's left?

QUESTION: That was the perfect setup for my comments. First of all, I'd like to speak on behalf of all the chemical engineers and chemists in the world. The point was made that it's not fun, and I think I've seen some activities where people are taught how to teach in the high school, and these are people who—as a society we may be spoiled and we may be this or that, but these people haven't had a lot of self-esteem in recent years, these high-school teachers. And if you can teach them a little bit about chemistry in this case—how to teach it, in a fun way—it really is a turn-on. It's incredible to see these people. Their personalities change, and when they get back in the classroom the kids respond.

You know, we may poor-mouth our kids and we may berate ourselves for putting up with our society, but there is still a lot of good in children, and if we can get that good turned in the right direction I think it will help us all in future generations. However, to do it on a nationwide scale, as opposed to these little bits here and there, would take money. Now who has money? Virtually no one now. The states are poor-mouthing it. The states are going broke, cities are going broke, and so what was an educational budget problem is now a disaster, I think, in terms of high schools.

Well, the Federal Government is supposed to have money, but it doesn't have much money either, except it puzzles me how we can sit and talk about the real world we're in—we have a recession going on and a lot of other problems—and yet we still continue to emphasize putting money into something which I'll give the 9-second byte and say the SSC [??]. Can you answer the question as to why we're funding that in this particular time frame?

LYONS: Well, you missed your shot at Chairman Brown. My notes tell me he is an enthusiastic supporter of the SSC. But he's gone.

WHITE: I'd like to challenge your original assumption that you need more money. I think that the United States spends more per student on education than any other country, and yet we come out at the bottom of the tests when they're given, as somebody indicated, and so I think it's not the money as much as how it's being invested.

American industry now spends on training and education in corporations the same amount as the Federal Government spends on education. So I think there has got to be more quality introduced in how we're spending that training and educational money.

BLOCH: Let me address that. But let me focus first on the money in education. I agree we're spending a lot of money. By the way, I'm not convinced that we are spending more than anybody else, because if you disaggregate it and look at how much we're spending on K-12, how much on undergraduate and graduate education, you might get a slightly different story.

The second thing, which I just don't buy, and I was in charge of part of it when I was at IBM, is that industry doesn't spend as much as the Federal Government on training and education. What they call "education" is many times customer training, which is, by the way advertisement. That's really what it is. So, let's be honest with ourselves about what we mean.

Now let me get to the SSC. There is nothing wrong with the SSC. The SSC is something that we should have. What is wrong with it is it comes at a point in time when we cannot afford more important things, and that shows our lack of priorities. Our priority setting in the Federal Government—and I was part of it by the way, no longer, so I can say it now—is not what it should be. In Congress it doesn't exist, despite Chairman Brown. The R&D budget is distributed over nine appropriations bills, or 10 by now, who knows, and there is no coordination, no looking over each other's shoulders, no strategy for it, and we're doling out a lot of money, $75 billion every year, or $76 billion every year. So we're not spending the money right. I agree we're spending a lot of money and we might even spend enough money, but we are not spending it right and we are not setting priorities.

QUESTION: I agree with Dr. Bloch's analysis of engineering education, undergraduate, requiring revamping, but if you want to leverage—we talked also about leveraging a minute ago—why are we not looking more at a way to get technology education, scientific education, into the leaders of this country, that is the political scientists, the lawyers and the business majors? It seems to me, at the undergraduate level, this is an opportunity which we have not been exploring and not experimenting with much, and I wonder if you have any ideas on how we can expand that?

WHITE: I don't know how you do that. It's certainly true that it's important. I was in Japan also just a couple of weeks ago and we met with all the leaders of maybe a dozen or so major corporations, and they were all technically trained. But at the same time I think that you all realize that you have to have an enthusiasm for science and technology. It's very hard to try to spoon-feed that to lawyers or people who don't seem to have that receptivity. I'm sure you've talked to some of those executives, and as soon as you start talking technically a big glaze comes over them, and I don't know how you get through that.

LYONS: We had an open house here two months ago, and we were overrun by some 14,000 young people who came here in hundreds of buses. It looked like the school bus yard down the road here when we were in the midst of that. I was asked by reporters more than once what this was all about, and I said we weren't trying to make anybody a scientist, we weren't necessarily even trying to interest anybody in perhaps considering a career in science; we were trying to catch the attention of the young people in the hope that as they went through their educational process they'd pay just a little more attention to matters technical, because we feel very strongly—at least I do personally—that the citizenry needs to be scientifically and technically literate, and the citizenry would include the members of the Congress and everybody else in the future.

But, by the way, one of the most remarkable things about that open house was not only that the kids had a good time—many of them wrote us little letters on the instruction of teachers I'm sure—but our staff had a marvelous time, and you'd go around here watching the dozens of staff who were giving little presentations, 10 to 15 minutes long, and they were very good at it and they clearly enjoyed it. So, among other things we've learned in our voluntary programs is that there is a great reservoir of teaching talent in the staff of a place like this, and we do try to spread it around.

I also know that some revisions of curricula in the universities have been aimed at this same idea of trying to instill a smattering of technical information in the general graduate. In fact, some of them have gone so far as to require courses in statistics for their undergraduates, which leads me to the next questioner, and I have to warn the panel you're about to be questioned by a full-fledged statistician.

BLOCH: May I comment first on this question? Your question is a very good one, and I would say the reason we don't teach non-scientists or non-engineers more about science and technology is poor preparation in the high schools. We are turning people off in high school with, you know, the attitude that mathematics is hard and science is dull. How often have you heard that? And that's one reason. It's not all black and white, however. There are some attempts, not more than attempts, there are a number of institutions today teaching a course that's called different things in different universities, but I call it "management of technology," which is taught in some of the business schools, in fact, in conjunction with the engineering schools. In fact, NTU [National Technological University, Fort Collins, CO] has a 2-year course like that, and I just talked to a group there, and the course is attracting people who don't necessarily have a science and engineering background, but they'll have a business background or a law background, or administration background, or whatever it is. So there are some attempts being made to cross-fertilize more. Now, I must say it's not in every school, in every institution.

QUESTION: The presentations today, all of which I thought were excellent, touched on a lot of the problems that have cropped up in the past and enumerated very nicely some of the solutions that will perhaps lead us into the future. My question deals with leadership. Are the solutions that will take us from where we are now to where we want to be too big for any one person or any one institution to lead us from A to B? We all do our local optimization hoping it'll get us closer to where we should be, but who should be leading us in this regard—the labs, the President, the Congress, DOC, AT&T, who? A leadership question.

LYONS: The answer to your question is yes.

LUCKY: It's a good question, and I really don't have an answer to it, but I do feel a vacuum in the leadership, a very serious vacuum, and as I said in my talk the bean counters have taken over; you know, they're substituting numbers for wisdom here. I was really impressed when Senator Albert Gore, a few years ago, started this high-performance computing communication business. He had a vision that has just had tremendous repercussions in the technological community. He stepped into where there was a vacuum and said, "Let's create a new infrastructure here for networking." And even though it took years to get any kind of authorization bill through Congress—already NSF and other people had geared up, including DARPA [Defense Advanced Research Projects Agency] and the technological community—people started doing things merely because there was leadership, even without money or anything like that. Just the creation of a vision at a high level was a wonderful thing. I think there are opportunities for other people in Washington to do that, in fact in business, too, but a lot of the business now is run as a numbers game and the vision and the leadership is missing. People will respond to leadership.

BLOCH: Let me jump in. Now I can talk free of my colleague here. Leadership can come from anywhere. But I think we have gotten to the point on this competitiveness issue, on technology, on education, where the leadership has to come from the President. Maybe when he is through with fixing the rest of the world, he'll turn to this task also. But that's where the leadership by now has to come from. And I have high hopes that with the changes that we have seen of late, with a campaign coming up, that there might be room for that kind of leadership. Look where leadership got us in Iraq. That's what it took. I think the problems we have with competitiveness, and with technology, and with education are all of a similar sort, and they take the same kind of leadership.

LUCKY: Erich, if I might comment on that, Bush was supposed to be the "Education President."

BLOCH: Yes. He said so.

LYONS: Both Dr. White and I are Bush appointees.

QUESTION: I wanted to comment on the previous question. I got up before Dr. Lyons mentioned that some universities are perhaps going to require sciences for general graduates, but what I've observed is that there used to be those science requirements, and many of the universities have dropped both their science and their language requirements for a general degree. We probably need to put those requirements back in. I suspect that would make a big difference in the general education of our leaders.

LYONS: Well maybe it's "unfun" as Bob Lucky said. Does anyone want to comment on that? Let me do a dirty trick here and ask Norman Ramsey to comment on that. The Harvard faculty wrestled with curricula at great length a few years ago, and that's what I was talking about—I was talking about statistics—and my own experience with that great university is it used to require a lot more science courses than they do now. They went to general education under President Couant, and that gradually was attenuated, and now they've taken another shot at it. Three of my children have gone through that great university and have gotten very little technical information. Norman, do you have a comment on that?

RAMSEY: There are changes every few years. In a certain sense they've been beneficial but chiefly because of the Hawthorne effect, namely, it's really helpful to change the system. I mean, people are enthusiastic about it. I think the amount of technical education given to the non-scientist is about as good now as it was a long period ago. I think there are problems, and I'll tell you tonight, there are various things that have happened in our country, some of which originate from TV, and they make it harder to interest people in things that take a long time to appreciate. I mean we saw in one thing that's been mentioned here in one connection, this 90-second byte, and really if you're going to get it over on TV it's got to be in 90 seconds. But the problem is that really exciting things in science take more than 90 seconds, and if people are not educated in that direction they have a problem with it.

But I think on the whole that there hasn't been much dilution of science in education compared to what it used to be. It had always been too dilute. There was a time when you said there was more earlier, and then you had totally free electives and they could do anything, and a lot of students totally ignored science.

LUCKY: Well, it's sort of indicative of our problems. I mean, tell the truth, isn't engineering looked down on at Harvard?

RAMSEY: Not by me it isn't. We do have a problem at Harvard, a well-known problem at Harvard, namely, having an engineering school—Massachusetts Institute of Technology—in the same town. If somebody says he wants to be an engineer, and he comes to you, you probably say, "Well, why don't you go to MIT?" That means that the university has, I think, de-emphasized the amount of attention to the engineering school. The university renamed it Engineering Sciences, and I think that's been very looked up to, but it's a problem of competition. For one year they merged, and engineering students each received a degree both from Harvard and MIT because they got it the year they were merged on engineering degrees, but then the source of the money dried up after a lawsuit.

QUESTION: I have a comment and a question about the issue of leadership. I heard that there are very few good 5-second sound bytes that probably would have qualified for television, but as to the concept of leadership, it's my opinion that leadership really has to come from something a little bit lower than the President, and that's typically family or some support structure, and I really haven't heard anything about the leadership of the parents and the family encouraging young kids not to be watching the television all the time, or to go into engineering, or to be educated in general. I'd like to hear the panelists' comments about educating the parents that educate the children.

BLOCH: Well, you're right. You know, when we talked about leadership before, we really talked about national leadership. But you're absolutely right. That, by itself, won't be sufficient, and the parents have to exert a lot more interest in education than apparently they do today, and they also probably have to be a lot more convinced of its value, sad as that might sound. So, it's a process that has to involve everybody, and that was the point I made in my remarks. It's not just the Federal Government or the state or the localities, or the parents for that matter, but our whole cultural environment has to change.

LUCKY: You know, certainly we all agree with you. But the problem is how do you do that? And I just don't see how the heck to do it. You know, one way to do it is to have a lot of money in engineering, or a lot of prestige, or a lot of sound bytes on TV about it. But that's not happening. We do have certain families, certain immigrant populations, for example, who put a lot of emphasis on education, and they contribute all out of proportion to our graduate education and so forth in engineering. So, there are family institutions that do this, but there are others that don't, and they're a major part of the United States. So, I don't know how to do it.

QUESTION: I'd like to make a comment. I think often children need to feel that there is a place for them if they go through this [educational process]. Currently the children in high school, if they're in a technology program and they decide they want to work in the summer, find that the programs that are available, for example the Department of Defense Science and Engineering Apprenticeship Program, take small numbers of students. Kids get the idea that you have to be a genius to go into these fields, and that's not really true. I think it's partly a question of just knowing that even though you're not a genius there still is a place for you if you have an interest in the field.

LUCKY: But I wonder if that is true. You know, I hear a lot of criticism that our engineering education system doesn't really nurture people along; what we do is try to test everybody out—you know, just put a lot of barriers up. And so there may be some truth that you have to be a genius to get through this the way we set it up right now, and I think you really need to change the system very much so, where you really try to pull people along instead of just setting up lots of barriers. You've got pass this math test and that thing, and all that kind of thing. You've got to prove that you can be an engineer. You can't just be anybody and walk up there and be an engineer.

QUESTION: People who like it continue to do it, and there are plenty of kids who actually do like it and continue to do it, but by the time they've finished high school they've gotten the idea that if they don't have a 4.0 in the field that they should try something else, when actually they're probably as bright as most postdocs that are out there.

LUCKY: Sure. And I think we have an elitist attitude about this that's got us into trouble.

QUESTION: And it would be nice if there were more summer programs. I know my own daughter is in a science and engineering apprenticeship program, and she benefited greatly from it. These kids can pick up these software packages in an instant at this age, and it made a tremendous difference in her attitude towards things. If there were more things like that there would be more students going into the field.

QUESTION: First, I'd like to congratulate Erich on coming up with a new term. Back, oh, half a decade ago anyway, we used to talk about the shortage of engineers and we held several conferences that determined that there really was no coming shortage. Then recently, as Erich said, the new term became "shortfall," and so the Manpower Commission a few weeks back held another conference to discuss the shortfall and decided that that was not going to be a problem anyway. Now, we have a new one called "under-production," and so I figure that's going to be good for a couple more conferences next year on the under-production of engineers.

But more seriously, you were talking about the education of the workforce and referred to Germany, and you know better than I do that they have some kind of program called "The Apprentice Program" over there, and Japan, I gather, also has at least a cutoff situation in which you either go on to college or you don't. It's pretty clear. However we, in the United States, have the dream—every parent has—that no matter what, his child is going to go through college, get a college degree, and make a lot of money. So therefore we have all of these—3,000 you said—minor colleges where they get their college degrees, and they don't end up making a lot of money because the degrees really aren't very good, and they don't get the education really to be a worker, either.

Can our society really turn back to this other kind of system where you decide at some stage that the child is not going to be a college graduate, he's going to be a worker, so he should go into some other kind of training?

BLOCH: I'm not so sure that you're describing the situation accurately. True, the United States never had—except in certain specific areas such as machinists, for instance—anything similar to what's called an apprenticeship program in Germany. That's true. On the other hand, I would not disparage these 3,000 institutions that I talked about, because they are doing a very important job. How well they are doing it, you know, we can have a discussion on, and I commented on that before. But they are there essentially for people that are not going through college or haven't made up their mind yet, because a lot of people transfer out of these 2- and 4-year schools into colleges and into universities. These institutions become a feeder for universities and colleges. So I wouldn't disparage them. I think they're fulfilling exactly that particular thing that in Germany is being fulfilled by the apprenticeship program.

There have been a lot of suggestions made in IEEE and elsewhere to institute something like an apprenticeship program. I think that's fallacious thinking. I don't think you can take a program that works in one country, transfer it somewhere else and hope it will work there also. The situations are different. The mobility of the workforce is completely different, especially that level of workforce. They [apprentices] are in a company for 6 months, and then they go to school for a year, then they might come back to another company, and on and on. So, I don't think that would work. What I plead for is essentially that we take that particular education that is between the high school and the universities, that we take that as seriously as we do the university education.

QUESTION: Maybe we can turn that around and make that a better education eventually for the workforce?

BLOCH: Yes. I agree with that. And the other thing is the continuing education. Once you have somebody there, you don't think, "Well, that will last for 50 years." It doesn't.

WHITE: My impression is that the community college system is something that is developing a new vitality, and I find that a number of corporations are now starting to invest significant amounts of money in community colleges. In fact, a number of our programs in manufacturing really reach out through the community colleges, and I could see this as becoming a much more powerful mechanism for the future.

QUESTION: Maybe we should have some kind of an AVEC-like [Adult Vocational Education Center] organization that says, "Here's what you should be teaching in math and science in the community colleges?"

DR. BLOCH: Heavens no. I'm sorry. But I have not much sympathy for an AVEC-type of university, of an organization. However, I must say that there is some quality control that's needed in that area. But I think we should think through how we're going to do that instead of just copying what I claim doesn't work very well in undergraduate education.

QUESTION: This is chiefly a celebration of NIST—this institute—over 90 years. It is my impression that this institute has been remarkably successful in helping productivity and innovation in American industry, if not even the world industry. My first part of the question is, am I wrong? And, if not, how can we be sure that what was good about this institute before will be even better in the future?

DR. LYONS: Well, we bureaucrats are always being asked, "Why are you doing what you're doing and spending all that money?" The answer to that question, which is really a budget examiner's question as to why we have the set of programs we do, in our case is very easy to answer, because we don't do anything here without guidance from our client communities. If it's science that we're doing, then we turn to the scientific community, if it's technology that we're doing, we're guided by all kinds of committees and workshops and structures that we've built up over the years. So that, for example with industry, industry is involved with us before we start, while we do it, and after we finish. I think almost no other Federal laboratory can say that. But as part of the planning process we always bring in people from industry, we go out to industry and ask questions and try out our programs. Increasingly, these days, we cofund with industry, we do collaborations. We have, as you know, a thousand guests every year who come here to work with us. And the fact of the matter is there is very little formal technology transfer necessary, partly because, as I guess what Bob [White] said, there isn't time for it anyway, but because we do all of these things with the clients, they tend to follow the work as it goes and withdraw the benefits as we progress.

I find that answer satisfying to us here at NIST and I think it's pretty satisfying to industry. But I long ago gave up trying to persuade budget examiners of anything.

QUESTION: I have some comments about engineering and science being fun. At Bell Labs in Indianapolis back in the early 1980's, we began a program of bringing inner city kids from inner city schools, fifth and sixth graders, into Bell Labs and having engineers and scientists there to show them what we did. And we recruited only enthusiastic teachers to do this and those kids are starting college now, and so we don't know how many years it's going to take for that to pay off, but we can target populations and bring them out and do that.

Secondly, about science and engineering being fun, the only reason I ever became an engineer was because it was fun. The people who inspired me as a youngster were people like Robert Heinlein—science fiction writers. My other job is a science fiction writer. But NIST is missing out on something here. One of the most famous writers of all that made science fun to me, or pseudoscience fun to me when I was a kid, was a fellow named E.E. "Doc" Smith. He worked for the National Bureau of Standards from about 1915 to about 1940. His books are still in print today. And according to Dr. Lucky's commentary about no role models on television for engineers, I have an editorial coming out in a magazine in about two months about that very thing. So, if you want to go out and buy science fiction, or push science fiction, or have your companies sponsor things to do with science programs like Burke's supporting "Nova" [public television science program], in the long run that's going to help.

BANQUET SPEECHES

Introduction of Clive Willis

John W. Lyons

Good evening. We have two items scheduled tonight. First, let me thank you all for coming, and I hope you enjoyed your meal. I've been more or less at the rostrum all day today. I'm sure you're sick of seeing me up here. But I nonetheless have two introductions to do, and I'm sure you'll enjoy the remarks, and we promise to keep it to the point and brief.

First, greetings from Canada. As I mentioned in my remarks this morning, this is, in fact, the 75th birthday of the National Research Council of Canada, and I was up there helping them celebrate earlier. Dr. Clive Willis, Vice President for Science of the National Research Council of Canada, has been kind enough to fly down this evening to be with us and to turn around and fly back in the morning.

Just a word about Clive. He is a physical chemist. Some of us appreciate that. Most of us here probably don't.

Dr. Willis did postdoctoral work down here at UCLA, but also at Saclay, in France. He worked in atomic energy in Canada. He taught some chemistry. He's been Senior Research Officer at the National Research Council, worked in developing the laser chemistry program there during the 1970's through 1981. He's held a number of positions at the NRC, and I won't go through this long list of those things, but he currently serves as the key scientific officer for NRC and, as I said earlier, he is a Vice President of the National Research Council.

Greetings from the National Research Council of Canada

Clive Willis

Vice President, NRC

Thank you, John. Good evening, ladies and gentlemen, Professor Ramsey. I'm here to say only a few words of greetings from the National Research Council of Canada to NIST on the 90th Anniversary.

There's a parallel between the two organizations and the synergy that worked, at least since you've reached teen age in 1916—I guess you became teenagers—and we've been working very closely ever since. There is a very strong synergy between the work that we do and the work that you do. We benefit enormously from the existence of NIST. We benefit as an organization, and as part of the North American community we benefit as a nation, in Canada, from the existence of NIST.

We cannot exist in the world of standards, in the worlds of technology, in the way we had done in the past, in isolation, one from the other. It's very much in that spirit that John gave greetings at our 75th celebration this summer, and it is very much in that spirit that I'd like to bring greetings from the National Research Council today.

Our organizations have grown up together. We've had three-quarters of a century, at least, of collaboration. Over those years we've shared many successes, many goals, and many dreams. And many of those dreams remain vital today. The conference that you have chosen to use to celebrate 90 years of existence at NIST is very similar to the theme that we chose for our 75th anniversary, one of competitiveness, of national competitiveness, but one of partnership in that competitiveness. And when we talk about partnership, we're talking about partnership not narrowly within domestic boundaries, but very much a partnership between the key research organizations of the world and, in particular, from our sense in the National Research Council, one with NIST.

The dynamics that we have faced in the past are stronger, will have to be stronger, in the next decade. The changes that are taking place in the world, the changes that are taking place particularly in the European situation, mean that to maintain the free trade relationship that we have between Canada and the United States and that we are now developing into very much a more North American situation, we have to bring true dynamism into that relationship, particularly in the area of standards, particularly in the area of technology, and very much in the area of competitiveness. Not that we compete, necessarily, nation to nation, but that we compete in a productive way in the global economy.

The European situation—they have their act together. We, very much, need to work with you to try to get our act together for the Canadian situation. So we very much appreciate your existence, we very much would like to wish you, *bon anniversaire* on your 90th birthday, and thank you very much for having me down here to join you.

Introduction of Norman F. Ramsey

John W. Lyons

It's now my great pleasure to introduce our featured speaker for the evening, Professor Norman F. Ramsey, Higgins Professor of Physics, Harvard University. I have here two pages of stuff, Norman, most of which I won't read, but I want to say a few things. We have something in common. We both have a long association with Harvard. He says I'm a true Harvard man, since he graduated elsewhere, but he's been there a lot longer and been more intimately associated with the place than I have. He got his Ph.D. in physics from Columbia University in 1940 and was there in the early exciting days of I. I. Rabi in the work on magnetic resonance and related subjects and has stayed with some of those interests ever since.

The things that I want to mention, first of all, of course, are that he was a Nobel Laureate in Physics in 1989, and we took enormous pride in that accomplishment because we had such a long association with Norman here at NBS throughout his career. He received the National Medal of Science in 1988.

I remember Norman mostly because of the years he served on our Visiting Committee. He actually has a pair of photographs on the wall by the cafeteria because he served two separated terms—it sounds like separated fields, come to think of it—on our Visiting Committee, I think 5 years apiece. And so he has two places on the wall, and we're generous folks and we give him two pictures.

But I recall sitting in those dining rooms in the evening and listening to Norman spin tales about the early days—and he does that very well—talking not only about Professor Rabi, but stories about Dick Feynman and the days at Los Alamos during the Second World War, and I have the fondest of memories of those times.

I also remember him having strenuous arguments with the arch-conservative Barney Oliver in those early days.

So we greatly appreciate Norman's service on the Visiting Committee, as I say two separate terms. He's been President of the American Physical Society and Chairman of the Board of Governors of the American Institute of Physics. He had a lot to do with Fermi Lab and a lot to do with the creation of the Brookhaven National Laboratory. And I have, as I say, here, a long recitation of other honors which, in the interests of time—and since he doesn't need that kind of introduction—I will skip.

So, it is my great pleasure to introduce Professor Norman F. Ramsey.

Science as a Source of New Technologies

Norman F. Ramsey
Higgins Professor of Physics
Harvard University

INTRODUCTION

As a scientist whose specialty is high precision, I have always found it difficult in after-dinner talks to make a smooth transition between banqueting and precision. Not long ago, however, I read of an event which relates banqueting to precision—or at least to precision in communications.

A wealthy couple on Long Island who were enthusiastic gatherers of wild mushrooms gave a dinner party for a number of their friends with the *pièce de résistance* of the banquet being wild mushroom souffles. Unfortunately, their dog ate one of the souffles before dinner, but those remaining were enjoyed by the guests. When the maid served the coffee she whispered to the hostess, "Madam, the dog is dead." The hostess was initially petrified, but quickly recovered and arranged for all participants to be transported to the hospital emergency room where their stomachs were pumped out before they were sent home. When finally the hostess returned exhausted from the harrowing experience she asked the maid, "What happened to the dog?" to which the maid replied, "He was hit by a truck."

I hope our communications this evening will be less ambiguous as we discuss the subject of "Science as a Source of New Technologies." I can outline my talk by saying that the first portion will be optimistic, the next pessimistic; and I shall close with cautious optimism.

OPTIMISTIC VIEW

Science is indeed a great source of new technologies and industries, but the route from fundamental scientific discoveries to their applications is often tortuous, long, and cloudy. I illustrate this by my experiences in two scientific fields.

In 1937 when I asked I. I. Rabi if I could work with him for my Ph.D. thesis, he said that he would be happy to have me join him but I should know that he was rather discouraged about the future of molecular beams since it seemed unlikely that future measurements could ever significantly improve on the few percent accuracy of his past experiments. But shortly after my arrival, Rabi invented the molecular beam magnetic resonance method which revolutionized that and other fields. As a result I had the good fortune to became the first in a long line of graduate students to write a thesis based on magnetic resonance.

As we began these experiments we were interested in measuring the magnetic properties of nuclei only for basic scientific reasons, and we never thought that there would be significant applications to technology. Twelve years later I invented the separated oscillatory field method which is effective at higher frequencies and is more accurate. It was 7 additional years before these methods were used in atomic beam clocks so much more accurate than any previous clock that they became the basis for a new international definition of the second. These clocks are now used extensively around the world, and it is a technology for which the United States has retained a dominant manufacturing role.

Totally different technological applications were started 10 years after the first molecular beam nuclear magnetic resonance experiments when Purcell, Bloch, and others invented the the nuclear magnetic resonance method (NMR) which was applicable to condensed matter. Bloch soon found experimentally and I showed theoretically that the resonance frequencies of the same nucleus were slightly different in different chemical compounds. Although these chemical shifts limited the accuracy of the nuclear magnetic moment measurements, they proved to be of great value in identifying compounds in chemical analysis. A different but related technology began about 35 years after the first magnetic resonance experiments with the successful combining of magnetic resonance with computerized axial tomography (CAT) scan techniques to produce the powerful medical diagnostic technique now known as magnetic resonance imaging or MRI. Although the medical applications of MRI are only now being well developed, the manufacturing of MRI equipment is already approaching a billion-dollar-a-year industry.

My second area of illustration is masers and lasers, where a much shorter time elapsed between the first ideas and important applications. But even in this favorable case the intervals are measured in decades rather than years.

In 1916 Einstein showed theoretically that when electromagnetic radiation fell on atoms the intrinsic probabilities for excitation from a lower energy state to a higher was equal to that for stimulated emission from the higher energy states to the lower. Since there ordinarily are more atoms in the lower states than in the higher, the net absorption usually exceeds stimulated emission. In 1951 Pound, Purcell, and I did some stimulated emission experiments with nuclear spin systems at negative absolute temperatures. At such temperatures there is a population inversion with more spins in the upper states than in the lower, so stimulated emission exceeds absorption. In these experiments, however, the amplification of the electromagnetic signal by stimulated emission was less than the resistive losses elsewhere. The first amplifier with net gain from stimulated emission was the ammonia molecular maser (Microwave Amplifier by Stimulated Emission of Radiation) invented by Townes in 1954. Six years later Kleppner and I invented the atomic hydrogen maser, which is still the most stable clock for periods of a few hours. In 1958 Schalow and Townes showed that the maser principles could be extended to optical or light frequencies, and in 1960 Maiman made the first operating laser to produce the now widely used lasers.

Technologies based on lasers have developed at a spectacular pace. A few weeks ago I gave a talk on lasers and included a list of laser applications which came to more than 35 major items, including the following: communications and fiber optics, medical diagnosis, laser surgery, welding, cutting, bar code readers, laser printers, video and compact disks, combustion and plasma diagnostics, monitoring atmospheric pollution, and computers.

These examples from just two fields of physics are clearly only a minute fraction of the cases in which science has been a source of important new technologies. Biomedicine is now spawning major new industries, but even in this rapidly moving field it should be noted that Avery's discovery that DNA was the fundamental genetic material goes back to 1944, and Watson and Crick's recognition of the double helix goes back to 1952.

Fortunately new scientific discoveries and developments continue at a rapid pace, and many can be expected to lead to new technologies. Science in the United States is still robust despite serious problems of financial support, and science in Europe is now fully recovered from World War II. In atomic physics, an example of an exciting new development is laser cooling of trapped ions. Incidentally, NIST is a pioneering institution in this field, with one of its staff, Dave Wineland, being a co-inventor of the idea of laser cooling and another, Bill Phillips, having discovered experimentally that atoms can be cooled about 100 times colder than predicted by theory—clearly an inverted form of Murphy's Law. It is too early to predict future applications of laser cooling, but one is the improvement of atomic clocks. The potential of this discovery appears as great now as magnetic resonance did 55 years ago.

PESSIMISTIC VIEW

With these optimistic views it might seem that we should have few financial and economic problems in this country, yet the following questions arise.

Why are we losing industries to foreign countries?

Why are the Japanese frequently more successful than we in developing new products even when they are based on U.S. scientific discoveries?

Why do we so often develop products that dominate the markets during the initial unprofitable periods only to have other nations take over with improved products when the market becomes profitable? Copiers, video recorders, and fax equipment are examples.

Why doesn't U.S. industry improve Japanese products and take back their markets?

Why are some countries more successful than we with large-volume consumer and commercial items such as video recorders and fax equipment?

Why did U.S. industry wait for Japan to become famous for high quality before improving the quality of U.S. products? Japan before 1950 was infamous for low quality, and Japanese industrialists now give primary credit to American consultants for starting them on the path to high quality.

Why is our Federal budget so out of balance?

Why do we have such an unfavorable international balance of payments, and why have we recently shifted from being the largest creditor nation in the world to the largest debtor?

Unless we do something about these problems soon, they are bound to worsen. As profits fall many corporations will spend less on developing new products, and competition with other countries will probably become more severe. During the first 20 years after World War II, American industry had the double competitive advantages that both industries and science abroad were still recovering from the war. Although foreign industries recovered from the war during the next 20 years, American industries still had the advantage that U.S. science was much stronger. Now, however, science in Europe has fully recovered. It is well-funded, often better than in this country. European scientists are excellent and are doing important work. Although the full recovery of European science adds greatly to scientific progress, U.S. industries lose a competitive advantage.

What has gone wrong? Since I have not made a detailed and quantitative study of the problems, I am less well qualified to discuss them than many of you in the audience. Nevertheless, the problems are of such great importance that they should be discussed from different points of view, including those of a research scientist. In my opinion, the following are some of our key problems.

Scientific discovery alone does not automatically lead to profitable new industries. In our highly competitive world, vigorous development, engineering, manufacturing, and marketing efforts are required. The leaders of Japanese industries seem to be more eager than ours to develop new industries. They may invent, buy, or even steal the original idea, but they are then willing to devote much time and money to develop the new product even if it takes some years. Such efforts in this country are often discouraged by excessive emphasis on this year's "bottom line."

During less competitive earlier years many U.S. corporations adopted the policy of purchasing small companies which had developed desirable new products as a substitute for supporting their own new developments. In less competitive times this may have been a successful policy, but now, with the primary competition coming from big foreign companies willing to risk large development expenditures, the market may be lost before the slower acquisition route is well started.

Unfriendly takeovers, along with threats of same, discourage longer-term development. If I were running a company I would want to spend considerable sums on research, on new product development, and on an emergency reserve fund. However, such a company would be a sitting duck for an unfriendly takeover, since a new management could promise an immediate big dividend at the risk of a long-term disaster.

At present most large corporations are directed by people whose backgrounds and training are primarily in finance, law, or business management and only rarely by engineers or others who whose specialty is product development. Although Henry Ford loved to make money, he also loved to make automobiles.

In this country more students receive law than engineering degrees, whereas in Japan it is the opposite. A Japanese industrialist once said the difference between the two is that lawyers help us to divide the cake but engineers make more cake.

At present, we are not even offering employment to the engineers who do obtain degrees. This could be interpreted that we have enough engineers, but to become competitive we need more engineers. I am told that the Japanese customarily assign more engineers than we to a product development project. This extra effort seems to pay off in better designs for products that are less expensive to manufacture and more attractive to customers.

Although our Government does a number of valuable things, such as support scientific research, it often provides impediments that weaken our competitive position. I mention only a few but I am sure you can supply a lengthy list of your own.

- Anti-trust laws were enacted to protect customers from national monopolies at a time when the most relevant competition was internal. Now, with strong competition from abroad, these laws are often unnecessary and frequently weaken our competitive position.

- If our country is doing particularly well in a field, the government often issues special rules and security restrictions which make us an unsatisfactory international supplier. I suffered from this a few years ago on my neutron research projects in Grenoble, France. After great effort my British colleagues convinced the British government to purchase a U.S.-made VAX computer. The computer was delivered first to England, but U.S. approval was required before this British-owned computer could be transferred to another country. As a result we lost months of time in obtaining U.S. approval to move it to France, even though there was no real security problem since there were already four identical computers in that laboratory. Such procedures do not encourage sales of future U.S. products.

- A major government failure is the lack of an equitable tax law that, averaged over time, balances our budget and even enables us to repay our national debt. It should be sufficiently steeply graduated to diminish rather than increase the financial gap between the poor and the rich.

Many of our products are less convenient for potential foreign purchasers because they do not conform to international metric standards. For example, in our Grenoble work we have to have extra sets of many tools and supplies to meet American as well as metric standards.

It is easy for a scientist to say that industry and the Government are at fault, but not our own profession. Should we scientists do more to push the results of our research on to industry? The current National Science Foundation programs of Centers for Science and Technology are efforts in this direction and may be beneficial if they do not diminish NSF support for other research. However, I believe it is more effective for industry to pull technological ideas from science than for scientists to push their ideas on to industry. We must be careful not to damage our flourishing scientific enterprise in attempting to aid our ailing industries.

Another problem is the cost of labor in the United States. I believe this factor is now relatively less important than it used to be, but I am no expert on this subject.

Although we have many excellent workers, many potential workers are lacking in education, skills, and motivation. This afternoon Erich Bloch and others emphasized the need for major improvements in our educational system, so I shall not to add to their remarks. However, I believe that simple improvements in our conventional schools will not by themselves solve the problems. Our total educational system is based on the assumption that the student will obtain much of his education and motivation at home from his parents and family, but many young people now have a home that is not helpful and is often harmful. Ill-adjusted young people with such home lives are now merely sent to conventional schools with the hope that an overworked teacher will somehow take care of the problem. In many cases such a person is not helped and may so disrupt the classroom that there is serious interference with the education of others. We must as a nation decide what to do in such cases.

I believe that many of our educational problems must be blamed on TV. The average young person now spends 7.3 hours a day watching TV, and by the time he is 18 years old he has witnessed 25,000 TV murders. This is a greater amount of time than is spent in school; most of the viewing time provides little of educational value and much is even harmful. In addition the TV medium has the inherent characteristic of conditioning its viewers to expect all information to come in exciting, 90-second bytes. Producers know that, if a program becomes dull for a short interval, many viewers will tune to another station. Therefore, most programs, even educational ones, are designed for short attention spans, and many people with such conditioning become impatient with education that requires sustained attention. Much of the most exciting knowledge is neither interesting nor understandable when it must be subdivided into 90-second or even 90-minute capsules.

The beneficial industrial "spinoffs" from expensive military and NASA projects are often discussed, but there are "negative spinoffs" as well. Some industries have become so conditioned to producing costly high-tech products that they have great difficulty developing and producing popular, low-cost consumer items.

CAUTIOUS OPTIMISM

Despite all these problems, I am cautiously optimistic. As a nation we respond slowly to developing crises, but when we do respond to serious problems we can be remarkably effective. We have many assets: there are many people in this country, we have successful industries that do develop new products and improve old ones, and science continues to be a rich source of new technologies. But to be competitive in the years ahead, we must begin immediately to solve our serious problems.

FRIDAY, NOVEMBER 15, 1991

Future of NIST and Introduction to NIST Reports

John W. Lyons

Director, National Institute of Standards and Technology (1990–1993)*

Welcome back to the second day of our birthday party. You won't have to look at me all day today. I've persuaded some other folks to moderate the second and third sessions. So I'm going to do the opening session and then sit back and enjoy the rest of it.

Today's part of the program is devoted to what NIST is up to and what we are likely to be up to as we move ahead in this decade. I want to do something that I didn't do very well yesterday, and that is to acknowledge the folks who put this meeting together. I think you'll agree that yesterday's cast of characters was outstanding. Everyone enjoyed enormously the presentations, running right through the evening. And for those selections I'm indebted to the Symposium Advisory Committee. I said yesterday that Director Emeritus Ambler chaired that committee. There were others involved—Bill Carey, Jenny Grasselli, Jack Hoffman, Bill Howard and Norm Ramsey, as well as Bill Schlichter who was asked to help out, and then of course, Bill died a year ago and did not participate.

There was also a more detailed Program Committee under Karl Kessler, whom I acknowledged yesterday, but there were additional people, Lyle Schwartz who will be up here chairing the afternoon session, Jack Snell, Don Sullivan, Churchill Eisenhart and Rich Cavanaugh. And I acknowledged, I think, Mat Heyman and Sara Torrence, yesterday, for arrangements, but also Paula Killen, Manny Horowitz, Kathy Kilmer and Barbara Houston. So, to all of those people go our thanks.

In the packets that are being handed out in the hallway, there are two documents, this rather substantial one called *Research, Services, Facilities*, and the NIST document which describes NIST to those who need to learn about us.

A third document goes with those two; it is essentially in press now and will come out in a few weeks called "The NIST Strategic Outlook," which will present more of the rationale for forward thinking and more of the comments that I made yesterday and am going to make this morning. If you wish to get a copy of that, just inform someone in the hall outside and we'll try to put you on a mailing list.

That document, in turn, is based on an inside document that I'm holding here called "NIST in the '90s: The Strategic Outlook," that we prepared earlier this year as part of our overall attempt to take a quality management approach to our business. Obviously one of the things you do, particularly when you have a new enabling act and a new director, is try to write down where you're going and why you decided that.

So we put together a strategic outlook—it was originally called a strategic plan until the Visiting Committee told me it is probably more of an outlook document—and then each of the component parts of the institution wrote true strategic plans which will govern their business for the next several years. I would hope that we will revisit those documents every two or three years.

My job this morning is to set the stage for the talks that you will be hearing during the day from the Laboratory Programs. The plan begins with a mission statement [fig. 1]. Our mission comes from our enabling legislation, and if you're familiar with some of the agonizing that has gone on about the mission of some of the Federal laboratories, you will appreciate how fortunate it is we are told what our mission is every time the Congress passes an Authorization Act and, in recent years, that's been about every other year. Of course the 1988 legislation that I referred to yesterday was a major overhaul and somewhat of an expansion of the mission.

We have taken from the rather lengthy document three areas to concentrate on—three goals [fig. 2]. One relates to service to industry, helping it go forward using technology to improve its competitive position. That's what we were talking about here yesterday.

However, that is not the only assignment we have: there are two more. I've grouped together a series of safety and health areas into a goal covering fire safety, building safety, clinical standards, and the like. There are assignments to us, by law, that tend to get lost in the noise of the fad of the year. I shouldn't call competitiveness a fad, but it is the top priority issue and it tends, in this town, to wipe out everything else.

* Lyons was named director of the U.S. Army Research Laboratory in September 1993.

The Mission of NIST

In partnership with industry and government, the National Institute of Standards and Technology (NIST) conducts research and provide measurement-related technical services to enhance competitive posture of the United States in global markets. The partnership covers the entire cycle from definition of needs and ranking of priorities, through execution of research programs, to assuring that the results are used by U.S. industry.

A second major element of the NIST mission is to conduct research in selected areas of public health and safety and the environment, again in partnership with industry and government. Some of these are mandated by special statutes earthquake hazard mitigation, elimination of chlorofluorocarbons and one, fire research, is part of the basic NIST authorization.

The final element of the mission is a broad program of scientific research to underpin the technology programs. This scientific research is motivated by NIST's charter to provide technical services to the scientific and engineering communities. These activities range from fundamental inquiries into natural phenomena to improving our knowledge of the fundamental constants on which the sciences depend for quantitative work.

These three aspects of the mission are explicitly stated in legislation. Unlike most Federal laboratories that derive their missions from those of their parent agencies, NIST is chartered by congress in broad and comprehensive legislation known as Authorization Acts. First written in 1900 and signed into law in 1901, the NIST legislation is periodically in recent years, annually updated. The Omnibus Trade and Competitiveness Act of 1988 made a major change in NIST's program by augmenting NIST's functions and capabilities. In a sweeping rewrite of the authorization, the Congress placed NIST in the forefront of Federal efforts to improve the use of technology in the competition for global markets.

Figure 1. NIST Mission Statement.

NIST GOALS

- Support industry
- Conduct selected programs in health, safety, and the environment
- Support scientific and engineering community through fundamental studies

Figure 2. NIST goals.

So one of the things management has to do is keep holding up these other assignments in a budget sense and in a priority sense.

The third assignment is, really, our role in the scientific community as good citizens, as the laboratory looked to by the community to do certain kinds of things, for example, handbook data, better values for fundamental constants, and a constant crusade to improve our measurement capabilities, in particular, with the basic International System of Units.

So we have these three component parts of the mission. The advice one gets today from the quality folks, our Baldrige [Award] people, is that the very first thing you do is think about who the customers are before you try to create a program. For us, that is spelled out in law. As I've said already, the first customer, whether it's the 1900 Committee Report that's carved in the wall in the lobby, or the 1988 Law, the first customer is the manufacturing component of industry.

Now that has, in recent years, shifted some from manufacturing to information and service, but there is still a major concentration on the manufacturing side of the business.

The second set of customers is our colleagues in the university community.

The third customer, all levels of government, particularly the Federal Government, is the major customer. This group reimburses us for about a quarter of our activities. We are still the central, all-purpose laboratory for much of the Federal Government and, increasingly, we work for state and local governments.

The final customer is the general public. The earlier versions of our enabling legislation said that we were to provide technical services to interested individuals providing, of course, they had some technical competence to receive our service. So everybody was originally the customer.

We do all kinds of things in our laboratory programs as well as in the new external efforts. It is useful for us, in thinking about how to balance the demands, to divide the work into at least these four categories. Actually, they fan out into more subcategories.

But we begin with the fundamental work. I don't like to call it basic research, because basic and applied have connotations that tend to aggravate some folks. But I think most of our staff know what we mean when we talk about fundamental studies.

Now, we need to have a foundation of that kind of work for an institution such as ours to keep current. The question for management always is, how much? Obviously, we are a technology laboratory as well as a science laboratory; how much good, long-term, fundamental, broad-gauged inquiry does a laboratory like this require in order to accomplish the rest of its mission?

Many people would say that we don't need to do any. I doubt they've ever run a first-class laboratory if they say that.

We find that you need a research component of this nature, at some level, in order to make the applied work be current, be state-of-the-art, be aware of what is going on, in order to make sure that the quality of the applied work is as high as we can go, in order to be able to recruit and maintain first-class staff. For a number of reasons that I'm sure most of you would accept, you need a research base. That certainly is our model for this institution and, as I said in my prepared remarks yesterday, we have developed over many, many years a culture here that insists that we do science, as well as good technology, and a staff that is able to move rather quickly back and forth from the fundamental work to the applied.

In fact, Professor Ramsey last night talked about how one moves from the basic to the applied, and back and forth, even in academic work.

Supporting technologies is really a category that includes a number of things that this institution is known for. To discuss that and the next one, I'm going to put up a visual [fig. 3] that may confuse you, but I have used it for the last year and a half, mostly in connection with the definitions in the Advanced Technology Program.

The supporting technologies include calibration services, new measurement techniques, reference materials—well-characterized standard reference materials, critically evaluated reference data, things of that sort that are independent of time in the commercial process.

In an oversimplified form, this figure goes from some kind of a new concept to making routine sales—obviously, also production—and to where the money flows back into the economy with attendant benefits to our standard of living. This is the product and process development timeline and, in reality, it's very complex, with lots of loops and failures and dead ends.

Given that the exploratory work has been done and we now have the new concept, there are two kinds of technology services that our friends in industry require from us. The first is—let me just use handbook data as an example—say, steam tables; that's what I call supporting technology. It doesn't matter whether you're building a new factory, and trying to design new heat exchanges from scratch and you need a good steam table to look up the data to design that or, if you have a very old factory that in some sense is falling apart and you want to replace the heat exchanger with a new, more modern and more efficient device—in one case you're somewhere in the middle here and designing a new plant, and in another case you're out at the end replacing the exiting unit in operation—you need that supporting technology, and industry counts on us to do that. Design engineers look up all kinds of things and, more often than not, they're looking at information that was either developed or evaluated by this institution. That's supporting technology, very important. The new legislation says, "Don't forget to keep on doing that," and we intend to expand that to the extent we're allowed to.

The other technology was hit hard yesterday by Erich Bloch, who didn't like this definition of generic pre-competitive technology. I don't like it either. It's

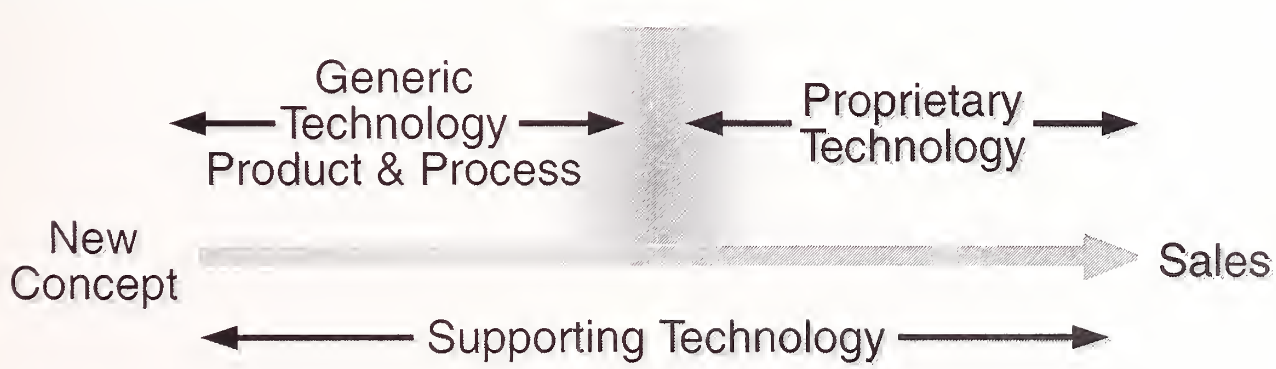

Figure 3. Supporting technology.

pre-proprietary that we're really stressing. It is the area of product and process development before individual companies convert it into trade secrets. This is a quasi-open area that is, because it's open, more or less generic—the information is shared among the parties—and because it has not yet become trade secrets, it is preproprietary.

This is an area in which we have often worked in our history, whether it is the development of radio or aircraft systems, or what have you, we have worked there until industry picked up the results and took them into proprietary-specific products.

Today, for example, you won't hear from Bob Kamper about superconductivity so much as optoelectronics—but our working in the new high-temperature superconductors, as well as the low-temperature ones, is generally in this area. And the high-TC superconductors, of course, are still largely open, still largely being discussed by the industry, because the problems are so tough. They want to talk to their colleagues and see what progress can be made.

The Advanced Technology Program of financial awards to the industry, or groups of industry, is by our rule, as published, restricted to this generic area. This is also the high-risk area where the chance of losing your investment is greater than on the side where you have solved the tough problems, decide to build the plants, and develop the markets.

So we will have both supporting activities and these generic activities in the laboratory. Probably the greatest example of the latter in recent years has been in our Factory Automation Program, a piece of which Jim Albus will address in his talk later this morning.

In our materials science and engineering efforts, where we mostly used to do things like phase diagrams aimed at products and product characterization, increasingly we're talking about materials processing. Industry itself is doing that as well. So we're shifting from product focus to process focus. It's also generally true that industry regards processing as somewhat less proprietary than product characterization and, in fact, the example of Sematech, where semiconductor process technology is being pooled, is probably the best instance of the change.

Finally, we have to move the results out to the user. There is a lot of talk in Washington about technology transfer [fig. 4]. We don't talk about that because, as I said yesterday, we tend to develop our plans with our customers and to do a lot of collaborative work in our laboratories with guest workers from industry, and the results are transferred automatically during the process. If you have to invent a transfer process after the fact, you probably did something wrong. In this institution it would be an unexpected problem.

TRADITIONAL NIST TECHNOLOGY TRANSFER MECHANISMS

- Publications
- Conferences and Workshops
- Calibration Services
- Standard Reference Data
- Standard Reference Materials
- Standards Library
- Laboratory Accreditation
- Standards Committee Memberships
- Research Associate Program
- Guest Researchers
- Special User Facilities
- Individual Collaborative Research
- Cooperative R&D Agreements

Figure 4. NIST technology transfer mechanisms.

Last January we significantly reorganized NIST for the third time in our history, into a set of major entities that we call laboratories. There are eight of them. If you add our external program management—we call that Technology Services—you have, really, nine large technical units [fig. 5].

Those of you who knew us a little better in earlier times will see that some of these entities are unchanged from the recent past. For example, we've had an electronics and electrical engineering focus now since 1978, and only changed the name from a center to a laboratory. The same is true for manufacturing engineering. On the other hand we used to, not many years ago, have three different chemical centers. We had a chemical engineering center, a chemical physics operation, and an analytical chemistry operation. We put all that together and called it Chemical Science and Technology.

Putting all the chemical units together into a much bigger entity, on the order of 300 people and a budget of close to $40 million, gives them a chance to take initiatives on their own, to have some financial flexibility and not be so small that every time they want $50,000 they have to come upstairs and talk to the director.

The same thing happened in physics. We now have one laboratory that encompasses our efforts in physics. We used to have two, but we put the Center for Radiation Research in with the laboratory that had, I guess, three or four different labels since the late 1970's, and now it's just called Physics. We talked about more elegant names than that, and I thought none of them were as descriptive as just Physics. And I couldn't

National Institute of Standards and Technology

Organizational Chart

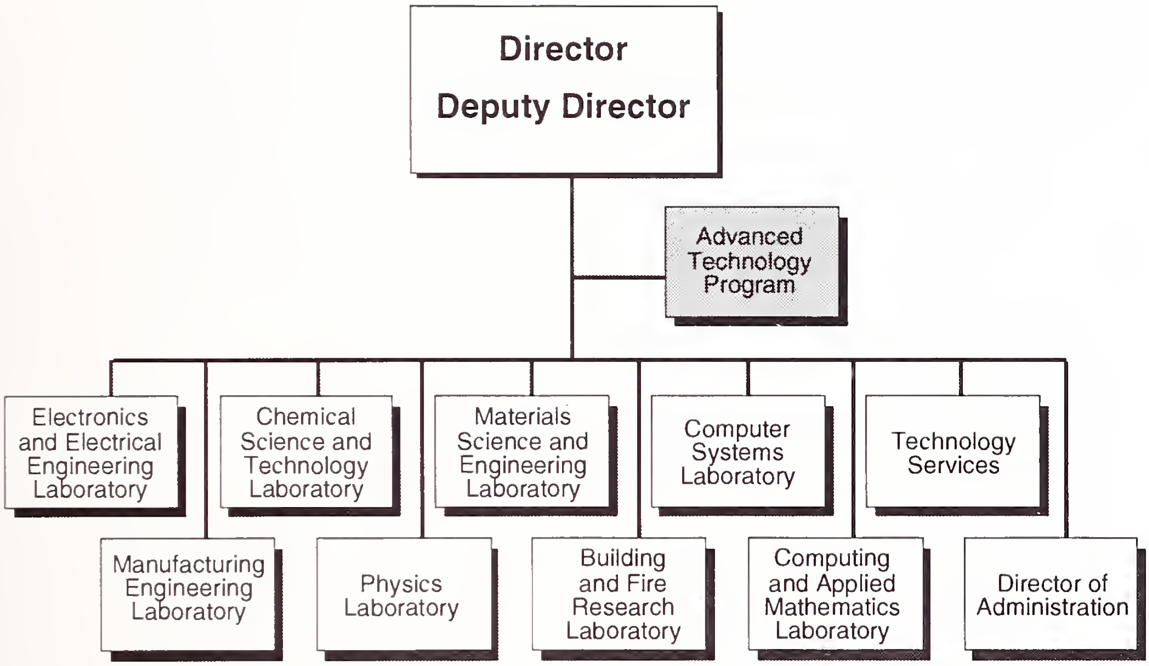

Figure 5. NIST organization.

imagine having an NBS/NIST institution without such a laboratory. So we have it, despite some considerable discussion over the label.

Materials Science and Engineering is unchanged from the earlier times. Two other functions, Building Research and the Fire Research Center, were not large enough to operate as separate entities in this environment, so they were pushed together into Building and Fire Research; in some sense, it is a return to the beginning because the Fire Research Center, in fact, came out of the Building Research operation in years past. However, we are keeping those separate in a budget sense, and we're operating with separate divisions focused on the Fire Program and the Building Program, and that will continue in the future.

Then we have the Computer Systems Laboratory, which used to be called ICST. The descendent of the applied mathematics function is now called Computing and Applied Mathematics. It does our statistical engineering, numerical analysis, operates the central computers and the computing network, and provides a good deal of service and advice and collaboration to the other seven entities.

This is how the laboratories are now structured. The rest of the day we're going to hear sample talks from these folks to give you some idea of the nature of each activity. It is by no means a complete look. This place is now big enough that even if you worked at it constantly you couldn't possibly visit all the technical staff in a year's time, so all you can do, really, is sample.

Now, in addition to what we'll hear today—I just want to remind you, once again, that the legislation in the late 1980's created some new programs. You won't be hearing from them today, but you're welcome to probe us about these efforts.

You've heard a lot about the Advanced Technology Program. That's moving up very sharply in the budget and it's now approaching $50 million. Concepts are on the table that might make that on the order of the Defense Advanced Research Projects Agency budget.

The Manufacturing Technology Centers are now at five, and they're almost certainly going to go to the order of nine or 10, maybe a dozen. Some people would like to see one in every state. I think that's a budget-limited activity.

The State Technology Extension Program is a small catalytic effort aimed at helping states do the equivalent of the Agricultural Extension Service. I mentioned that yesterday.

Finally, we have this explosive phenomenon represented by the Malcolm Baldridge National Quality Award, an effort that we run from NIST.

As I said at the end of my remarks yesterday, we have a very vibrant laboratory program that is strongly supported by the Administration. The Office of Management and Budget said in last year's budget submission that it wanted this laboratory program to double in 5 years. That's an extraordinary statement, and those of you who have served on the Visiting Committee and the Boards of Assessment know that we've been dead flat in real terms since the late 1960's. But the Bush Administration has decided that this is a place to invest in, and they're going to do that. The questions before the Congress are, how much of the investment can go in the external programs and how much in the laboratories.

The Optical Revolution in Electronics

Robert A. Kamper
Director, NIST Boulder Laboratories
(retired January 1994)

I want to start by thanking many colleagues in NIST, both in Boulder and in Gaithersburg, and also in the Optical Computing Systems Centers at the University of Colorado and the University of California, San Diego, who provided a lot of material for this talk.

I'll start with some grand generalizations and then talk of three examples of optical technology that are growing rapidly just now. We have strong programs in optical telecommunications and optical frequency standards at NIST, and we are just getting into the optical computers.

Comparing Photonics and Electronics

The title of my talk is, really, an overstatement. As I see it, there's no real "revolution" in which optics—or photonics, as we call it nowadays—is taking over from electronics. They are like apples and oranges in the same fruit salad. They are complementary, and they're used best in combination.

The prime example of this is the ordinary integrated circuit, which is really a little miracle of photography. It's made out of many layers which cover a field about a centimeter across. They are sharp and accurate and register to a few hundred nanometers, and it's all done by a photographic process.

But to get further into the comparison of the two technologies, one should look at a few general characteristics. First let's look at speed.

Both in photonics and in electronics, devices that switch in times of the order of a picosecond have been demonstrated. There are lasers which can generate pulses a few femtoseconds wide, but they have to be in repeating trains, and they don't carry information at that rate. For conveying information, the best switching speed we have is about a picosecond, and that's ample for present purposes and also for a long way into the future, because in most electronics systems the speed is limited by the interconnections. The best you can do with interconnections, of course, is in free space where the velocity of light is a foot per nanosecond, and that's available to both technologies. In optics it's available on the micrometer scale, but in electronics you have to go to big dishes and satellites before you can use it effectively.

Both technologies use waveguides. In optics we use dielectric waveguides, and in electronics we use metal waveguides that are a little slower than free space, but not much. And commonly, in electronic microcircuits, we use strip lines that are mismatched, so basically you're charging a capacitor through a resistor every time you send a pulse through them, and this does slow things down considerably.

Moving to what I'd loosely call topology—I know that's not a strictly accurate use of the word—optics lends itself very well to 3-dimensional structures and connections down on the microcircuit level at a scale of a few micrometers, but with electronics you're more or less restricted to a flat substrate. But with multi-layers you can have cross-overs, and in fact, new back-plane technologies are overcoming this limitation by having so many layers that you essentially have a 3-dimensional structure.

The limit to how small a signal you can handle is set by noise. Thermal noise is common to the two technologies. Shot noise depends upon the energy carried by the individual moving particles. It so happens that it's very similar in normal devices in both technologies. In the near-infrared the energy of a photon is about one electronvolt, which is roughly what an electron carries in a normal semiconductor circuit. But with electronics you can be more clever. With superconductors you can go to much lower impedance circuits and work at much lower voltages, and you can overcome shot noise.

Packing density is important, because with the limitation on the speed of communication between elements you have to worry about how close you can put them together in a complex circuit. One of the limits is how small you can make the transmission lines and, in both cases, if you want enough bandwidth to carry pulses which are less than a nanosecond long, then you have to make lines which are a few micrometers wide. You have to separate the lines by a few micrometers.

As to the minimum device size, in optics you're limited by the famous Airy disk, which is the size of the minimum diffraction pattern you can make at the sharpest focus you can get. This is of the order of the wavelength divided by the numerical aperture, and it usually comes out to be a few micrometers. In electronics you can do much better here.

If you have of iron atoms on a gallium arsenide substrate, then 20 to 50 atoms in a clump act like a metal and can conduct electricity and therefore, in principle, could be made into some kind of device.

If you have a string of cesium atoms laid out on a gallium arsenide substrate, then you have the beginnings of a wire, or a connection. And if you can put down enough atoms to make the string thick enough to be a 3-dimensional structure, with three layers or more, then it can conduct electricity and be a wire. So you can make tiny structures for electronic applications.

But, of course, for every generalization there's an exception, and I'll finish the talk by showing you an optical device that consists of a single mercury ion.

Another limitation of the packing density is dissipation of heat. It's difficult to dissipate more than about a watt per square centimeter into air. Into liquid you can do a little better—20 watts per square centimeter. But there is certainly a limit, and for very fast, very complex systems, you need to worry about how much heat is dissipated.

Figure 1 shows a few technologies compared in this respect. On the vertical axis we show the speed, and we show the power dissipation on the horizontal. Some figure of merit would minimize both, so the meritorious high ground is down at the bottom left part of the diagram.

The figure shows a few superconducting devices which are both fast and dissipate very little energy. It also shows some of the more advanced semiconductor devices. The normal technology that we use every day, which is in mass production, is further out on this part of the diagram, and the one optical device I've shown is the self-electrooptic effect device (SEED), which is a device developed at the Bell Labs for optical computing. It's not a pure optical device. It's a hybrid device that receives an optical signal, converts it to electrical and then converts it back to transmit an optical signal. Of course, it has not had the benefit of as much development as the other devices shown on the diagram.

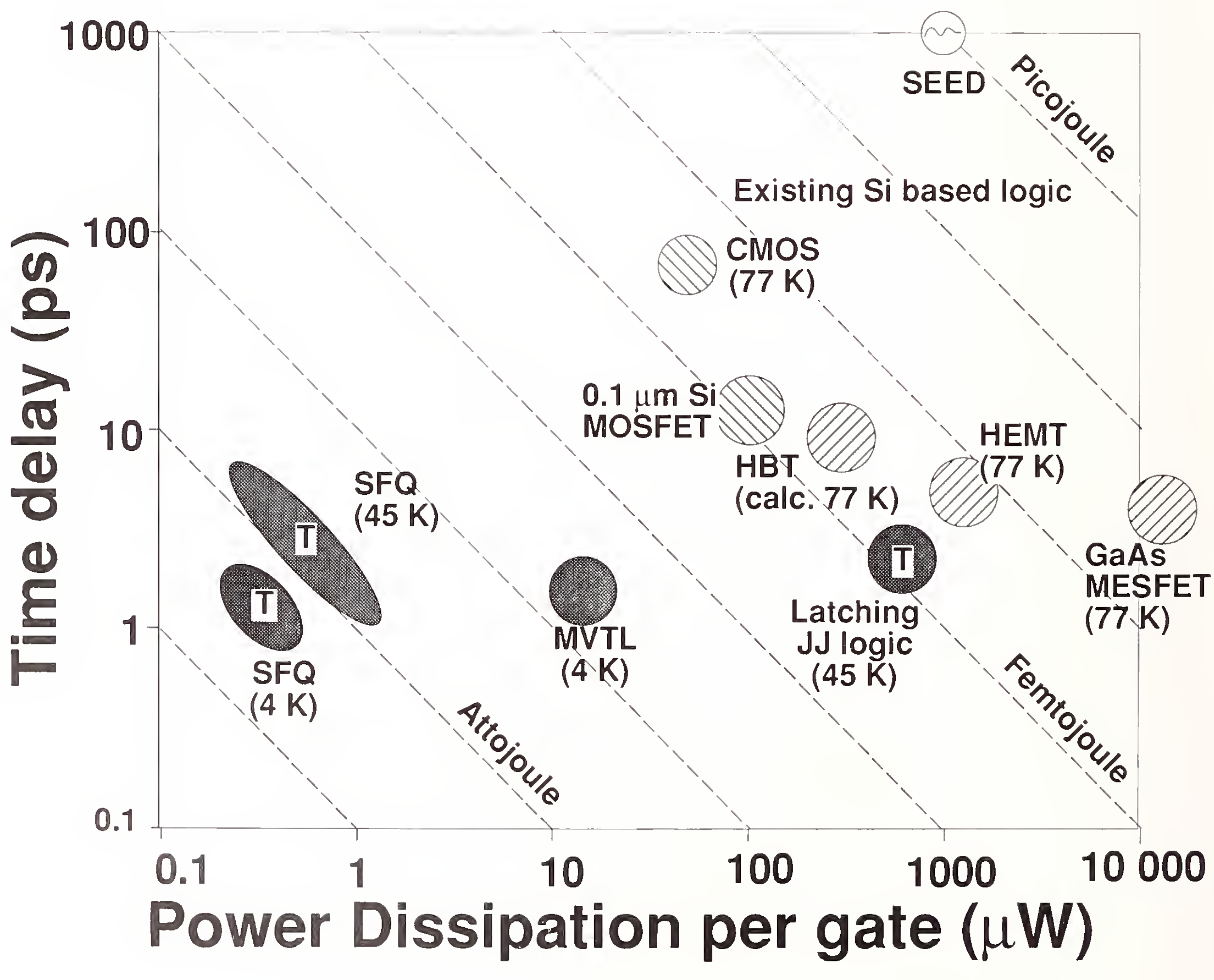

Figure 1. Comparison of technologies.

Pure optical devices, which depend upon optical bistability, usually need a lot of power because they need to be driven very hard, so they're off the scale.

Let me now talk about the basic technology that makes photonics and electronics similar, and that is integrated optics.

One of the basic elements is the optical wave-guide in a substrate. There are several ways of making optical waveguides, all of which we're able to do in our labs at NIST. You can modify the substrate itself by ion exchange or by diffusion or some other process, usually through a mask. Usually you make a structure that's a few micrometers across and then usually you put another layer on top to protect it. This is applicable to glasses and to electrooptic materials. Or you can evaporate or deposit layers by molecular beam epitaxy or other technologies. Again, you put the waveguide itself down through the mask. You apply this to glasses, polymers, or semiconductors, and again there's usually a protective layer on top. This makes very nice waveguides with quite small attenuation.

If you dope the waveguide with a rare earth and pump it with light of the right wavelength you can make a laser. Or you can make surface emitting lasers, consisting of multiple layers of gallium arsenide, aluminum arsenide, or mixtures. The cavity is defined by mirrors, consisting of interleaved layers of aluminum arsenide and gallium aluminum arsenide with quarter-wavelength periodicity which makes them into efficient mirrors. The region in between is the gain region, which is either gallium arsenide or a superlattice of gallium arsenide and gallium aluminum arsenide. If you pump this with light, then it lases and emits vertically from the surface. People have also run these as laser diodes by passing current through them and pumping them that way.

Another side of integrated optical technology which I'd like just to mention, because it brings in our Superconductor Program, is focal plane arrays. A focal plane array is a 2-dimensional array of infrared detectors that are used to receive and process images. Our contribution to this technology is a device that is being developed by Eric Grossman. It's a superconducting thermal detector. In order to isolate it from the substrate, it is made very small, and coupled to the radiation through a log periodic antenna. The device works by the kinetic inductance effect, which is the variation of the penetration depth into a superconductor with temperature near the critical temperature. If you can make a device which is sensitive to the resulting variations of inductance, then this becomes a very sensitive thermal detector with the unique advantage that it has no Johnson noise because it has no resistance. Its noise is entirely due to the fluctuations of the radiation you're looking at.

Optical Telecommunications

The first widespread optical telecommunication system was constructed in France about 200 years ago. It was engineered by a man called Claude Chappe. It consisted of what we would nowadays call a star network of communication lines in the form of semaphore stations at 10 kilometer intervals. The person at each semaphore station watched the next one through a telescope and would repeat exactly what he saw with his own semaphore. This was the first optical repeater, a device that is used commonly nowadays. And in fact the repeater spacing of 10 kilometers is quite respectable. It is much better in some modern systems, but it is still respectable. This system was used widely to help fend off the enemies of France during the French Revolution. Of course, it was shortly superseded by the telegraph, then by telephone and microwave links, etc., and then optics came back. Optical fiber telecommunications had an extraordinarily fast development. It was in 1966 that Kao and Hockham first predicted theoretically that if you could get rid of the impurities in silica it would be possible to construct an optical wave-guide that would have low enough attenuation to carry signals over many kilometers. Then the first practical waveguides were developed in the early 1970's, and we've gotten to the stage where nowadays optical fibers have taken over most long-distance communication.

In the United States, optical fiber lines carry 95 percent of the trunk line traffic now. Across the Atlantic the situation is constrained by a Federal Communications Commission regulation which demands that half the traffic go by satellite. This is due to end next year, and probably optical fiber will take over there, too. Optical fibers are also used for short-distance communication to connect computers together. They have taken over at an extraordinarily fast rate.

The basic optical fiber consists of a fiber of very pure silica, about 125 micrometers in diameter, with a core in which the refractive index is enhanced by doping. If you have a fairly fat core, maybe 50 to 80 micrometers in diameter, you get what's known as a multimode fiber, because several modes of propagation can be carried. If you make the core narrow enough, then just a single mode can propagate, and this is the preferred technology nowadays. The core has to be about 8 micrometers across.

The modes in a multimode fiber are distinguished by the number of nodes in the radial and the azimuthal directions. With the single mode fiber, of course, there is just a single spot of light in the middle.

The problem with multimode fibers is that it's very difficult to make all the modes arrive at the far end of the transmission line simultaneously, so it's difficult to use very high data rates in a multimode fiber over long distances.

Nature has been very kind to technology in the characteristics of silica. The attenuation of a good silica fiber is dominated by Rayleigh scattering at short wavelengths. This falls off with longer wavelength as the fourth power of the wavelength. The limit comes when you run into the vibration bands of the crystal. These can be pushed further out by using heavy metal chlorides, for example, which are just being developed now, and it leaves two really good transmission windows which are used for communications.

A small absorption peak between the windows is the remnant of the hydroxyl radical which was the main thing that needed to be removed in order to make practical fibers.

With a single mode, the only reason why signals should disperse is chromatic dispersion of the medium. The chromatic dispersion of the medium itself and the effects of the geometry of the waveguide happen to cancel, by sheer luck, at 1.3 micrometers wavelength with a fiber of the simplest refractive index profile. You can actually push the region of cancellation about by using more complex profiles, but nature was very kind to us at 1.3 micrometers wavelength.

Let me describe the evolution of the technology. At the moment we're at the stage of simple optical fiber links with repeaters. This is basically the state of sophistication of the telegraph. All the complexity of a modern telephone system, such as switching, digitizing, and multiplexing, is still in the electrical technology. Then for long-distance transmission the digitized signal just turns a laser diode on and off for optical transmission through the fiber to distances up to 100 kilometers in a single link. Then the optical signal is converted back to an electrical signal, and all the complication of the system at the far end is electrical.

If you need to go more than 100 kilometers, you need a repeater that converts the optical signal to electrical and cleans it up, amplifies it, and then retransmits. It's expensive and it's also, of course, the least reliable part of the system.

The lines we use now can transmit about 1.2 gigabits per second.

The next step is to try to get rid of the repeaters. The first step is an optical fiber amplifier, consisting of a regular silicon fiber doped with erbium and driven by visible light. Optical fiber amplifiers are now quite well established.

Then to get rid of the dispersion of the signal over long distances and avoid the need to reconstruct the signal, one can take advantage of the "soliton effect." The soliton effect is a compression of pulses that happens in the right conditions of nonlinearity and dispersion of the transmission medium. It was discovered back in the early 19th century by a Scottish engineer called John Scott Russell, who was working on the improvement of canal barges. He was out one day observing canal barges when he saw one have a collision in which it stopped abruptly. The bow wave continued down the canal. He thought this was curious, so he got on his horse and chased it for a few kilometers until it came to a point where the canal changed its configuration and it was dissipated. But up to that point it just held together. He was very surprised, but he worked out the first theory of how it happened. And now it's about to be used in telecommunications. The next transatlantic cable will probably use the soliton effect to preserve its signals.

The next step is to increase the channel capacity. We're just using 1.2 gigabits of channel capacity now, and that's enough for present purposes. But if we want more, the next step is to go to the primitive equivalent of an AM radio station where you have several stations on different wavelengths, so once again you'd have a complete electrical telephone system, but you can now use the fiber on different wavelengths to provide independent channels of communication.

An experiment done at Bell Labs several years ago demonstrated this by multiplexing 10 channels on 10 different wavelengths on the same fiber to achieve a data rate of 20 gigabits.

Another experiment in Japan, by Nippon Telegraph and Telephone Corporation (NTT), demonstrated the transmission of pulses over a distance of 10,000 kilometers using the soliton effect to preserve their shape, and optical fiber amplifiers to sustain the power.

Finally, to take full advantage of the potential of optical fibers, we'll go to communication which will bring in the full sophistication of modern digital radio. It will use very pure signals and heterodyne receivers. With that it will be possible to have a channel capacity that's 3 orders of magnitude greater than the 1.2 gigabits we're using right now. The potential is there and can be developed in the future.

Another development which is in progress is to expand optical technology to local distribution, after solving the problem of switching and signal handling and multiplexing with optical devices instead of electrical.

At NIST we have been involved in the development of the optical fibers themselves for about 15 years, working with the Electronic Industries Association to establish measurement techniques for all the quantities that affect performance, some for multimode, some for single mode fibers. The latest example is the measurement of the geometry. The aim here is to make a standard for measuring the geometry of a fiber with an uncertainty of about 100 nanometers. For this we use what you might call the ultimate mechanical micrometer, and a scanning confocal microscope, which is an optical device. They agree to a few tens of nanometers, which is remarkable for mechanical and optical devices.

Looking forward to the future, Doug Franzen and his group within NIST's Electromagnetic Technology Division are developing a sampling oscilloscope. The sampling pulses are generated not by a laser diode but by an optical fiber laser. They're compressed by the soliton effect, and they are combined with the signals to be sampled at a nonlinear optical device which then gives the correlation between the two. The repetition rate of the sampling pulses is offset from that of the signal to be sampled, so they slowly march through, and one can receive the information at a reasonably slow rate and use a slow detector, even though the waveform itself might be repeating at a very fast rate.

To support wavelength division multiplexing, Sarah Gilbert of the same division is working on a wavelength standard using an absorption in the acetylene spectrum.

Optical Computing

Let us move on to a more speculative field, optical computing. Optical computers probably will never be pure optical devices. They will almost certainly be hybrid systems of one kind or another. They will take advantage of some of the particular virtues of optical effects, and they'll have special architectures which do this.

The first advantage of optics is that you can get Fourier transforms for free, so you can do very good analog computing. If you put an object at one focal point of a lens, then you get the Fourier transform at the other. This has been used in the past for processing images from synthetic aperture radar, for example, although I believe it's no longer done that way.

Another example is an optical image delay, created by Ed Kelly at NIST in Gaithersburg. He is trying to photograph very fast electrical discharges in their early stages, so he needs to delay the whole image until the camera can get started. He reflects the whole image back and forth among the mirrors over a path of about a hundred meters, which amounts to a delay of a few hundred nanoseconds. This is enough to allow the cameras to start. And of course this delayed image contains an enormous amount of information.

Moving to digital computers, the advantage seen for optics is for the interconnections in a massively parallel computer. One concept which is being developed at the University of California at San Diego consists of two 2-dimensional arrays of processors which are connected with programmable connections using light beams. The connections to clocks, etc., are all handled by a computer-generated hologram which distributes the signal from one array to another. Programmable arrays steer the dynamic signals.

Another idea is the neural network computer, which consists of nodes, each of which receives input from several other nodes and gives an output which is a weighted combination of the inputs. This lends itself to optics too, because it too has to be a machine that handles a large number of parallel signals. A chip has been developed for such a computer at Mitsubishi in Japan. It's an 8×8 array of optical and electrical hybrid devices that receive optical signals and have variable sensitivity to them which can be programmed in. Their outputs are optical signals.

A neural network computer is not programmed—it learns—so it is a very different concept from a digital computer.

Another concept, from the University of Colorado Optical Computing Sciences Center, consists of a loop of optical fiber in which pulse trains are manipulated and sustained by means of a 2×2 optical switch. You can use this as a counter, or you can assemble signals with it, or you can use it for logic. It is a serial machine.

The functions proposed for optical computers are basically the functions which we can't do with digital serial machines. We're hoping to do image processing, pattern recognition, and soft logic, which can accept ambiguous and conflicting information and construct evasive answers from it like a human brain does.

Figure 2 lays out the prospects. It is a plot of speed versus complexity. The whole of present-day digital computing technology lies to the bottom left of the diagram. Optical neural networks might reach the area near the top right. The brains of a few representative animals are marked on the same diagram for comparison, to keep our ambition in check.

Optical Frequency Standards

I will finish by going briefly through optical frequency standards. The present frequency standard is a resonance of the cesium atom, which is observed by an atomic beam method. An optical standard would be 5 orders of magnitude higher in frequency. The connection between the two must be made on a routine bases to make the optical standard practial.

This was done in the early 1970's by Don Jennings' group in Boulder. The project made The Guiness Book of World Records by measuring an optical frequency. Dave Wineland is now developing a system for a standard. It uses an electromagnetic trap for holding mercury ions, which you can manipulate until you get a single mercury ion trapped in the trap, and play like a fish on a line with a laser which is tuned near its fundamental resonance in the ultraviolet. The transition which is proposed for the standard is a weaker transition from the ground state. When the mercury ion is in the upper state the strong resonance is shut off, so you can actually see a single ion winking on and off as its resonance is enabled and disabled by the weaker transition. When this system is developed into a frequency standard, it will probably have 4 orders of magnitude more accuracy than the cesium beam we use now.

Acknowledgments

I thank Ronald Ono and Bart Van Zeebrock for figure 1 and Singh Lee for figure 2.

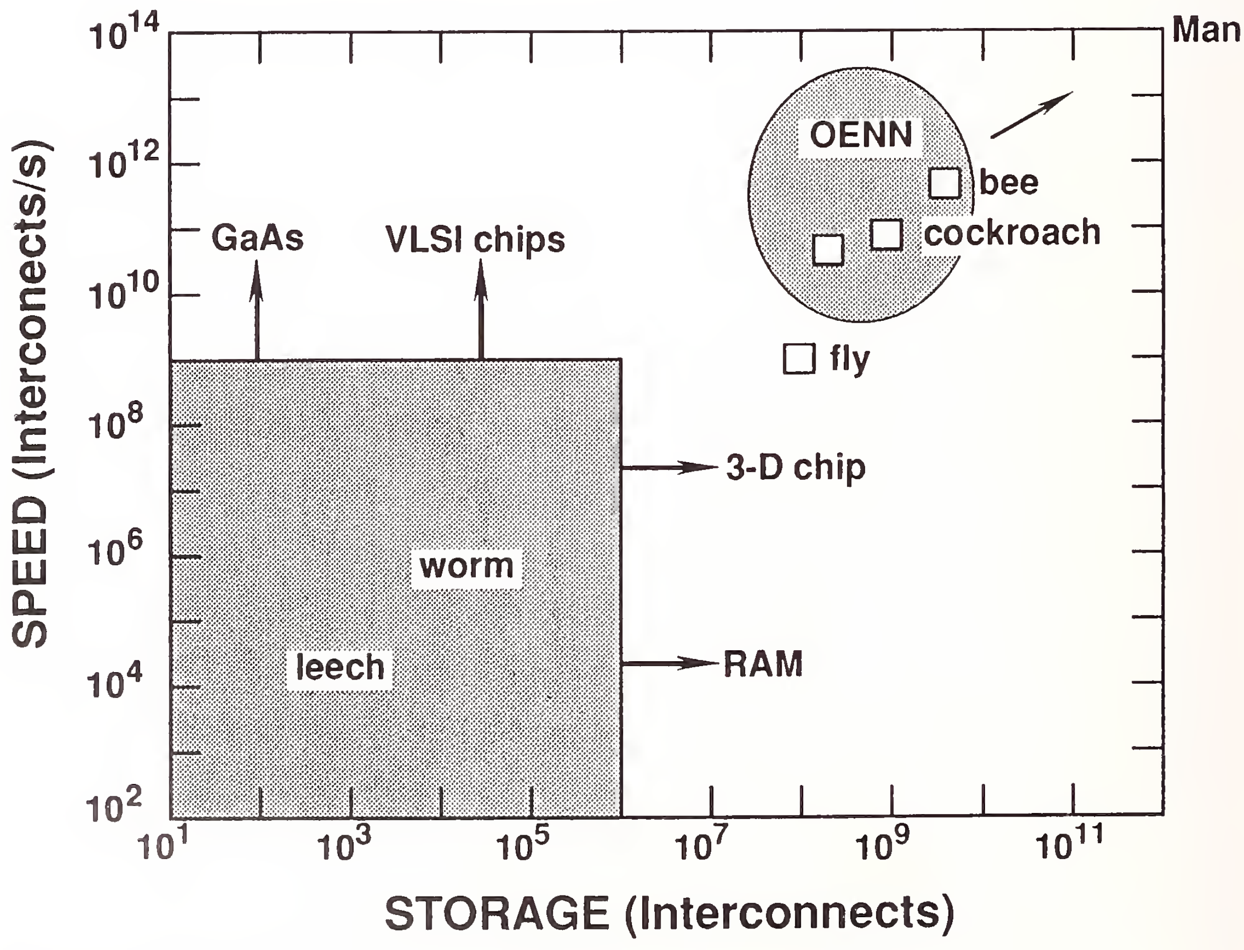

Figure 2. Potential of optoelectronic neural network.

A Theory of Intelligence

James S. Albus

Chief, Robot Systems Division, Manufacturing Engineering Laboratory

The title of my talk, I'm sure, strikes some of you as presumptuous, and the idea that I'll cover the subject in 30 minutes is even more presumptuous. But what I hope to accomplish in the next 30 minutes is to give you a brief overview of the theoretical foundations that support our research in intelligent machine systems here at NIST in the Manufacturing Engineering Laboratory.

Many would argue that we simply don't know enough to formulate a theory of intelligence. But even to address the issue of intelligent machine systems you must have some sort of theory, either explicit or implicit, and I believe it's important to make your scientific presumptions as explicit as possible.

I think that everyone will agree that much is unknown and will remain unknown for a very long time in this area. Certainly we know extremely little about perception and cognition. Our understanding of how to represent knowledge and compute belief is primitive at best. We have some basic understanding of language and communication, but how that fits into the theory of intelligence, or intelligent systems, is not entirely clear. The notion of reason and emotion is cloudy and prescientific in many cases. Certainly the relationship between the mind and the brain is a mystery, and is likely to remain so for many, many years.

Having said that, it's also important to realize that much is known, and progress is very rapid in a number of fields related to an understanding of intelligence. Certainly in the neurosciences, progress is very rapid in understanding the physiological, anatomical, and chemical bases of behavior. In computer integrated manufacturing throughout the world, many millions of dollars are being spent in Europe, in Japan, and in the United States in understanding computer architectures, understanding how to represent knowledge about objects and processes, distributed data bases, communications, and multi-processor operating systems. A great deal of work is going on in robotics related to manipulation and locomotion. Smart weapons systems were on display on television earlier this year in the Gulf War. Unmanned air vehicles are the most well developed, with undersea vehicles coming along very rapidly. Land vehicles are more difficult, but still progress is being made.

Artificial intelligence is giving us an understanding of how to analyze images, recognize objects, formalize our reasoning, do problem solving, and conduct planning. Work in adaptive control and neural nets is leading us to an understanding of how systems can be designed to learn and to forget. Game theory is giving us a good understanding of how to deal with uncertainty and to make the best possible decisions under uncertain conditions. Signal processing for radar and sonar are giving us insights into how to fuse data from multiple sources and how to correlate information to draw decisions and understand what's happening in a noisy environment.

Thus, there is a great deal of background for a theory of intelligence, but we don't have a theory yet in the sense that a theory must define what intelligence is and should explain where it came from, describe how it works, and finally tell how to build it.

An operational definition of intelligence is "the ability to act appropriately in an uncertain environment." Appropriate action is defined as that which maximizes the probability of success. Success is the achievement of behavioral goals.

I think it's important that we not limit our definition of intelligence to subjects beyond our understanding. We need to include systems that we do understand together with a whole range of concepts that we don't understand. Our definition of intelligence needs to span the spectrum from that of a thermostat to that of the most complex computer system that can ever be built, from that of an insect to that of an Einstein.

At a bare minimum, intelligence requires the ability to sense the environment, to decide about the environment, and to control action.

That includes the ability of a thermostat to sense the temperature in the room, to decide to turn the furnace on and off, and then actually throw the switch. That is the basic minimum.

Higher levels of intelligence are able to recognize objects and events, to store and use knowledge about the world, and finally to reason about and plan for the future.

The most advanced forms of intelligence have abilities to perceive and understand in deep and sophisticated ways, to choose wisely, and to act successfully in a complex, competitive, and hostile world.

Intelligence is a product of natural selection. The only real proof for intelligence comes from nature, where more successful behavior tends to be passed on. Intelligent creatures are more likely to survive and propagate than those that are less intelligent. Thus, intelligence, like natural selection itself, is driven by competition between individuals within a group and between groups in the world.

The basic elements of intelligence are shown in figure 1. Actuators act on the environment. In the natural world, actuators are muscles and glands; in the artificial world there are motors, actuators, pistons, and transducers of various types. Sensors sense events and objects in the environment. A sensory processing system somehow makes sense out of what the sensors are reporting, transforming sensory input into perceived objects and events.

A world model sits at the center of this system. The world model is the system's best estimate of the state of the environment plus the state of the intelligent system itself.

The world model contains a database, or knowledge base, and a set of active elements that are able to answer questions, make predictions, and update the database. Based upon what it knows about the world, the world model can predict what the sensory input system should observe. This allows the sensory processing system to compare what is predicted with what is observed, to do recursive filtering, and to update the world model based on correlations and differences.

Perceived situations not only update the world model, but are also transmitted to a value judgment system which evaluates them as good or bad; as beneficial or

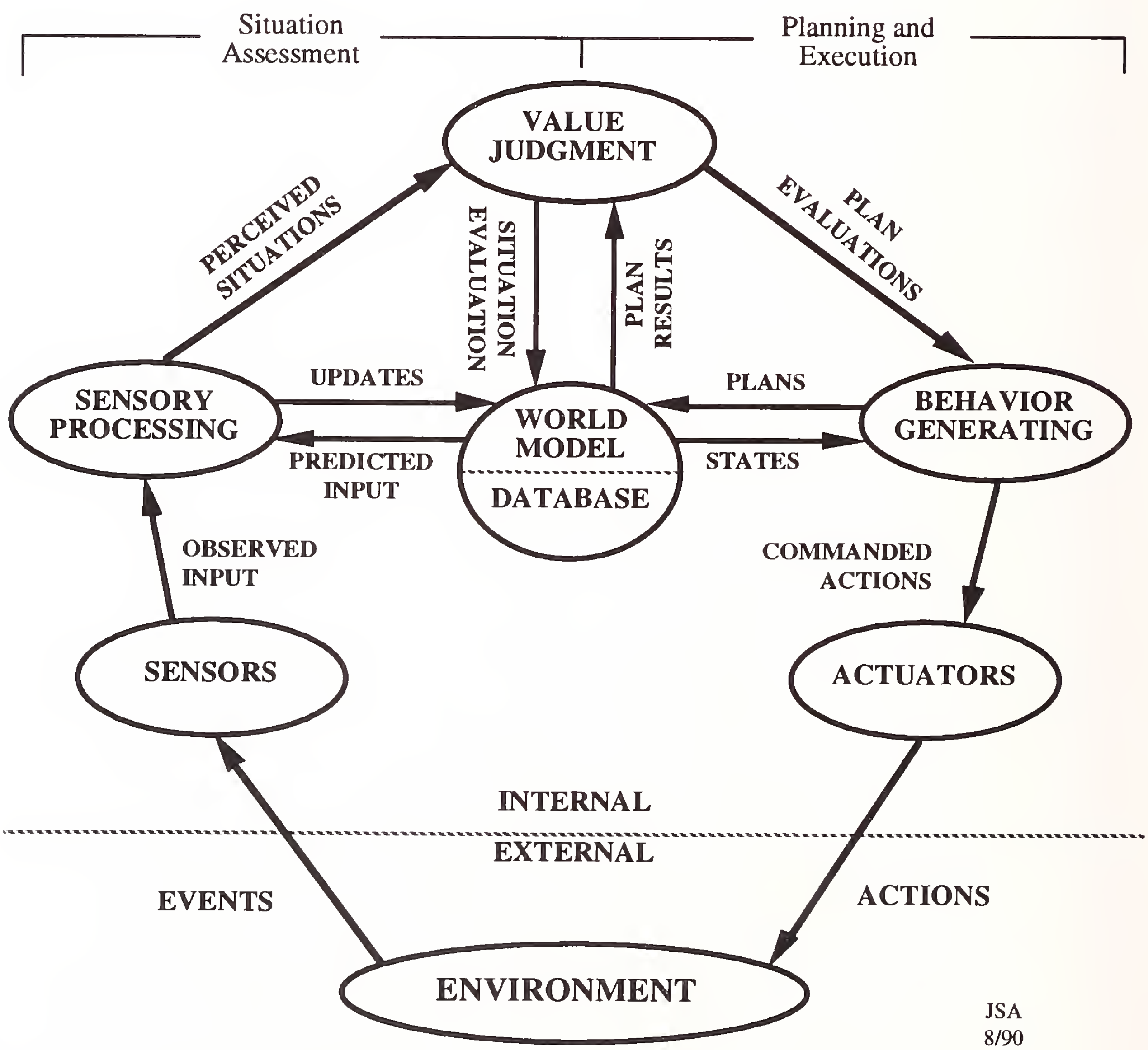

Figure 1. Basic elements of intelligence.

harmful; as dangerous, risky, or safe. The world model can attach evaluations to objects that are perceived.

The behavior generating system both plans and executes actions. It plans actions by hypothesizing plans to the world model. The world model then predicts, based upon what it knows about the world, what the result of the hypothesized plan would be. The value judgment system then generates its evaluation of whether that result would be good or bad, or better or worse than some other plan. The behavior generating system then, as a result of this planning loop, selects one action as opposed to another for execution. It also not only selects that action, but monitors that action and servos the output to the plan.

Each of those individual elements of intelligence are relatively well "understood." I put "understood" in quotation marks here because I don't mean that there is nothing more to learn. What's really not understood is the system architecture that ties the elements together, defines what the communications pathways are, specifies the syntax and the frequency of communications, and defines the organizational structure—both hierarchical and horizontal.

It's been observed from psychophysics that perception and control have limits on organization and capacity for processing and controlling information. George Miller, back in the 1950's, summarized this information in a famous paper entitled "The Magic Number 7, Plus or Minus 2."

The human brain seems to sort of clump information in groups of seven, plus or minus two, items. A more recent paper revised this to three groups of less than or equal to three things. But it comes out about the same. This is one of the reasons why your telephone number has seven digits in it, with maybe an area code. This is typical of many groupings. Words tend to have five to nine letters in them; sentences tend to have five to 10 words.

This implies that there is about an order of magnitude at each level of chunking. An intelligent system has a typical control bandwidth of about 100 hertz at the very bottom. At the top, plans are made on the order of a day, or a week, or a month. How do you build a control system with a span of control that stretches from a single individual at the top, to several million muscles at the bottom, with plans that extend from days at the top, down to several milliseconds at the bottom? Well, you do that in groups of five to 10 things. At the bottom position, velocity and force are servoed with about 100 hertz bandwidth. Dynamic paths are recomputed about 10 times a second. Clearance to obstacles for simple motions like reaching and grasping are computed about once per second. Simple tasks, such as taking a drink of water, are decomposed into a sequence of elemental moves, such as reach to the glass, grasp it, lift it to your lips, tilt it, and so forth. Simple tasks take 5 to 10 seconds. Complex tasks requiring a minute or more are decomposed into simple tasks. Small group behavior on the order of one hour is decomposed into segments of a few minutes' duration—and so on to days, weeks, months, and years.

Above one day, rhythms are imposed upon intelligent systems from outside. For example, the rising and setting of the sun, the social rituals that take place on a weekly basis, the seasons of the year, and so forth, all impose external rhythms on the human intelligent system.

This decomposition process is hypothesized to reside in an organizational hierarchy where elements are clustered into nodes and layers.

This organizational hierarchy can be imposed on a work station or a work cell in a manufacturing environment. At the highest level we have orders coming in, they are grouped into batches, and parts are routed between work stations. At the next level, work stations deal with trays of parts so that tasks are assigned to individual machines such as robots and machine tools. At successively lower levels, the control hierarchy plans paths, generates trajectories, and servos the position and force of the tool as it moves across the part.

If we take the outputs of these control modules and plot them as state vectors in state space against time, we get state trajectories. Thus, a high level task such as (assemble AB) is broken into a series of lower level tasks such as (fetch A)(fetch B)(mate) and (fasten). Each of these then is broken into a (reach) (grasp) (move)(release). These are then broken into trajectory segments, and finally the trajectory segments are servoed.

The decomposition of tasks is fundamental to intelligence. We define a task as an activity that starts with a start event and ends with a goal event. There are other kinds of tasks which are continuing, but we will not deal with them here. Tasks are decomposed into a series of subtasks at each level recursively, so that each subtask from a higher level becomes a task into the next lower level. As you descend the hierarchy, tasks become more specific, and frequencies become higher. As you ascend the hierarchy, the range and span of control get larger and goals become more global.

Much of what happens in task decomposition is the result of learning accumulated over a period of time. Part of our research in the Manufacturing Engineering Laboratory is to formalize how to put task information into a format similar to a recipe. For example, a cookbook has recipes describing how to bake a cake. If you want a chocolate cake you look up "chocolate cake." The cookbook may show a picture of what the finished cake is going to look like. It will give a list of ingredients and a procedure section that tells what to do in what order.

This is what we call a task frame. A task frame for manufacturing is shown in figure 2. The *goal* is the event that successfully terminates the task. The *object* is what is to be acted upon. A set of *para-meters* gives priority, status, timing, and in some cases stiffness matrices and tolerances.

Agents are the subsystems that are going to perform the task. *Requirements* include the feedback information required from the world model as well as well as the tools, time, resources, and materials that may be required to perform the task. Various enabling and disabling conditions may be listed.

Finally, the task frame contains a *procedures* section that is essentially a list of commands to send down to the next lower level. At that level there is another task frame that will accept those commands and further decompose them until, at the bottom, action occurs.

Plans can be totally precomputed, or they can be partially precomputed, or they may be generated in real-time by planning algorithms that search over the space of possible futures and select those actions which give the best evaluation.

The knowledge database contains state variables, entity frames, and maps. Entity frames define attributes such as geometry and surface characteristics. Maps define the arrangement of parts in space. Information in the knowledge database may be provided *a priori*. For example, in a manufacturing environment the parts we want to make are known and are described by a product data description. Additional information may be provided by sensors, such as cameras or touch probes.

TASKNAME	-- task identifier
goal	-- event that successfully terminates or renders the task successful
object	-- identification of thing upon which task is to be performed
parameters	-- priority -- status (e.g. active, waiting, inactive) -- timing requirements (e.g. speed, completion time) -- coordinate system in which task is expressed -- stiffness matrices, tolerance, etc. -- identification of source of task command
agents	-- identification of subsystems that will perform the task
requirements	--feedback information required from the world model during the task -- tools, time, resources, and materials needed to perform the task -- enabling conditions that must be satisfied to begin, or continue, the task -- disabling conditions that will prevent, or interrupt, the task
procedures	-- a state-graph, state-table, or program defining a plan for executing the task -- planning algorithms that may be needed -- functions that may be called
effects	-- expected results of task execution -- expected costs, risks, benefits -- estimated time to complete

Figure 2. A task frame.

Entity frames and maps are cross-referenced so that the entity frames contain in their data structure pointers to where the entity appears on the map, and each pixel on the map has a pointer back to the entity covered by that pixel. When the intelligent system has a complete understanding of the world, its entity database and its map database are fully cross-referenced and the system can easily move back and forth between them.

For example, a knowledge database for a machine tool at a particular level in the control hierarchy contains state variables, such as state clock and sync signals; feedback information indicating what has been observed by sensors; system parameters, such as coordinate transformations; limits of travel; and the entity frames that define the position and geometry of as-is or to-be part features, such as surfaces, pockets, and edges. Finally there are maps which may define displays for operators to visualize a part or a process.

The concepts presented here are amplified in a paper just published by the Institute of Electrical and Electronics Engineers (IEEE) in *Transactions on Systems, Man, and Cybernetics*. Some of the applications of this theory to intelligent, real-time control systems developed in the Manufacturing Engineering Laboratory include the Advanced Deburring and Chamfering Work Station and the Composites Work Station. The entire Advanced Manufacturing Research Facility (AMRF) itself was designed using these concepts. We currently have a project with the Army for unmanned land vehicles, with the Bureau of Mines for coal mining, and with the Defense Advanced Research Projects Agency on controls for the next generation of nuclear submarines. This control theory has been applied to the NASA Space Station Flight Telerobotic Service, and to the Air Force Next Generation Controller Program. A project that's just getting started is the Next Generation Inspection System. This theory will also provide the basis for future standards for intelligent machine systems. Current efforts are directed toward a methodology for engineering design and development of intelligent machine systems.

Let me conclude by saying that progress is rapid in many fields; a theory of intelligent machine systems is achievable; and the advent of intelligent machines will revolutionize civilization, very much the way the steam engine and the electric motor brought about the first industrial revolution.

The first industrial revolution was a result of the substitution of mechanical energy for muscle power in production of goods and services. The next industrial revolution will come from the substitution of machine intelligence for human intelligence in the control of industrial processes.

In the past there has been over-optimism in this field, and a great number of predictions have not yet come true, mainly because people underestimated the complexity of intelligence.

Intelligence is hard to build. The scientific and intellectual challenges of intelligent machines are at least as sophisticated, and complex, and deep as those of nuclear physics and molecular biology. The current lack of a widely accepted general theory of intelligence is one factor that impedes progress in this field. Hopefully, the work at NIST that I have described will open the door to rapid progress in the development and application of intelligent machine systems.

Chemical Compositional Mapping at the Micrometer Scale—and Finer

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I. Introduction

A. Macroscopic Versus Microscopic Chemical Measurements

The subject of this paper is chemical compositional mapping, the measurement of the chemical composition of solid matter on a spatially-resolved basis by methods of microbeam analysis [1,2]. The conventional radiation-based methods of analysis, such as x-ray fluorescence, neutron activation, the various forms of optical emission spectrometry, and mass spectrometry, generally require that the specimen be measured in its entirety, or at least over a dimension of several millimeters. Specimen masses measured by these macroscopic techniques typically range from grams to milligrams. For some techniques, the characteristics of the radiation are such that the entire solid specimen is penetrated by the incident excitation radiation as well as by the secondary analytical radiation, e.g., neutron activation analysis. For other techniques, the specimen must be dissolved to create a solution that is injected into the measurement system, e.g., inductively-coupled plasma emission optical spectrometry and inductively-coupled plasma mass spectrometry. The effect of both situations is to integrate the chemical measurement over the whole of the specimen, or at least a significant fraction thereof. Such macroscopic measurements have the advantage that a global view of the specimen is obtained, but such a view is obtained at the expense of any knowledge of possible chemical inhomogeneities within the specimen. Microbeam analysis methods provide the capability for exploring these chemical inhomogeneities on the scale of micrometers to nanometers.

B. How Small Is a Micrometer?

Unless a person is directly involved with microscopy, objects with dimensions on the micrometer scale are sufficiently far below the range of human experience as to represent a quite abstract measurement. Figure 1 shows an example of the micrometer scale in terms of a familiar material, hair. A human hair averages 70 micrometers in diameter, so the analytical techniques which will be covered in this paper are capable of sufficient lateral spatial resolution to place 70 discrete analysis locations side-by-side across the diameter of a hair. Also shown in figure 1 are technological objects, glass fibers with dimensions in the 20-50 micrometer range. These fibers are actually used as compositional standards for the microbeam analysis techniques discussed in this paper.

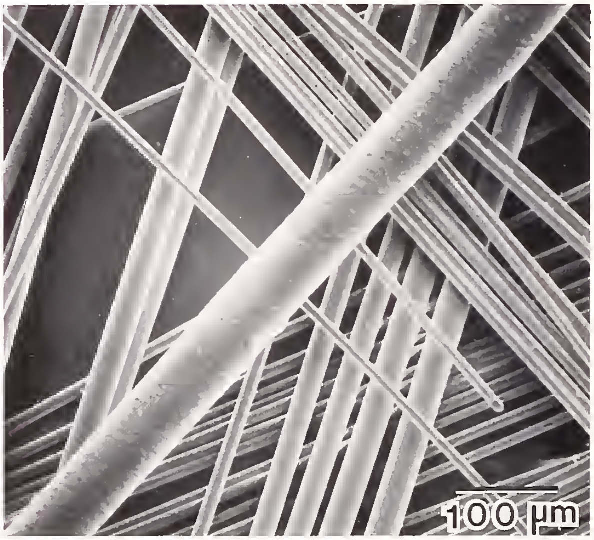


Figure 1. Illustration of the micrometer scale. A scanning electron micrograph of a human hair (approximate diameter, 70 micrometers) is shown, along with glass fibers.

C. Why Make Chemical Measurements on the Micrometer Scale?

When we examine solid matter on the scale of a micrometer, in many cases a chemically differentiated microstructure is found. Across a wide range of physical, biological, and technological fields, the behavior of many of the macroscopic properties of matter is controlled by chemical structure and processes that occur on a spatial scale ranging from micrometers to nanometers. Examples include the strengthening mechanisms of metal alloys and ceramics in materials science; solid state catalysis reactions in chemical processing; the membranes and sub-cellular structures of living cells in biology; particulate pollutants in environmental science; and the complex electronic and mechanical devices of advanced technology. Excellent popular introductions to technological developments involving "diminishing dimensions" are given in recent articles in *Scientific American* and *Smithsonian* [3,4]. The *Scientific American* article describes the ever-decreasing scale of electronic devices [3]. The examples cited include arrays of solid state lasers with an overall length of 6 micrometers, but composed of alternating layers of GaAs and AlGaAs that are only 0.2 micrometers thick. An even smaller fabricated electronic structure is the "quantum dot," a composite of GaAs and AlGaAs that confines an electron in a "zero-dimensional" trap. The physical size of the quantum dot is only 50 nm. While the micro-miniaturization of electronics is a well-known development spanning the past three decades, the *Smithsonian* article describes the very recent development of microscopic machines, an entirely new field of microtechnology. This field makes use of the materials manipulation and fabrication techniques of semiconductor manufacture to create motors and mechanical sensors with micro-meter dimensions. Such structures are only one manifestation of the revolution of scale that has been occurring in recent years. Figure 2 shows a schematic representation of the range of structures of interest to science and technology, spanning the scale from single atoms and molecules, through atomic clusters, to the organization of nanostructures and microstructures of solids. To successfully fabricate such structures, composition must be manipulated on an extremely fine scale. To understand and monitor such processes and products, detailed knowledge is required of the composition on the microscopic scale of the heterogeneities inherent in each system. Compositional mapping by means of microbeam analysis techniques provides this information.

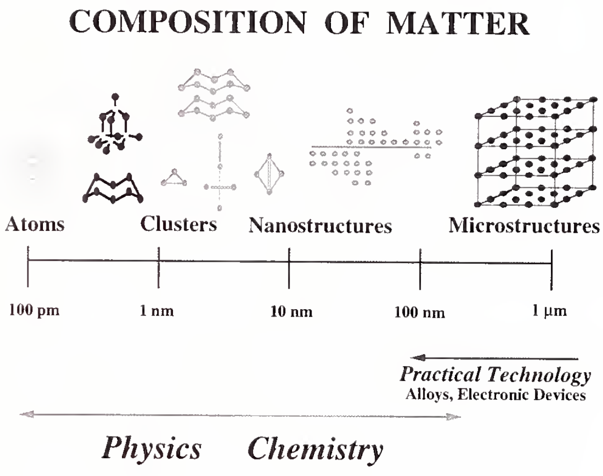


Figure 2. Schematic illustration of the size scale of modern technological development, from atom dimensions to micro-structures (figure from Rance Velapoldi, NIST).

D. What Is Microbeam Analysis?

In the context in which it will be used in this paper, "microbeam analysis" or "microanalysis" refers to those analytical techniques that permit the user to specify the spatial location of the analysis [5]. Spatially selected analysis can be accomplished by focussing beams of electrons, ions or photons to form a small probe, typically in the range from micrometers to nanometers. In discussing microanalysis, it is important to distinguish the microanalysis concept from that of trace analysis. Microanalysis only implies that a technique is spatially selective. The mass of material selected is very small, ranging from picograms (10^{-12} grams) to attograms (10^{-18} grams), which seems to imply that a microanalysis technique is capable of detecting at trace levels. The term "trace," however, refers to a constituent that is present as a minute fraction of the analyzed sample. The fractional level that qualifies as a trace is not rigorously defined and depends to some extent on the sensitivity of the analytical method that is applied. An arbitrary concentration scale for microanalysis techniques can be taken as:

major: > 10 weight percent

minor: 1 to 10 weight percent

trace: < 1 weight percent

II. Microbeam Analysis

A. General Principles

The general characteristics of a microbeam analysis method are illustrated in figure 3. Two different approaches to achieving spatially resolved analysis are possible, the microprobe approach and the microscope approach. In the microprobe approach, a source of primary radiation, typically photons, electrons, or ions, is focussed by an appropriate lens (glass, electromagnetic, or electrostatic, depending on the nature of the radiation) to form a probe on the specimen. The primary radiation interacts with the atoms of the specimen, causing the emission of secondary radiation whose energy or mass is characteristic of the atom or molecular species present in the analyzed volume (the basis of qualitative analysis) and whose intensity is related to the amount of each species present (the basis of quantitative analysis). The characteristic secondary radiation is measured with an appropriate spectrometer and detector. The size of the volume that is analyzed is determined by a convolution of the incident probe diameter and the range of the primary and secondary radiation in the specimen. Generally, the linear dimensions of the analyzed volume are micrometers or smaller, depending on the technique involved. To create an image with the microprobe, the finely focussed beam is scanned across the specimen in a raster pattern, and a measured secondary signal is used to modulate the intensity of a cathode ray tube (CRT) scanned synchronously. Alternatively, the signal intensity, I, is stored in a digital array (X, Y, I), as a function of the digitized values of the beam position, X and Y. The digital array of data is converted into an analog image for display by means of a computer color display.

In the microscope approach, a large-diameter beam of primary radiation is used to excite the specimen over an extended lateral distance, and lenses placed after the specimen focus the secondary radiation directly into a true image. The geometric relationship of the ray paths of the image is maintained through the spectrometer, so that an image from a selected narrow band of the secondary radiation is formed on a spatially sensitive detector, and all other radiation is excluded. By proper adjustment of the spectrometer, an image of a particular characteristic radiation is formed. Localized microanalysis is performed in the microscope mode either by placing an aperture in the optical path to restrict the information to a selected area, or for systems in which the imaging detector can be made of an array of discrete detector elements, the information recorded by each detector element can be examined separately. Spatial resolution in the microscope mode depends on the focussing characteristics of the lens/spectrometer system for the radiation of interest.

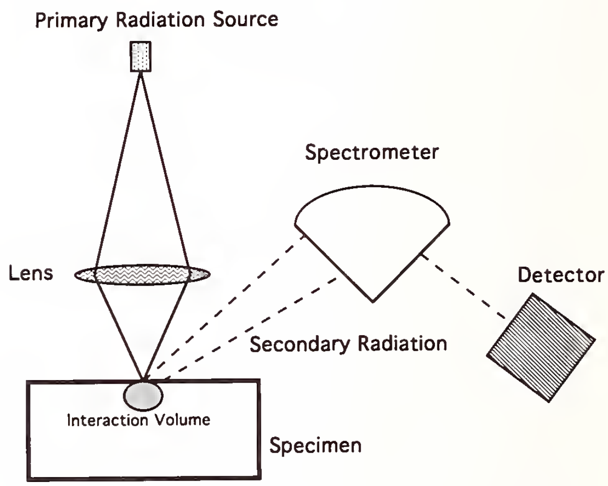


Figure 3. Schematic illustration of the general principles of microbeam analysis. Primary radiation from a source is focussed through a lens to form a probe. The interaction of the primary radiation with the atoms of the target stimulates the emission of secondary radiation that is characteristic of the specimen. A spectrometer and detector are used to measure the secondary radiation.

III. Electron Probe X-Ray Microanalysis

The principles of electron probe x-ray microanalysis are illustrated in figure 4(a) [1,2]. A focussed beam of energetic electrons (energy in the range 5-30 keV) impinges on the specimen and undergoes elastic and inelastic scattering, creating an interaction volume with micrometer dimensions. One of the inelastic scattering processes is inner shell ionization, illustrated in figure 4(b), in which the energetic beam electron transfers sufficient energy to an atomic electron to eject it from the atom. The excited atomic state decays with transitions of outer shell electrons, and the difference in energy between the shells can be expressed either in the ejection of another outer shell electron (the Auger process) or by the emission of a photon (the characteristic x-ray process). The characteristic x-rays produced in the interaction volume propagate through the specimen and are measured by an external spectrometer. The energies of the measured x-rays are used to identify the species of atoms present (qualitative analysis). The spectrum is measured by one or both of two types of spectrometers. The energy dispersive spectrometer (EDS) operates on the principle of photoelectric capture of a photon in a semiconductor detector with proportional conversion of photon energy to charge. The wavelength dispersive spectrometer (WDS) operates on the principle of Bragg diffraction from a crystal. The EDS continuously observes the entire energy range of x-rays generated from the value of the incident beam energy down to a value of approximately 100 eV. The WDS offers higher spectral resolution (8 eV vs. 150 eV for Mn Kα at 5890 eV), higher count rate capability, and better detection limits, but only views a narrow 8 eV energy window of the spectrum and must be mechanically tuned to other desired energies in the energy range. A combined EDS/WDS measurement strategy is best, because the strengths of each type of spectrometer complement the weaknesses of the other type.

Quantitative analysis seeks to relate the measured x-ray intensity to the weight concentration of each species in the interaction volume. Unfortunately, several

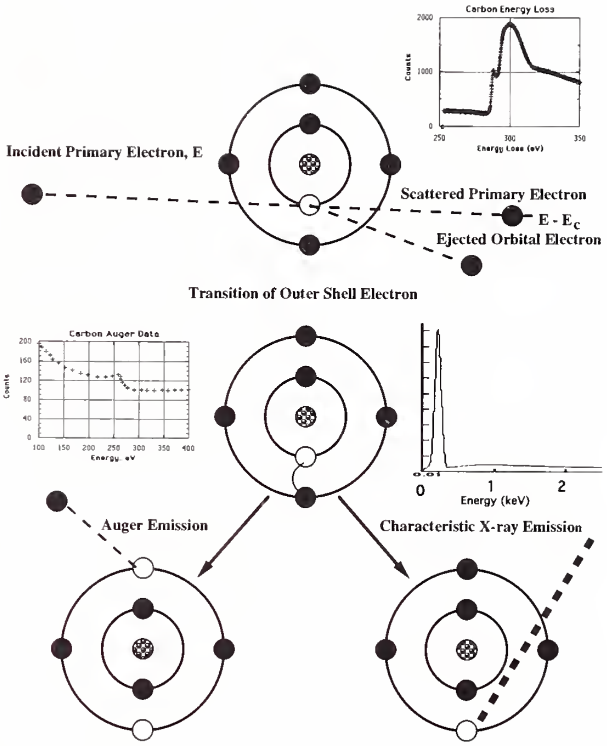
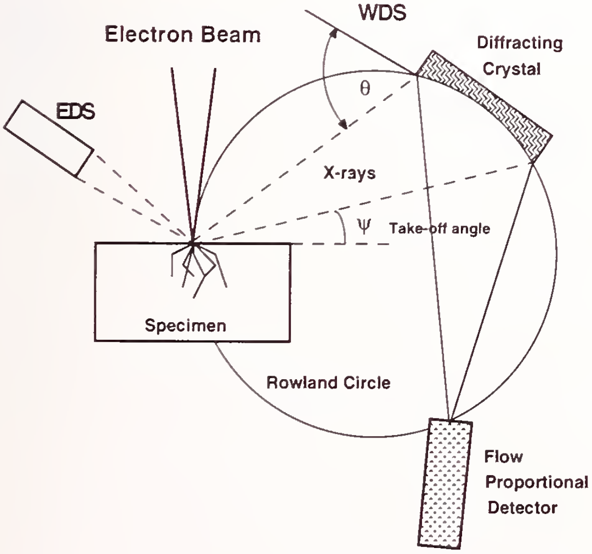


Figure 4(b). Inner shell ionization and characteristic x-ray emission.



Figures 4(a) through 4(c). Schematic illustration of the principles of electron probe x-ray microanalysis. **Figure 4(a).** Beam-specimen-spectrometer.

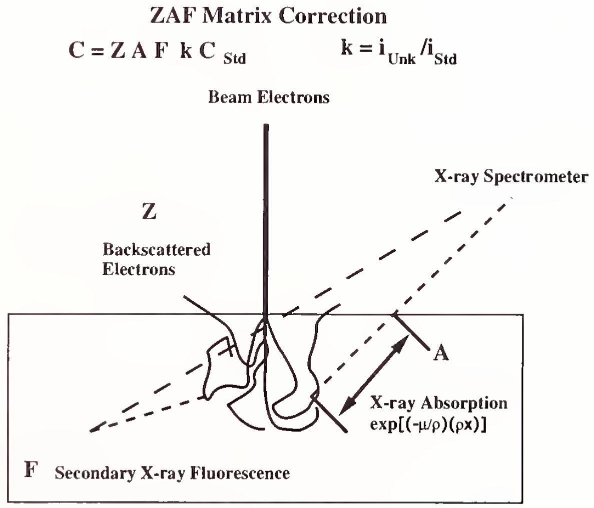


Figure 4(c). Physical origin of corrections to measured radiation for electron backscattering/penetration, x-ray absorption, and x-ray induced secondary fluorescence.

physical factors modify the generated intensity to yield the x-ray intensity that is actually measured outside the specimen, as shown in figure 4(c). Electron backscattering and electron penetration vary strongly as a function of atomic number. X-rays propagating through matter undergo photoelectric absorption and scattering, which depend on the atom species present. Finally, a consequence of photoelectric absorption is that the absorbing atom is ionized and the subsequent decay of the excited state can produce still more characteristic x-rays, a process known as secondary fluorescence. The composition, which is unknown, influences all of these physical (matrix or interelement) effects. Fortunately, because the physics of electron and x-ray interactions with solids is well understood, an accurate quantitative analysis procedure is possible by measuring standards under identical dose conditions and calculating physical corrections for the matrix effects. The standards that are required for this procedure are remarkably simple, consisting only of pure elements, or for those elements which are not stable in a high vacuum, simple binary compounds can be used (e.g., GaP for P). The simplicity of the required standards provides a great deal of "analytical flexibility," that is, the capability of dealing with an unknown of arbitrary composition without having to create standards close in composition to the unknown. This is especially important since it is very difficult to produce standards that are homogeneous on a micrometer or sub-micrometer scale, since phase separation tends to occur in multi-element mixtures. With pure element standards, the distribution of errors is such that the analysis is accurate within 4% relative in 95% of all determinations. Because of the existence of an x-ray continuum background due to the x-ray *Bremsstrahlung* that underlies all characteristic peaks, the limit of detection is typically 1000 parts per million (0.1 weight percent) when the x-ray spectrum is measured with energy dispersive x-ray spectrometry, and 100 parts per million with wavelength dispersive spectrometry.

Conventional analytical practice with the electron probe microanalyzer is to identify specific locations or features of interest on the specimen in images obtained with the scanning electron microscope mode of operation or with the associated optical microscope. Quantitative analyses are then performed at single locations, or along a vector selected by controlling the beam or stage position digitally. These single point or vector analyses are often supported by qualitative "dot" maps that depict the lateral distribution of constituents, but without quantitative image information.

IV. Compositional Mapping by Electron Probe Microanalysis

The principle of compositional mapping by electron probe microanalysis is shown schematically in figure 5 [6,7]. Compositional mapping is achieved by scanning the beam (or, alternatively, the beam position can be fixed and the specimen stage scanned) in a digitally-controlled raster pattern, measuring the x-ray spectrum by energy and/or wavelength spectrometry at each beam location, and performing a complete quantitative analysis. All of the corrections and standardization steps used in conventional single point analysis are applied in compositional mapping, and in addition, certain instrumental artifacts that arise as a result of scanning the beam off the optic axis of the spectrometers must also be corrected. By employing a combined EDS/WDS measurement strategy, 10 or more constituents can be mapped in parallel, resulting in a great savings in time. The result of these procedures is a set of digitally-stored data matrices of the actual concentrations of the constituents at each location. Not only are the final concentrations available, but these values are supported by the statistics of the measurement at each location. These data arrays of concentrations can be converted to an image and displayed with a digital image processor. The display is constructed so that a particular shade of gray or a color corresponds to a specific concentration value.

An example of a compositional map is shown in figures 6(a) through 6(c), which depict zinc at the grain boundaries of polycrystalline copper as a result of the phenomenon of diffusion-induced grain boundary migration [8]. Figure 6(a) shows a gray-scale presentation of the concentration data, with the display adjusted to produce a black-to-white range for 0-10 weight percent zinc. It must be emphasized that the complex structure observed in the zinc diffusion zone is a *compositional* structure. This sample is metallographically polished to a mirror finish, and no visible discontinuity exists where the zinc concentration is elevated.

Digital image processing permits great flexibility to change the presentation of information rapidly, allowing the analyst to optimize the visibility of features of interest while maintaining the integrity of the compositional data. Computer-aided imaging provides a variety of image processing algorithms as well as gray or color scales. Often the choice of the gray or color scale can profoundly change the visibility of a feature. The human eye has much more sensitivity to color than to a gray or intensity scale. In figure 6(b), the same

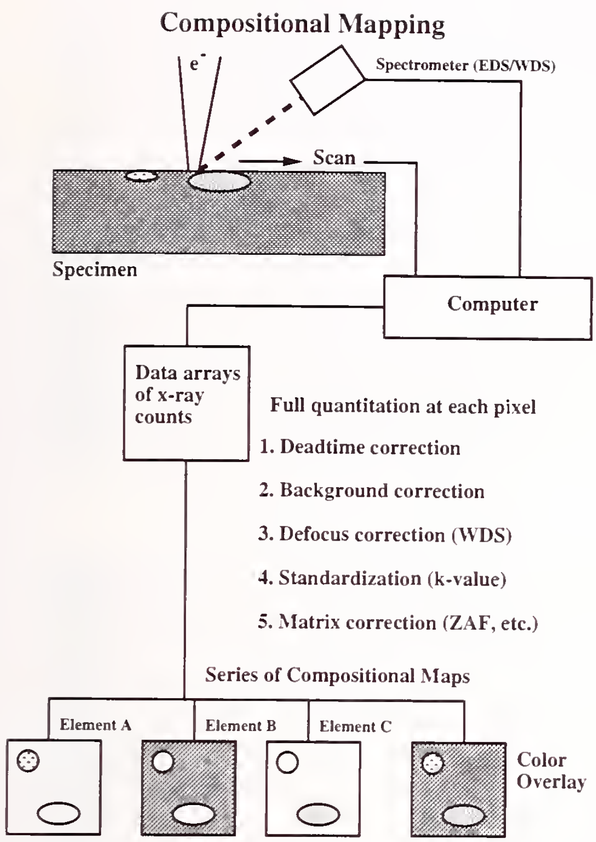
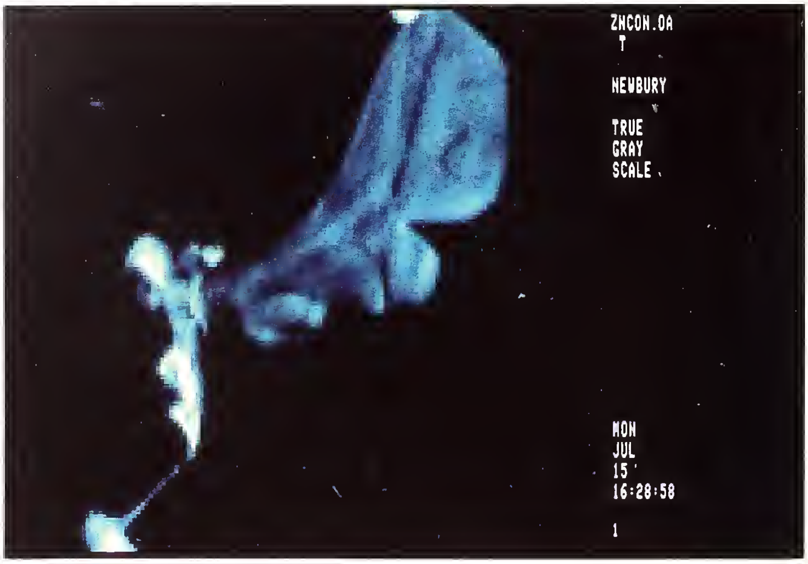


Figure 5. Schematic illustration of the principles of compositional mapping with the electron probe x-ray microanalyzer.

data used in figure 6(a) is presented in "pseudocolor" scale with the color scale constructed so that alternating color bands are in high contrast. In this presentation, a narrow boundary (bottom center) becomes visible that could not be seen in the gray-scale representation of figure 6(a). However, with this color choice the complex structure in the broad diffusion zone becomes much more difficult to understand because the "attention value" of each color bears no relation to its position in the scale. In Figure 6(c) the data is presented with the thermal scale, a pseudocolor scale constructed from the sequence of black body colors. This scale has the advantage that the attention value increases monotonically. The image shows the same complex structure seen with the gray scale, but with the added advantage that the dynamic range of sensitivity is expanded to include the visibility of the narrow boundary seen in Figure 6(b). In addition, the regular progression of colors gives the viewer a direct representation, at least to a first order, of quantitative relationships in the image, since specific colors can be recognized and assigned to their equivalent numerical value in the scale printed at the bottom of the image.

Image processing algorithms can be used to enhance the visibility of features of interest prior to gray or color scale depiction. Figures 7(a) and 7(b) show compositional maps for gold and platinum from a diffusion couple where diffusion occurred near the melting point of gold. The direct gray-scale representation suggests that weak compositional contrast exists within the gold layer. By forming the product image (C_{Au} x C_{Pt}) shown in figure 7(c), the regions where the concentrations of gold and platinum are both maximized can be highlighted. The ratio image (C_{Au}/C_{Pt}), figure 7(d), highlights where gold is maximized relative to platinum. Both the product and ratio images greatly enhance the visibility of the complex compositional structure within the gold layer. Weak contrast can also be amplified with the image gradient function, a two-dimensional derivative operator. Figures 7(e) and 7(f) show the magnitude of the image gradient, which emphasizes the boundaries between the gold and platinum layers, while the direction of the gradient, Figures 7(g) and 7(h), shows the internal compositional structure of the gold layer.

In general, the problem of displaying information from quantitative compositional maps involves trying to present simultaneously x-y positional information and numerical concentration information in the same image representation. The gray or color scale approach can give an effective presentation for "single band" images, that is, those in which only one constituent is represented, as in the examples of figures 6 and 7. From such images, the relationship between structure and concentration can be readily explored, because the computer display permits rapid readout of the numerical concentration information at each pixel as a cursor is moved within the image. However, the display problem is often made more difficult because we are usually interested in comparing maps of two or more constituents from the same field of view. The problem thus becomes one involving recognizing spatial and concentration relationships among constituents in different images. A traditional solution to this problem is to use primary color overlays, as illustrated in figures 8(a) through 8(b), which can be applied to two or three constituents. Each map is displayed with a different primary color (red, green, or blue) as an overlay to form a single image. Pixels where two constituents co-exist appear in secondary colors (magenta, cyan, or



Figures 6(a) through 6(c). Compositional maps of zinc at the grain boundaries of polycrystalline copper as a result of diffusion-induced grain boundary migration. **Figure 6(a).** Gray-scale presentation (0-10 weight percent corresponds to the range from black to white).

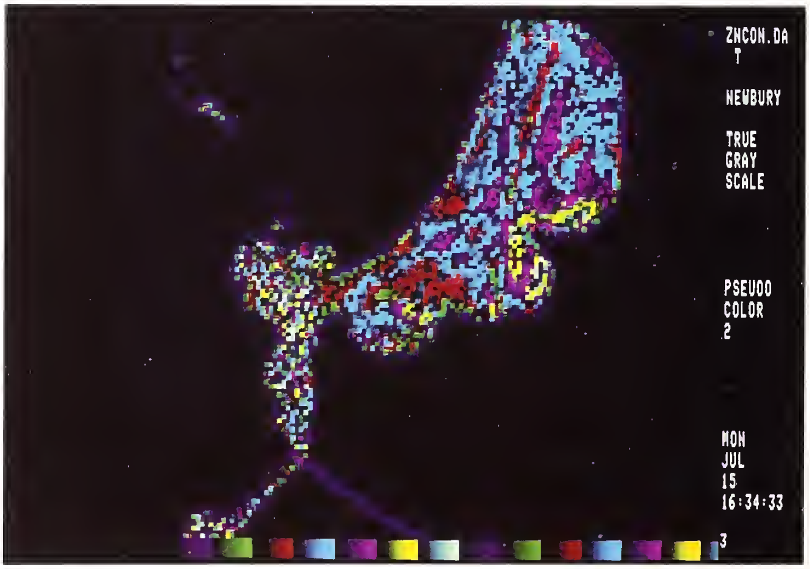


Figure 6(b). "Pseudocolor" scale with the scale constructed with contrasting alternating color bands; the color scale = 0–10 weight percent.

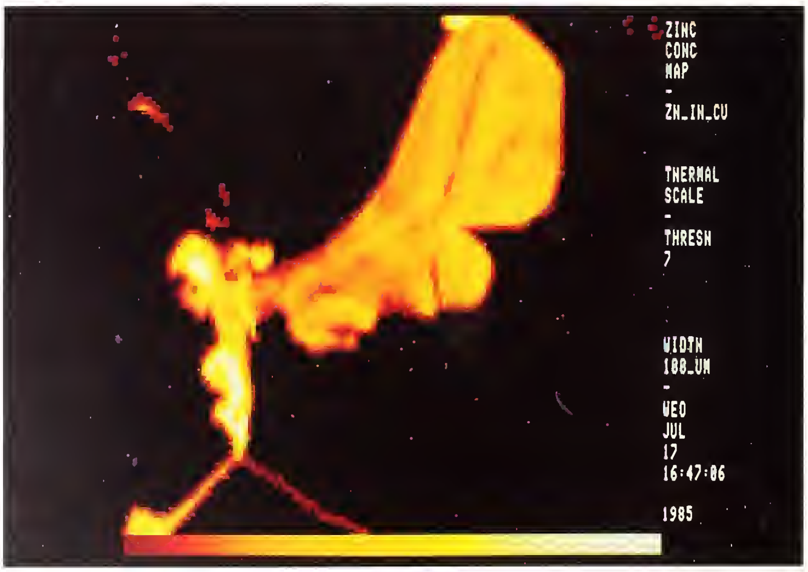
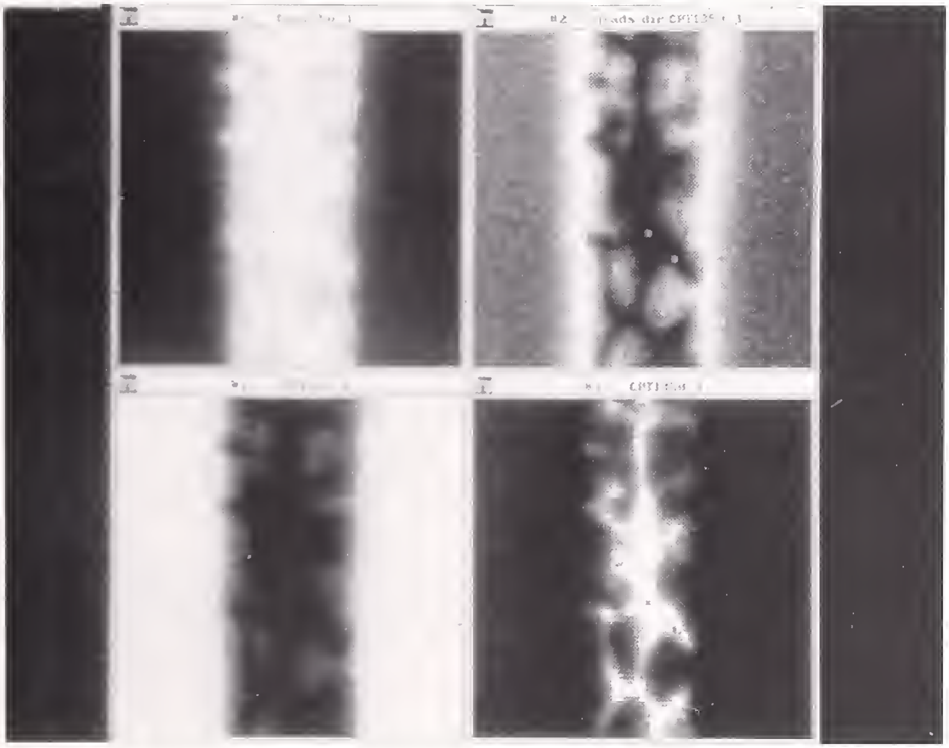
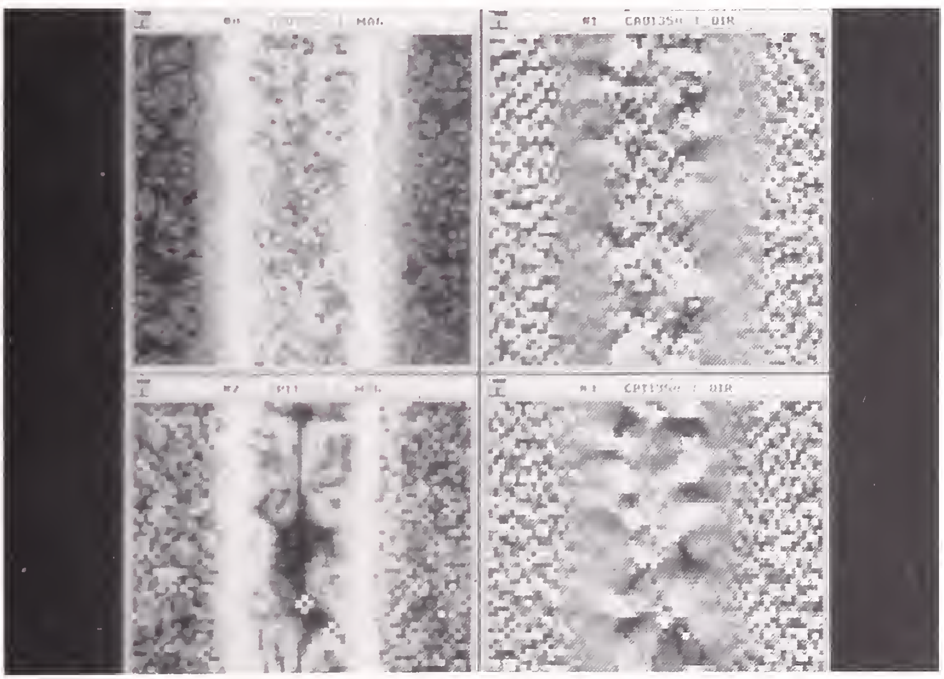


Figure 6(c). Pseudocolor scale constructed from the thermal scale, the sequence of black body colors; the color scale = 0–10 weight percent. Image width = 100 micrometers (specimen courtesy D. Butrymowicz, MSEL, NIST).



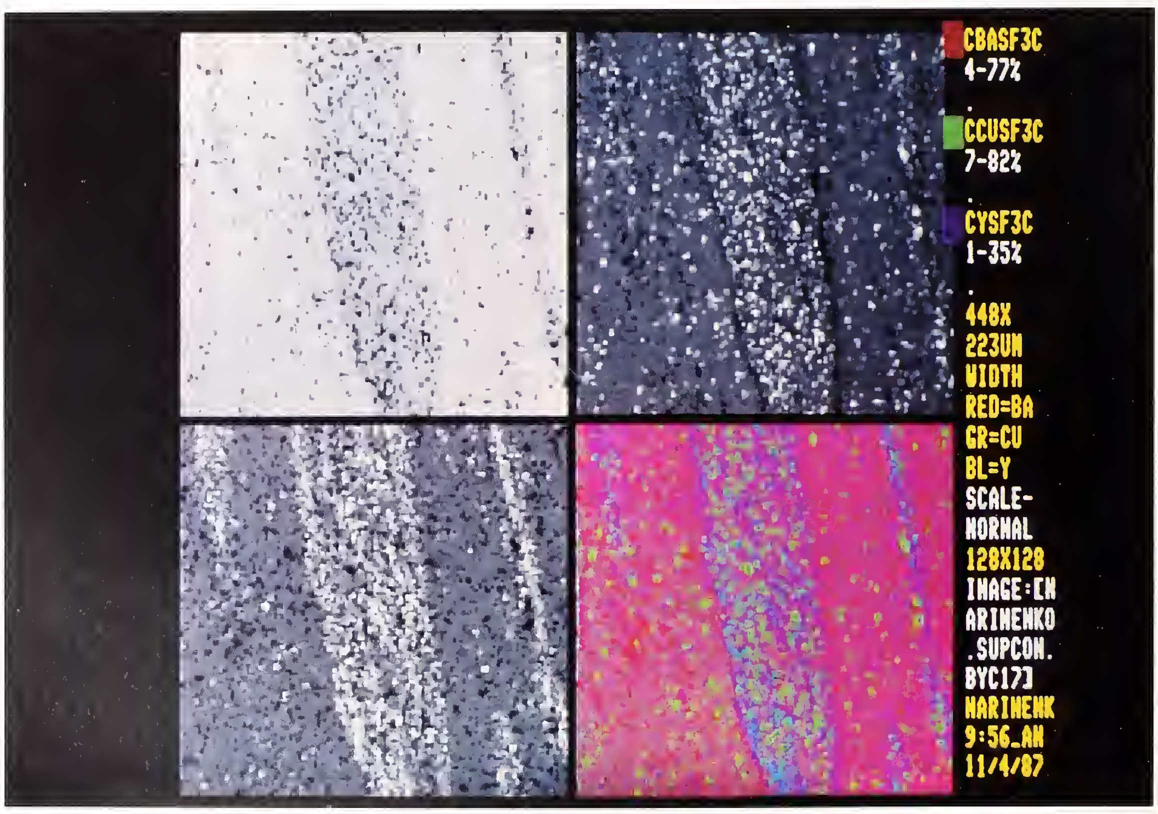
Figures 7(a) through 7(d). Compositional maps of a gold-platinum diffusion couple illustrating the application of image processing functions: **figure 7(a)**—Au map, upper left; **figure 7(b)**—Pt map, linear gray scale depiction, lower left; **figure 7(c)**—Au x Pt, upper right; **figure 7(d)**—Au/Pt, lower right.



Figures 7(e) through 7(h). Figure 7(e)—Au, magnitude of image gradient, upper left; **figure 7(f)**—Pt, magnitude of image gradient, lower left; **figure 7(g)**—Au, direction of image gradient, upper right; **figure 7(h)**—Pt, direction of image gradient, lower right. Image field width = 107 μm (sample courtesy C. Handwerker, NIST; images courtesy R. Marinenko and D. Bright, NIST).

yellow) or where all three co-exist, in white. The secondary colors can be shown fully saturated, or they can be altered in hue in response to the relative concentrations, as has been done to produce the orange hue for the binary Ba-Cu phase and the "hot pink" Y-Ba-Cu superconducting phase in figure 8(d). In practice, however, it is difficult to produce a robust color scale for such representations in which specific colors can be recognized and identified with particular numerical values, especially when problems of color recording and reproduction are considered. The simultaneous depiction of the individual element concentration images in gray scale along with the color overlay of the three images to form a composite image, as shown in figure 8, is particularly effective, since this display permits rapid reference among all of the images.

To enhance the quantitative display of compositional maps, researchers at NIST have developed the "compositional histogram image (CHI)," a form of bi-variate or tri-variate scatter plot, which simultaneously presents numerical information for two or three constituents [9]. The creation of a CHI is illustrated schematically in figure 9. Consider two compositional maps of constituents $C_A(x, y)$ and $C_B(x, y)$ from the same field of view. A new array $CHI(C_A, C_{B,n})$ is calculated whose dimensions are the ranges of the concentrations C_A and C_B. As each pixel in the compositional maps $C_A(x, y)$ and $C_B(x, y)$ is evaluated, the corresponding address in $CHI(C_A, C_{B,n})$ is incremented. The resulting array $CHI(C_A, C_{B,n})$ contains the total number of pixels, n, (frequency) for each possible pair of concentration values, C_A and C_B. This array can itself be depicted as an image by encoding the frequency with a color scale. The thermal color scale is found to be especially effective, adjusted so that an address with a single count is displayed as deep red pixel against a black background. Figure 10(a) shows an example of a CHI calculated for the barium and copper compositional maps from figure 8(a) and figure 8(b). The CHI is dominated by a compact high intensity feature that has three linear



Figures 8(a) through 8(d). Color overlay (superposition) of single band images. **Figure 8(a)**—barium, upper left; **figure 8(b)**—copper, upper right; **figure 8(c)**—yttrium, lower left; **figure 8(d)**—color overlay, with barium = red, copper = green, and yttrium = blue. Image width = 223 micro-meters. Specimen: $YBa_2Cu_3O_7$ high T_c superconductor (sample courtesy John Blendell, NIST; images courtesy R. Marinenko and D. Bright, NIST).

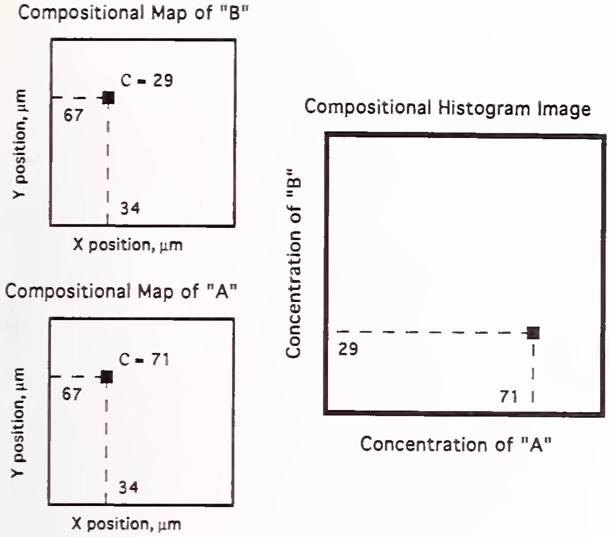


Figure 9. Schematic illustration of the calculation of a composition histogram image (CHI) from two compositional maps.

features which radiate from it. Since the axes of the CHI are calibrated in numerical concentration, the values of C_A and C_B that describe the compact feature can be immediately found. The x-y position information of the original maps has been lost in the creation of the CHI. To recover positional information, an algorithm called TRACEBACK has been developed to construct an x-y pixel mask that locates those pixels in the original x-y space maps which contribute to a specified region of the CHI. Consider again figure 10(a), where a box has been constructed around the high intensity feature. The pixel mask from all locations which contributed to this feature in the CHI is shown superimposed in color on the original compositional maps in figure 10(b). The high intensity feature in the CHI picks out the continuous superconducting phase, which is the dominant feature of the original compositional maps. When one of the radiating linear features is selected, figure 10(c), the corresponding pixel mask selects the discontinuous phase, figure 10(d), a minor feature of the original maps. Note that TRACEBACK recovers every pixel in the original images with the specified composition range, including some features that consist of only single pixels.

An example of the application of the CHI to the diffusion study in the gold-platinum system is shown in figure 11. The gold and platinum areas appear in the CHI as high intensity spots, and the diffusion zone appears as a low intensity band that joins the spots. A selection of this band in the CHI is shown in white, and the pixel mask produced by TRACEBACK is depicted in outline on the original maps. The diffusion zone is found to be irregular in position and width.

The CHI technique can be readily extended to three constituents. As shown in figure 12, the three-dimensional CHI is depicted in the form of a cube. The three-dimensional character of the cube can be better understood when constructed and viewed as a stereo pair, or alternatively, when placed in a dynamic display program that permits rotation of the data in real time.

As a measure of the information that can be simultaneously viewed in an advanced computer-aided imaging display, figure 12 is a composite image that contains the three-dimensional CHI, the mask of selected pixels, and the superposition of that mask upon the original compositional maps, with the mask shown as an outline. It is often necessary to examine multiple sources of information, and the capability of *simultaneously* displaying different images and highlighted subsets of data provides a needed stimulus to the viewer to recognize subtle relationships among structure and compositional features.

While it is an extremely useful technique, compositional mapping by electron probe microanalysis has significant limitations [6,7]. The lateral resolution is limited by the finite size of the interaction volume, which is defined by the effects of elastic and inelastic scattering, to dimensions of approximately 1 micrometer. The sensitivity is adequate for minor constituents, but mapping trace constituents below 1000 parts per million can only be achieved with a large investment of data accumulation time, in excess of 10 hours. Other microanalysis techniques can overcome some of these obstacles.

V. Compositional Mapping by Secondary Ion Mass Spectrometry

The traditional route to trace analysis while simultaneously achieving the spatial resolution of microanalysis has been to employ methods of microbeam mass spectrometry, such as secondary ion mass spectrometry (SIMS). Mass spectrometry has the inherent advantage of an extremely high spectral peak-to-background ratio, often exceeding $10^6/1$, coupled with the possibility of efficient signal collection. As illustrated in figure 13, the SIMS technique utilizes a primary beam of energetic ions (typically oxygen, argon, or cesium at 2-20 keV) to collide with atoms lying at the target surface and to eject some of them in a process known as sputtering. A small fraction of these sputtered atoms is ionized in the sputtering process,

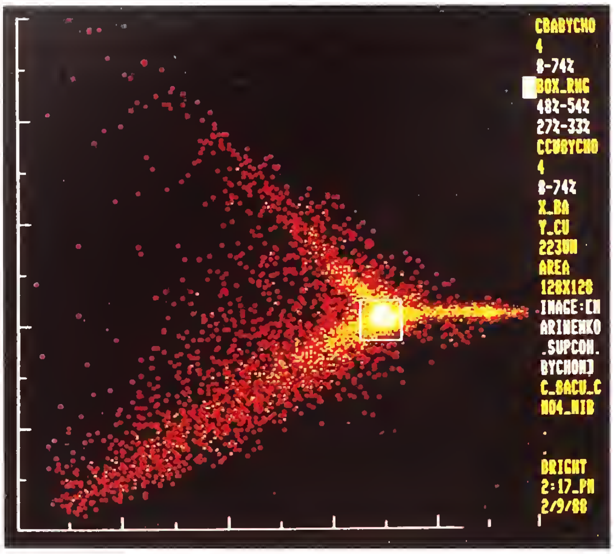


Figure 10(a). Example of a CHI calculated from the compositional maps of barium, figure 8(a) and copper, figure 8(b).

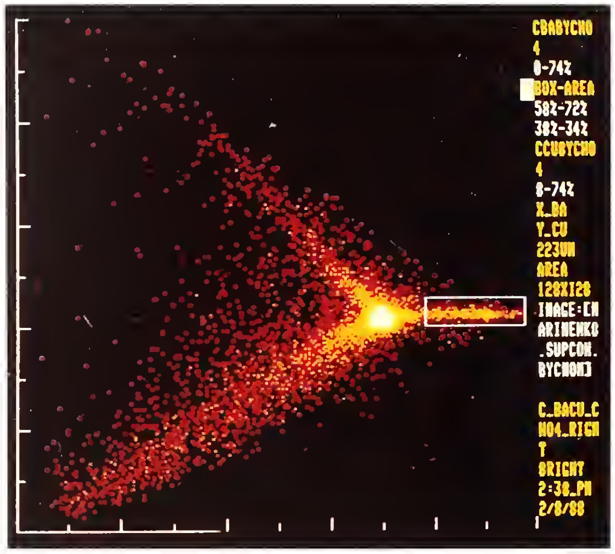


Figure 10(c). Selection of the linear feature in the CHI.

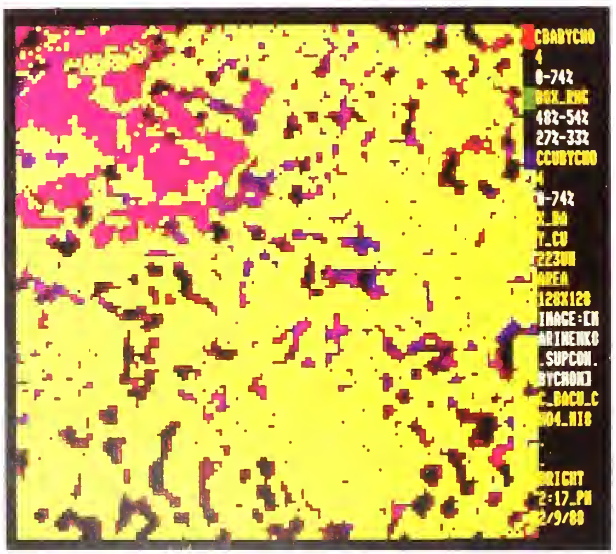


Figure 10(b). Mask of pixels produced by the TRACEBACK algorithm from the area outlined in white in the CHI. The mask is superimposed on a two-color overlay of the original barium and copper compositional maps. Image width = 223 micrometers.

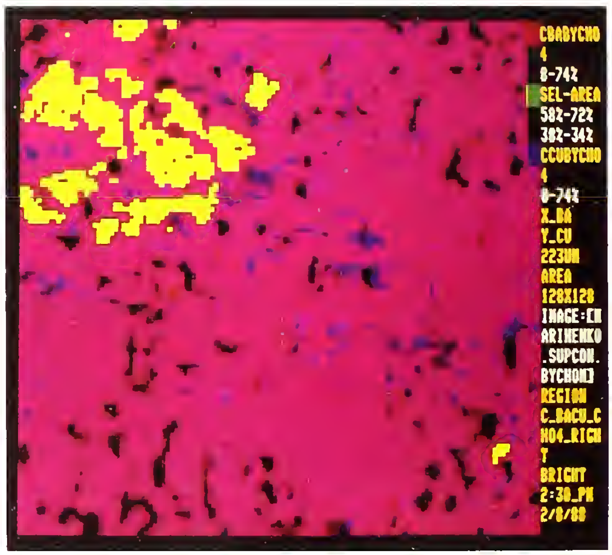


Figure 10(d). Mask of the selected linear feature pixels in figure 10(c) superimposed on the original maps. Image width = 223 micrometers (sample courtesy John Blendell, NIST; images courtesy R. Marinenko and D. Bright, NIST).

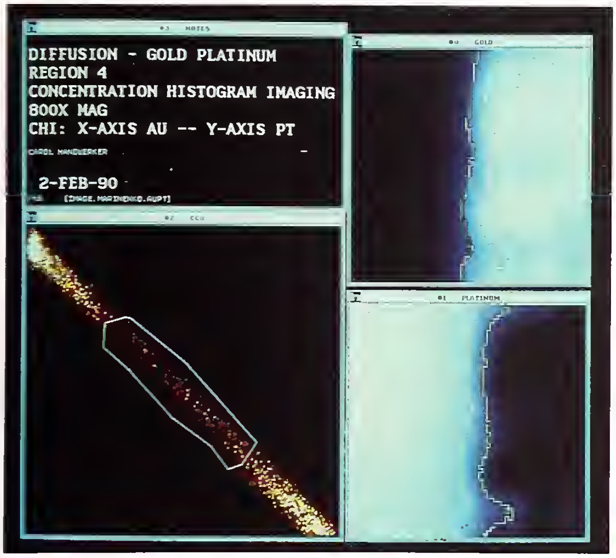


Figure 11. Application of the composition histogram image technique to a diffusion zone between gold and platinum. The compositional range outlined in white in the CHI selects the pixels outlined in white in the original compositional maps, showing the location of the diffusion zone. Image width = 125 micrometers (sample courtesy C. Handwerker, NIST; images courtesy R. Marinenko and D. Bright, NIST).

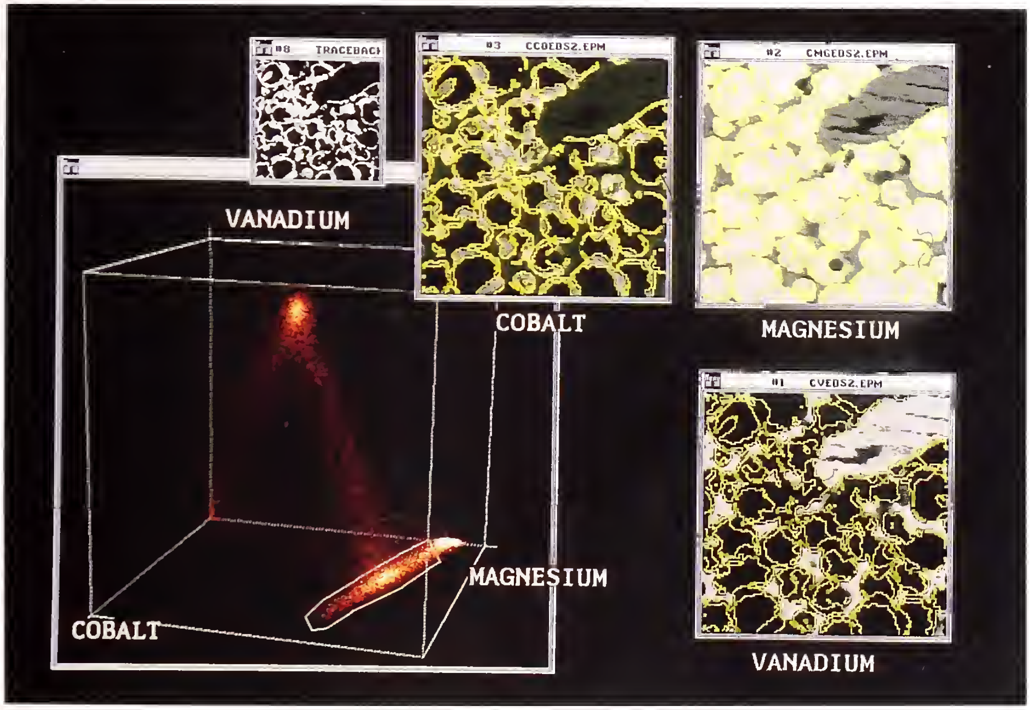


Figure 12. Three-dimensional CHI from compositional maps of a magnesium-vanadium-cobalt ceramic. The region of the CHI highlighted in white produces the pixel mask shown in the inset. The pixel mask is shown as an outline superimposed on the original compositional maps for each constituent (sample courtesy Carol Handwerker and John Blendell, NIST; images courtesy R. Marinenko and D. Bright, NIST).

forming the so-called secondary ions. The secondary ion trajectories are manipulated by electrostatic collection fields into a mass spectrometer, where they are dispersed according to their mass-to-charge ratio and are then detected with single ion sensitivity.

Since both the primary and the secondary ions are charged, it is possible to achieve spatially-resolved analysis by focussing the primary ions to form a fine probe (microprobe mode) or by focussing the secondary ions to form an image (microscope mode). An example of a scanning ion microprobe image of oxygen on a silicon surface is shown in figure 14 [11]. The limiting resolution of the ion microprobe is set by the size of the smallest probe that can be focussed which carries

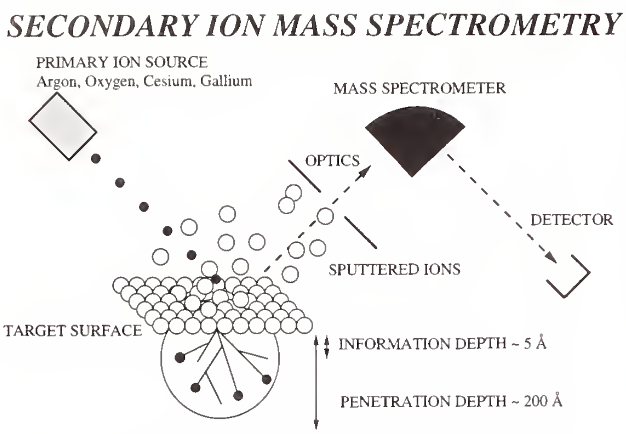


Figure 13. Schematic illustration of secondary ion mass spectrometry (illustration courtesy G. Gillen, NIST).

enough beam current to create a statistically meaningful image. An example of an ion microscope image of aluminum in an aluminum-lithium-copper alloy is shown in figure 15 [12]. Ion microscope images have a lateral resolution of 0.5-1 µm, a limit determined by the energy spread of the secondary ions and the chromatic aberration of the electrostatic secondary imaging lens system.

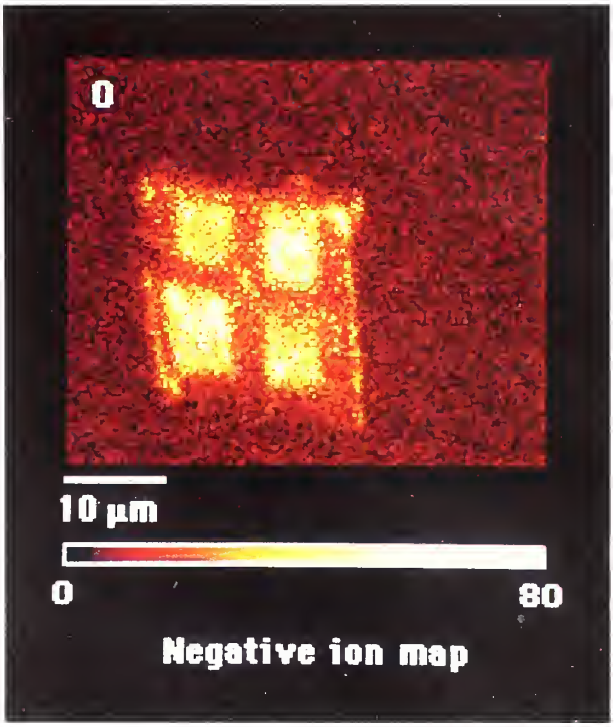


Figure 14. Scanning ion microprobe image of a thin layer of oxygen deposited during a scanning tunneling microscope scan of the surface of a silicon single crystal (image ccurtesy J. Bennett and J. Dagata, NIST).

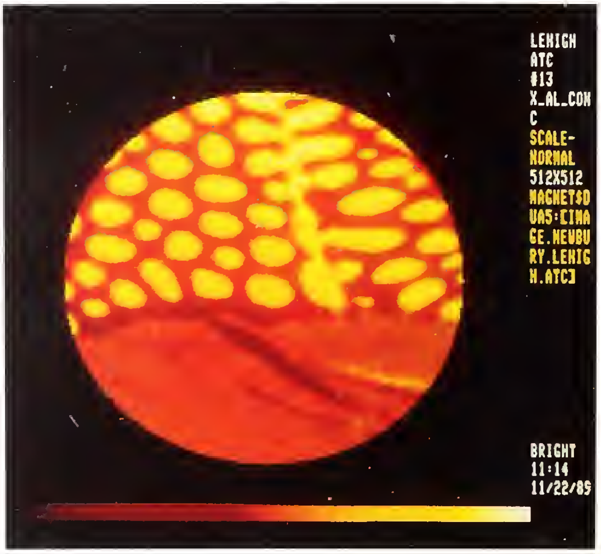


Figure 15. Secondary ion mass spectrometry/ion microscope image of aluminum in an aluminum-lithium-copper alloy. Image diameter = 150 µm.

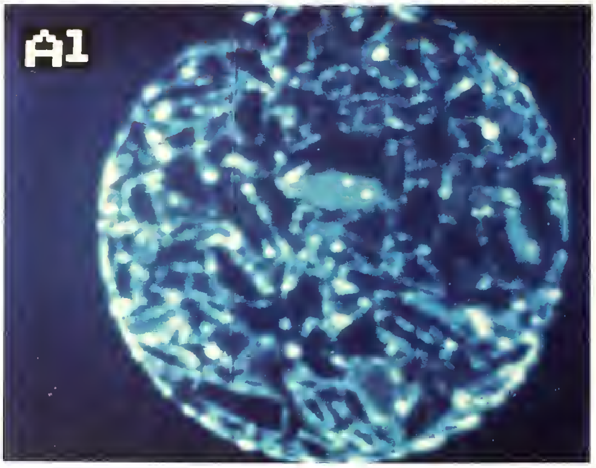


Figure 16. Secondary ion mass spectrometry/ion microscope image of trace aluminum (100 parts per million nominal bulk level) in reaction-bonded silicon carbide. Image diameter = 150 µm.

Because secondary ion signals are highly abundant and are relatively free from background, SIMS can achieve trace sensitivity ranging from parts per million to parts per billion. Moreover, this trace sensitivity is not restricted to single point analysis, but is retained in the imaging mode. Figure 16 shows an ion microscope image of trace aluminum in reaction-bonded silicon carbide [13]. The aluminum corresponds to a bulk level of approximately 100 parts per million. The image reveals that the trace aluminum constituent is heterogeneously distributed at the micrometer spatial level.

Such elemental ion images can be recorded in about 10 seconds, permitting rapid surveying of specimens, even at trace levels.

Another important aspect of SIMS illustrated in figure 13 is the shallow depth of sampling of the secondary ion signal. The instantaneous sampling depth of the secondary ion signal is approximately 1 nm, which affords a high degree of surface sensitivity. Thus, SIMS compositional maps can be measured which are representative of surface distributions. An example of such a surface sensitive image is shown in figure 14, where the oxygen has been deposited as a monolayer as a result of a chemical reaction stimulated during imaging with a scanning tunneling microscope. Because of the shallow sampling depth, each SIMS image actually represents a thin slice through the specimen, the thickness of which depends on both the instantaneous sampling depth of the secondary ions and the amount of material that must be removed to achieve a required level of sensitivity. Table 1 shows the effective "image thickness" needed to detect different levels of image contrast (1% and 25%) at various concentration levels [14]. For contrast at the 25% level, SIMS can be seen to be a surface sensitive technique with a depth sensitivity better than 10 nm for concentrations as low as 0.0001.

Table 1. SIMS Image Sampling Depth

Concentration Dependence

Concentration (atomic)	depth (Contrast = 0.01)	depth (Contrast = 0.25)
0.5	0.74 nm	1.2 pm
0.1	3.7	5.9
0.05	7.4	12
0.01	37	59
0.001	370	590
0.0001	3.7 μm	5.9 nm
0.00001	37	59
0.00001	370	590

Specimen: oxidized manganese; ionization yield = 0.083; spectrometer transmission = 0.1; detector efficiency = 1.

A major area of application of SIMS related to the shallow sampling depth is the determination of the distribution in depth of elemental constituents [10, 15]. In addition to the shallow sampling depth, this capability results from the trace sensitivity achievable from femtogram (10^{-15} grams) to attogram (10^{-18} grams) sample masses and the carefully controlled erosion of the specimen provided by sputtering. The SIMS measurement effectively peels the specimen an atom layer at a time while simultaneously measuring the atom species in that layer. Figure 17 shows the results of typical depth profile measurements of the distribution of boron that was ion-implanted in silicon. The depth axis is quantified by measuring the depth of the sputter crater after sputtering by mechanical or optical means. The concentration axis is quantified by relating the secondary ion intensity integrated through the whole profile to independent measurements of the total dose of the implant. Depth resolutions of 5-10 nm, total depths of 5 μm, and sensitivities as low as hundreds of parts per billion can be achieved in optimum situations. SIMS depth profiling is particularly useful for studying the distribution of elements implanted in electronic materials to modify properties selectively.

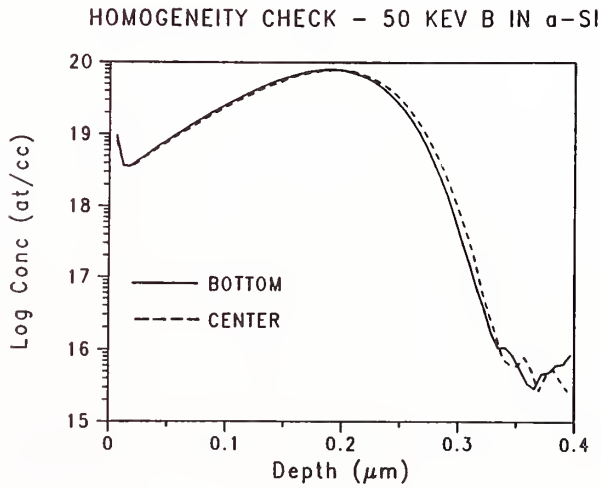


Figure 17. Secondary ion mass spectrometry/ion microscope depth profile of boron that was ion-implanted at 50 keV into silicon. Two profiles are shown, one located at the center of the wafer and one at the bottom edge (example courtesy D. Simons and P. Chi, NIST).

Finally, the imaging mode and the depth profiling mode can be combined to create an "analytical tomography mode" for compositional mapping [16]. By collecting digital SIMS images as a function of sputtering depth, information becomes available to reconstruct the three-dimensional distribution of elemental constituents. This reconstruction is accomplished in the digital domain, and the results are then viewed on an analog display from the digital image processor. Figure 18(a) and figure 18(b) show examples of analytical tomography applied to characterize the three-dimensional distribution of carbon at the grain boundaries of a $YBa_2Cu_3O_7$ superconducting thin film. A single two-dimensional image of the carbon distribution found at a depth of 0.5 micrometers below the surface is shown in figure 18(a). In figure 18(b), a stack of these

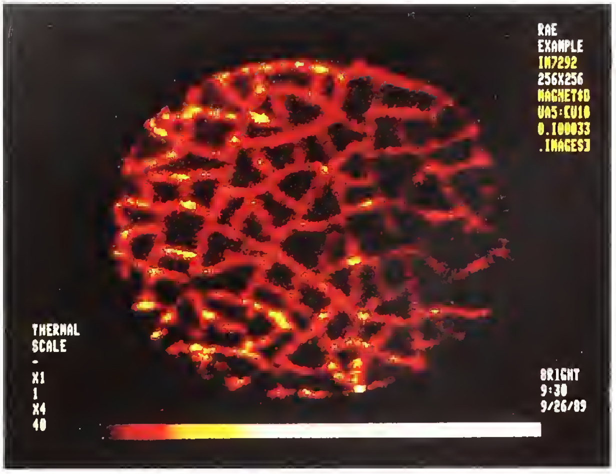


Figure 18(a). Secondary ion mass spectrometry/ion microscope image of carbon at the grain boundaries of $YBa_2Cu_3O_7$.

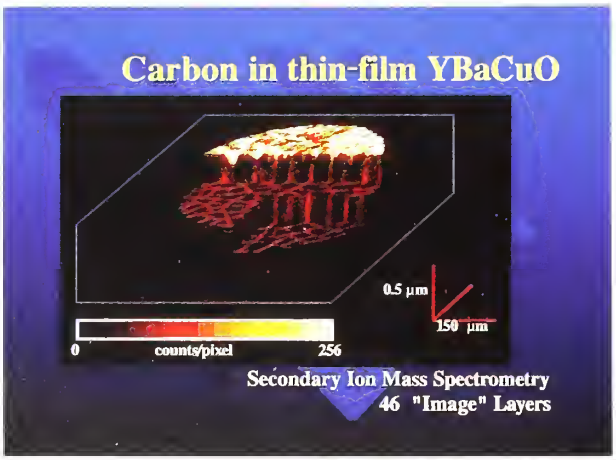


Figure 18(b). "Analytical tomography" created from a stack of images similar to 17(a) showing three-dimensional distribution using an image construction algorithm. Note difference in the lateral and depth scales (example courtesy G. Gillen, NIST).

two-dimensional images has been assembled to give the effect of a three-dimensional display by means of a projection algorithm that permits the viewer to select vertical and horizontal planes through the data. The thermal scale has been used to encode the relative concentration scale.

A major theme in the development of SIMS has been the pursuit of trace sensitivity from progressively smaller specimen dimensions. An eventual barrier to trace measurements from small volumes exists because of the finite and limited number of atoms that can be ionized directly during the sputtering process, collected from the specimen region, transmitted through the mass spectrometer, andeventually detected. Table 2 lists the dimensions of the cubical volume that must be consumed by sputtering to achieve a measurement with a precision of 10% at various levels of concentration for a species (oxidized manganese) which is ionized with relatively high efficiency (approximately 8%). At a concentration level of 0.001 (1000 parts per million), the minimum size of a cubical feature that could be measured is 0.12 micrometers, while to achieve 0.00001 (10 parts per million), the feature size increases to 0.54 micrometer. Thus, despite its high sensitivity, SIMS as it is currently practiced is significantly limited in its trace analysis capabilities below a spatial resolution of 0.1 micrometers. This situation may be improved by the introduction of post-sputtering ionization methods, such as photon bombardment of the sputtered assemblage of neutral atoms to increase the ionized fraction, and by more efficient collection and transmission of the secondary ions.

Table 2. SIMS spatial resolution and trace sensitivity [measurement at 10% precision; 8% ionization (oxidized manganese)]

Concentration (atom fraction)	Dimension of Minimum Cube (micrometers)
0.1	0.012
0.01	0.025
0.001 (1000 ppm)	0.12
0.0001 (100 ppm)	0.25
0.00001 (10 ppm)	0.54
0.000001 (1 ppm)	1.2

VI. Trace Nanoanalysis

The first achievement of "trace nanoanalysis," that is, trace sensitivity at nanometer scale spatial resolution, has recently been achieved [17]. Trace nanoanalysis has been demonstrated with the technique of analytical electron microscopy combined with parallel detection electron energy loss spectrometry (AEM/PEELS).

Analytical electron microscopy, illustrated schematically in figure 19, is based on the same physical interactions as electron probe microanalysis. In the EPMA, spatial resolution is limited by elastic scattering of the electrons in the target that cause the beam to "bloom" into an interaction volume with micrometer dimensions. Use of substantially higher electron beam energies, 100-400 keV for AEM versus 5- 30 keV for SEM/EPMA, can overcome this problem [18]. Because the cross section for elastic scattering decreases with the inverse square of the energy, high beam energies lead to a significant improvement in spatial resolution since the reduction in elastic scattering means that the electrons are more likely to remain in the focussed probe as they propagate into the specimen. However,

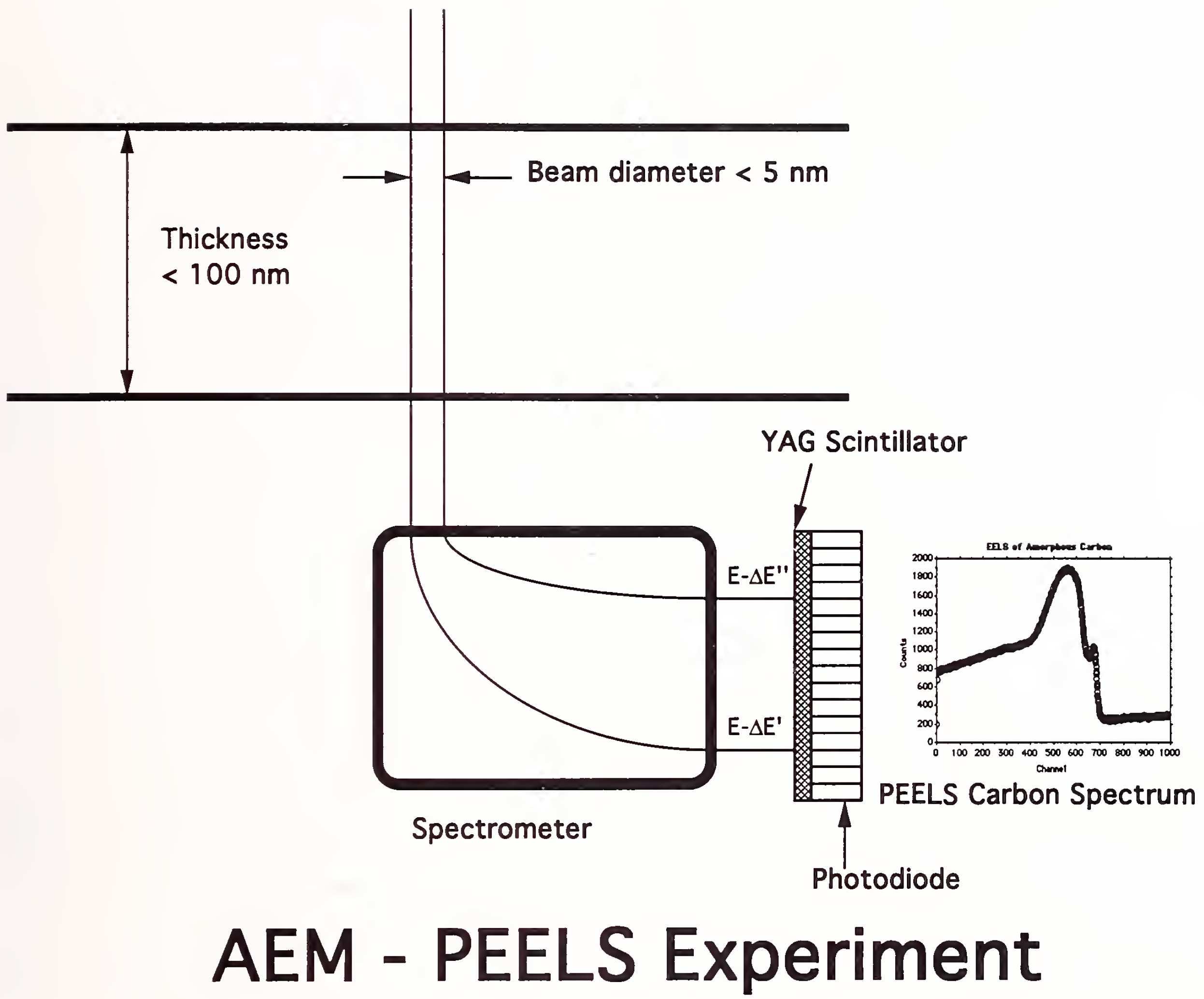


Figure 19. Analytical electron microscopy: schematic illustration of specimen and spectrometer configuration.

this potential improvement in lateral spatial resolution at high beam energy is lost in bulk specimens because the total range of the electrons increases as well. To avoid this problem, the specimen thickness must be reduced to that of a thin foil or particle, 100 nm or less. With high beam energy and a thin specimen, lateral spatial resolution approaching that of the diameter of the focussed beam, 1-10 nm, can be achieved.

The analytical spectroscopies available in the AEM are again based on the inner shell ionization scheme shown in figure 4(b) [18]. Energy dispersive x-ray spectrometry is the most common analytical measurement applied in AEM and is capable of reaching concentrations as low as 0.1 weight percent (1000 ppm). However, the use of thin specimens in the AEM permits examination of the direct ionization process. Because the incident beam energy is sharply defined (typically within 2 eV in 200,000 eV), the energy of the beam electron following inner shell ionization is also sharply defined. This so-called "energy loss electron" is characteristic of the critical ionization energy of the particular atomic shell and the states into which the bound electron can be scattered [18]. Parallel detection electron energy loss spectrometry (PEELS) consists of dispersing and simultaneously measuring the transmitted electron intensity as a function of energy loss, generally over the range 0-2 keV, by means of an array of detectors on a photodiode.

PEELS has significant advantages in absolute sensitivity over EDS. The inelastically scattered electron is dispersed over a narrow angular range, so that a spectrometer with a modest collection aperture can capture a large fraction of the available signal. By comparison, the x-ray measurement loses several orders of magnitude of this possible signal. First, the de-excitation is partitioned into the Auger and x-ray paths shown in figure 4(b). Generally, the x-ray yield is only 1-30%, depending on x-ray energy. Second, the x-rays from the subsequent de-excitation of the ionized state are emitted into 4π steradians, while due to geometric constraints, the x-ray spectrometer can only measure about 2% of this solid angle. Because of this high absolute sensitivity, PEELS can measure minimum feature sizes of pure element targets as small as 1-3 nm, corresponding to sample masses in the range 0.001-0.01 attograms (approximately 10-100 atoms). Despite this high absolute sensitivity, the electron energy loss spectrum has an inherent high background due to a continuum of other inelastic scattering processes. The resulting poor peak-to-background for characteristic edges has been regarded as limiting PEELS to a fractional detection limit in the range of 1% [19].

Trace nanoanalysis by AEM/PEELS has become possible because of the recognition of EELS spectral features with a much higher inherent peak-to-background and the development of spectral processing techniques to extract these features selectively [20]. ''White lines'' are resonances of narrow energy width that appear at the ionization edge energy for many elements in the pure and/or chemically bound states. These resonance structures can be selectively extracted by spectral filtering that makes use of the ''second difference'' method. In the second difference method, three PEELS spectra are measured, with an offset of a few electron volts among the three spectra. The energy difference among the spectra is selected to be similar to that of the resonance feature width, about 6 eV. A second difference spectrum is then calculated by taking differences among the three spectra and scaling. In addition to emphasizing the true spectral features such as the white line resonances, the second difference spectrum also eliminates channel-to-channel gain variations among the discrete detectors of the photodiode, any fixed pattern detector background, and the true spectral background.

Figure 20 shows an example of trace nanoanalysis achieved at the NIST-NIH Nanometer Analysis Facility on a field-emission AEM/PEELS system [17]. The specimen is NIST Standard Reference Material 610 (Trace Elements in Glass). Microscopic shards of SRM 610 were prepared by dry grinding to produce particles sufficiently thin for the PEELS technique. A beam energy of 100 keV, a beam current of 6 nA and a probe size of 3 nm were employed. The second difference PEELS spectrum shown in figure 20 was measured from a volume of material with lateral dimensions of 10×10 nm (defined by scanning the beam) and a thickness estimated (conservatively) to be no greater than 100 nm. This volume of SRM 610 contains approximately 1 million total atoms. Many of the trace elements present in SRM 610 are at a level of 50-200 parts per million atomic. The individual PEELS peaks of the transition metals and rare earths labelled in figure 20 correspond to the detection of only 50-200 atoms within the analyzed volume! To demonstrate that the peaks in figure 20 are ''real'' and reproducible, figure 21 shows repeated measurements on several particles. The peaks for the various elements are

SRM610 Glass (NIST)

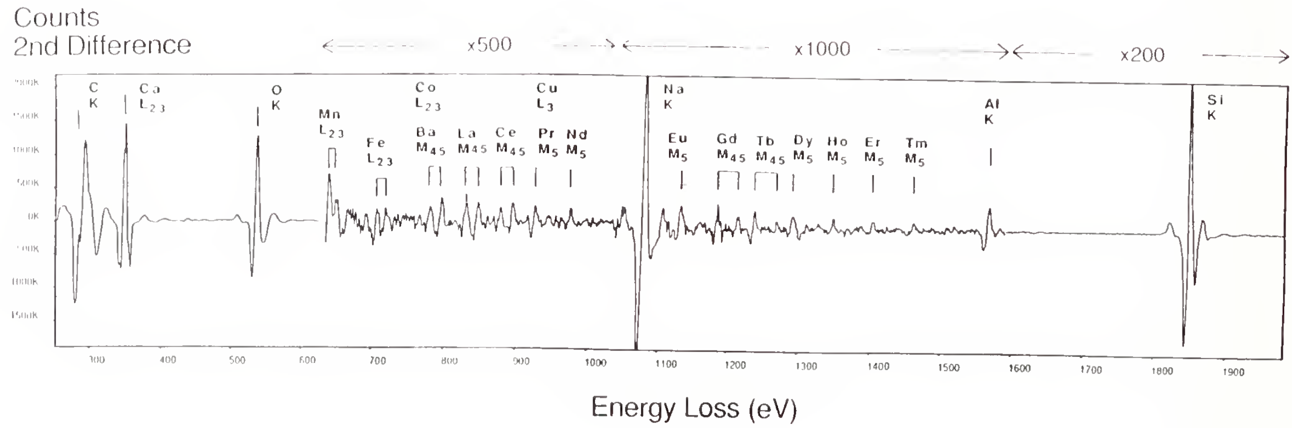


Figure 20. Analytical electron microscopy/parallel detection electron energy loss spectrum of NIST SRM 610. Second difference spectrum.

seen to vary somewhat from particle to particle, but this is reasonable because of the statistical variation expected in the small number of atoms being measured, even if the constituents are homogeneously distributed. In fact, this measurement represents the first time that homogeneity at the trace level has been examined with such high spatial resolution [17].

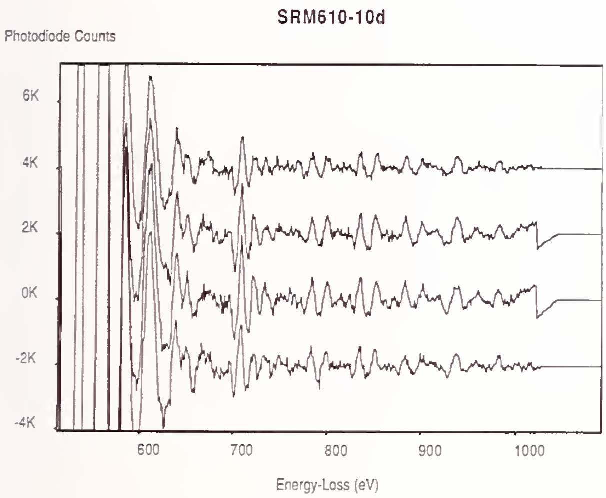


Figure 21. AEM/PEELS spectra of different particles of NIST SRM 610, demonstrating reproducibility of the measurement.

VII. Summary

Compositional mapping can be carried out by a variety of microbeam analysis techniques, a few of which have been highlighted in this paper. The general trend with these methods has been toward the development of progressively finer spatial resolution and higher sensitivity. The development of the mapping mode has been stimulated by the power of images of composition to convey information more effectively to an analyst than merely having tables of compositional values. The particular strength of compositional mapping is that the images are supported by the numerical composition values at each picture element. Thus, when a feature of interest is recognized in the compositional map, the pertinent concentration values can be readily recovered. The combination of images and data provides a powerful characterization tool for the microscopic world, leading to better understanding of the properties and processes of the macroscopic world.

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Molecular Dynamics on Surfaces

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I would like to describe research underway at NIST in the area of molecular dynamics on surfaces. Recent advances in laser technology and new concepts in ways of using lasers have made it possible to explore the details of chemical reactions at surfaces. These new time-resolved and quantum-state-resolved studies are frequently called "molecular dynamics" (fig. 1). When you hear a phrase like "reactions at surfaces," you may think of applications in catalysis or corrosion. You may think of applications in semiconductor device fabrication, such as chemical vapor deposition (CVD) or photo-etching. Or you may think of device operation in which the dynamics of electrical carriers are influenced by processes occurring at interfaces. I will describe our recent basic research results which, we hope, will influence all these applied areas.

These new laser approaches are useful because of the speeds at which electrons, atoms, and molecules move. Figure 2 shows a nitric oxide (NO) molecule about to hit a silicon (Si) surface. Chemical bonds act like springs, and the atoms (N and O in this case) vibrate. Typical vibrational periods are short, $\approx 10^{-13}$ s. NO also rotates; the time for NO to rotate end-over-end is about 10^{-12} s. NO is moving toward the surface; at ordinary temperature, T, it moves a distance equal to its length in $\approx 10^{-12}$ s. When it hits the surface, NO can either bounce off or stick. Which path it takes depends on the efficiency of energy transfer between the

Molecular Dynamics on Surfaces

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(partial support AFOSR, DOE)

A. Time - and quantum state - resolved laser studies of energy transfer, chemistry, carrier dynamics

B. NIST Results

1. Vibrational Energy Transfer: CO (v=1)/Pt (111)
2. Laser-Induced Desorption of NO from Pt (111), Si (111)
3. Laser-Induced Dissociation of Mo $(CO)_6$ on Si (111)

[4. Nonlinear optical probes of semiconductor surfaces]

C. Interactions and Impact

Figure 1. Introduction.

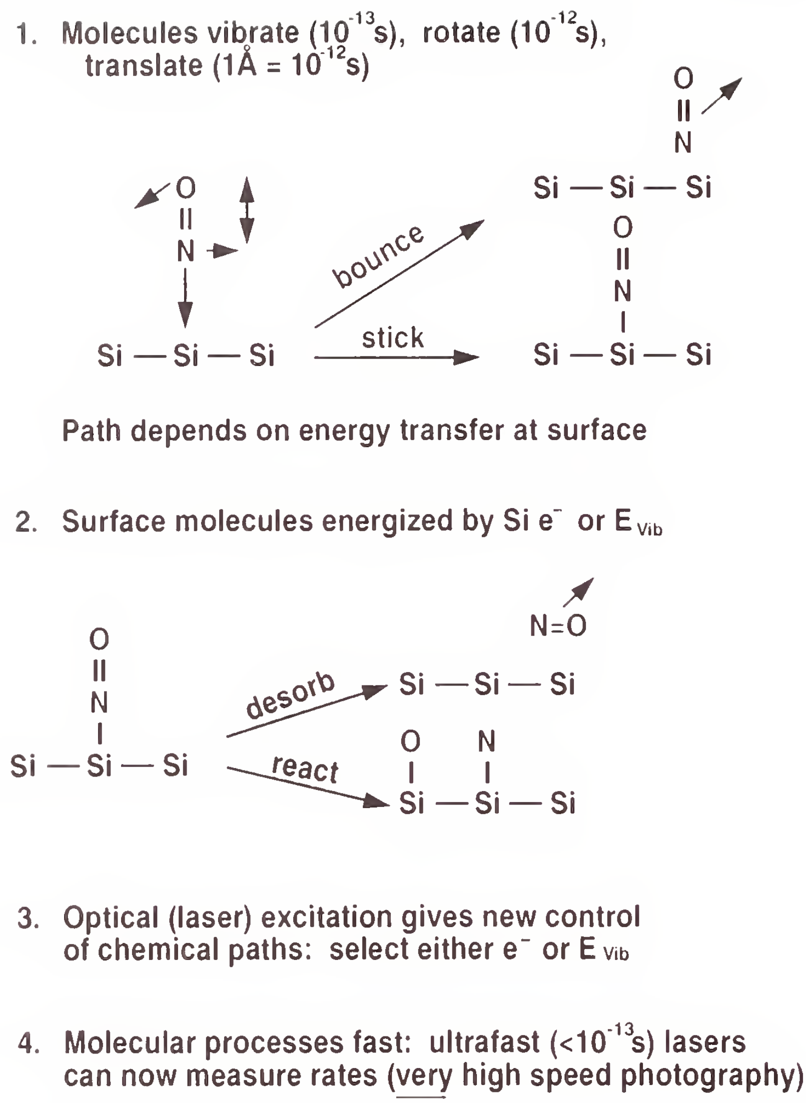


Figure 2. New approaches to surface processes.

molecule and the surface. If the electronic and vibrational motions of the Si do not absorb the vibrational, rotational, and translational energy of the NO, then it will bounce off, just like a baseball hitting an outfield wall. If it is adsorbed on the surface, it can do several things. It can be energized either by electronic or vibrational excitations, and it can pop off the surface (desorb), or it can dissociate forming surface oxide or nitride layers.

Creating or removing these surface layers is crucial in processes like CVD. In ordinary thermal processes at a particular T, there is no control of which path NO may take. However, optical excitation can give control of chemical paths. By choosing light of an appropriate color, one can excite particular chemical bonds, selectively causing particular reactions. This permits low T processing of materials, which is important for semiconductors easily damaged by thermal heating. These molecular motions are inherently fast. With new ultrafast laser pulses ($\leq 10^{-13}$ s) we can actually measure such processes in real time. The ultrafast lasers permit a new kind of very high speed photography: essentially, we take pictures of molecules as they are breaking old bonds and forming new ones.

I will describe successful experiments and future plans in four areas (fig. 1). When I use the word "we," I am not referring to my personal research but to that of a NIST team of scientists whose names are shown in figure 1.

(1) We used laser pulses of <10^{-12} s duration to measure the time for vibrational energy to go from

molecules on a metal surface to the metal substrate; specifically, we studied carbon monoxide (CO) on platinum (Pt).

(2) We used several different lasers to determine the mechanism of breaking the chemical bond between NO and a Pt (metal) surface and a Si (semiconductor) surface.

(3) We used different lasers to study the chemistry of the metal-containing molecule, molybdenum hexacarbonyl, Mo $(CO)_6$, on a Si surface.

(4) We are trying to develop and implement new laser methods of probing hot carriers and transient surface properties at semiconductor interfaces. Item (B. 4) is in brackets in figure 1 because the laboratory to do the non-linear interface studies is still being set up.

In further describing these four projects, I will try to place the NIST role in perspective, especially vis à vis related basic and applied work being performed worldwide, and particularly by U.S. companies like Bell Labs and IBM, with whom we have longstanding and mutually beneficial interactions. The experiments are all state-of-the-art and require advanced ultra high vacuum (UHV) apparatus for surface preparation and characterization, and advanced laser sources, some of which are unique at NIST. The ideas and results are new—so new that most of them have not yet been published, or have been within the last year. I do not have time to describe experimental details, but our experiments are noted for their extreme difficulty.

In the first of the four research areas, we determined the rate and mechanism for energy to flow from vibrationally excited adsorbed molecules to a metal substrate (fig. 3). There are many reasons to care about vibrational energy transfer (VET) between molecules and surfaces: 1) sticking, desorption, surface mobility, and chemical reactions are all activated by E_{vib}; 2) surface spectroscopy, i.e., the widths and shifts of vibrational absorptions probed by many techniques, is related to vibrational energy transfer; 3) at least for molecules on surfaces, there are no good predictive theories; 4) until our ultrafast laser experiments, there were no data. For the first experiments for molecules on a metal single crystal, we decided to study the vibrational dynamics of CO/Pt(111), which is the adsorbate/substrate system best characterized by conventional techniques. The experimental approach is to excite the C-O stretching vibration with an infrared (IR) laser pulse of duration $<10^{-12}$ s (=1 ps). A second ultrafast laser pulse measures the transient absorption spectrum for CO/Pt as a function of pump-probe time delay t_D. For a simple system, you might expect the vibrational energy to decay exponentially with a characteristic time constant, T_1. At the bottom of figure 3 are the first spectra ever obtained for vibrationally excited molecules on a surface. The unexcited absorption gives a narrow Lorentzian line (black dots). When the pump pulse excites the CO, the absorption shifts, broadens, and becomes asymmetric ($t_D = 0$). But within a few ps, the spectrum returns to its unexcited equilibrium value. The decay time is very short, only 2 ps. The vibrational energy, when it leaves the C-O bond, in principle could go many places, e.g., to the Pt-C bond, but it does not. Instead, it couples to the electrons of the metal substrate, creating an electron/hole (e/h) pair in the Pt. To test out these ideas about the coupling of e/h pairs to surface vibrations, we are now doing a reverse experiment in which a pump laser creates hot e/h pairs in the Pt, and the IR probe laser monitors the rate at which the hot carriers cause vibrational excitation in the surface layer.

The NIST group pioneered the field of vibrational relaxation at surfaces, but there are now many groups doing related studies. The results show great variety in terms of the rates and mechanisms of VET (fig. 4). These were unknown until our time-resolved measurements. A group at AT&T recently determined the relaxation of carbon monoxide on copper (CO/Cu) to take 2 ps, the same as our CO/Pt result. Although 2 ps may sound like a short time, it is nevertheless 120 vibrational periods of the C-O bond. If the CO is attached to isolated metal atoms, either on a dielectric surface like silicon dioxide (SiO_2), or in the gas phase, then the e/h-pair damping mechanism is unavailable, and the vibrational relaxation time, T_1, becomes much longer, hundreds of ps. At very low T on insulator surfaces, T_1 can be very long. 5×10^{-3} s was measured for CO on salt (NaCl), more than 10^9 slower than on a metal surface. A much studied surface is Si covered with hydrogen (H). Vibrational energy transfer involving the Si-H bond has been investigated by groups at AT&T, Centre National de la Recherche Scientifique in France (CNRS), and IBM. Since this Si-H quantum is much less than the indirect bandgap for Si, e/h pairs can not be created and the T_1 is quite long, 10^{-9} s. The groups at IBM, AT&T, CNRS, and many universities have pursued these experiments for several reasons. One is an interest in catalysis and the question of how long vibrationally excited molecules persist, whether they are created by lasers or by non-laser catalytic reactions. A second is the mechanism of Si thin film growth, where surface H is very important. And many groups are interested in the coupling of carriers (e/h) to surface states, both at metal and semiconductor interfaces. I hope it is clear that the development and demonstration of these new laser

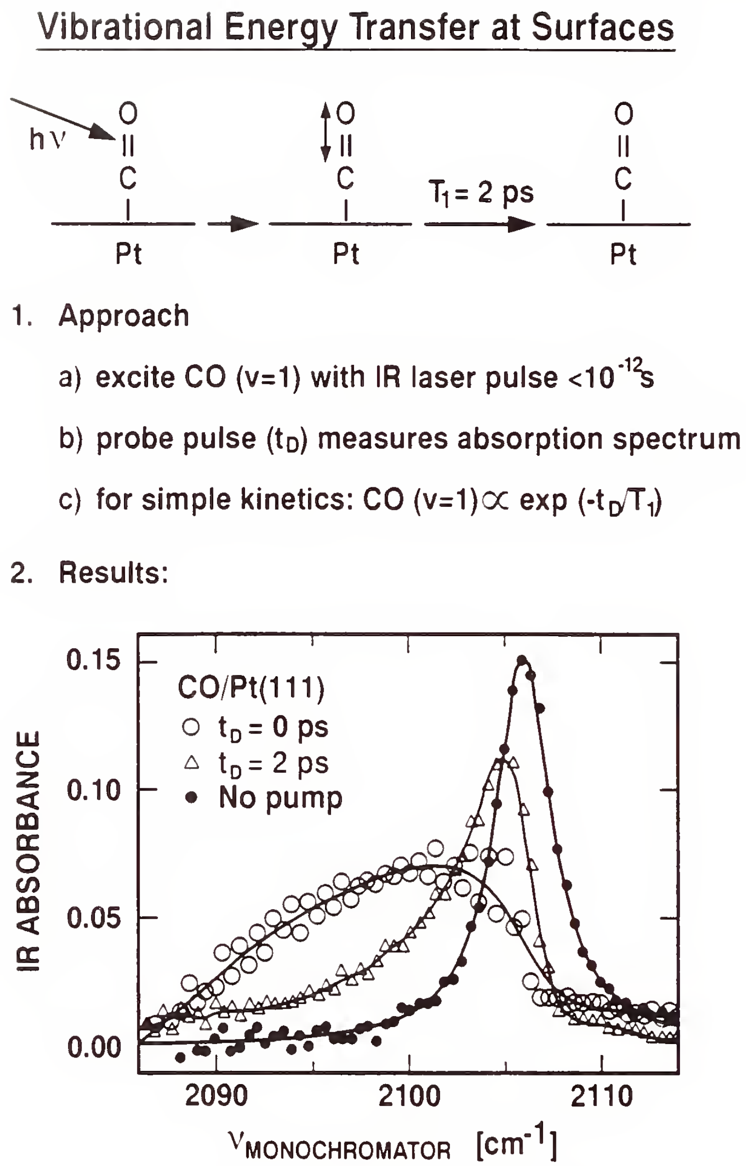


Figure 3. Time-resolved absorption spectra of vibrationally excited carbon monoxide on a platinum metal surface.

methods to probe surface dynamics will be useful in many types of studies in addition to vibrational energy transfer.

A second area where NIST has played a pioneering role is in quantum-state-resolved studies of molecules desorbing from metal and semiconductor surfaces. We did experiments where a laser pulse is absorbed by a metal substrate, causing surface molecules to desorb into the gas phase: NO on Pt is shown as an example (fig. 5). A second probe laser detects the desorbed NO, and determines the internal vibrational and rotational energy of the molecules, as well as their velocity leaving the surface. By studying the dependence of the NO yield and energy on the angle, intensity, and frequency of the desorption laser, the NIST group discovered a new mechanism for this surface chemistry. The bond between the Pt and the NO breaks when a hot e^- from the bulk Pt goes to the surface and creates a short-lived, negatively charged NO^-. The NO^- accelerates back toward the surface, effectively compressing the Pt-N bond. After about 10^{-14} s, the e^- returns to the substrate, and the distorted Pt-N bond breaks,

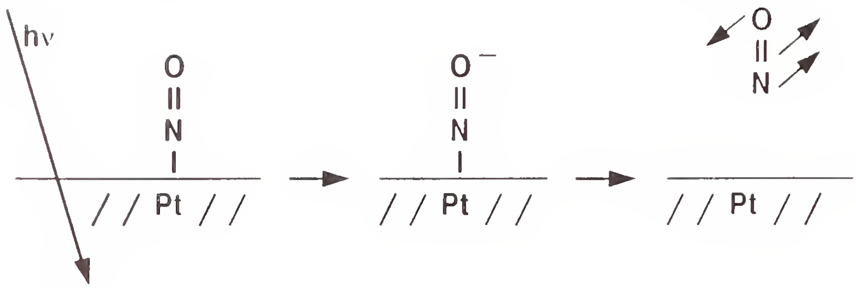
System	T_1 (s)	Mechanism
CO/Pt	2×10^{-12} (NIST)	e/h pairs
CO/Cu	2×10^{-12} (ATT)	e/h pairs
CO-Rh/SiO_2	1.4×10^{-10} (NIST)	2-phonon image dipole
Cr $(CO)_6$(gas)	8×10^{-10} (NIST)	4-phonon anharmonic
CO/NaCl	5×10^{-3} (U. Ind.)	9-phonon image dipole
H-Si/Si	10^{-9} (ATT, CNRS, IBM)	4-phonon anharmonic
HO/SiO_2	2×10^{-10} (NIST)	4-phonon anharmonic

Figure 4. Variety of rates and mechanisms of vibrational energy transfer on surfaces.

with the NO desorbing. When NIST researchers first proposed this mechanism a couple years ago, some scientists were initially skeptical because of the short lifetime of the hot electron. In the last decade there have been many studies of unusual surface chemistry, thought to be caused by lasers simply heating the surface. For instance, because of the interest in catalysis on metals, researchers at Exxon and elsewhere studied laser desorption of hydrocarbons, which they interpreted in terms of a thermal mechanism. However, the NIST-proposed hot electron mechanism is now widely accepted, and has been invoked to explain related laser-induced desorption experiments done very recently at IBM, AT&T, Sandia, Max-Planck in Germany, and elsewhere.

Compared to the chemistry on metals, NIST studies of light-induced chemistry on semiconductor surfaces have shown different mechanisms for reactions (fig. 6). It has been known for years that if a semiconductor is illuminated by light where the photon energy exceeds the gap between valence and conduction bands, then e/h pairs are created in the bulk. Some of the carriers migrate to the surface where they can do useful chemistry. For instance, recently IBM scientists studied how the etching of Si is enhanced by laser radiation, and many companies have used laser methods to study solar energy conversion based on semiconductors in electrochemical cells. However, at NIST we recently discovered a new and different mechanism for chemistry on semiconductor surfaces. Our experiments studied a Si(111) 7x7 surface in which NO is bound to specific Si surface atoms (the ones shown in blue in figure 6, called "adatoms," as opposed to adjacent "rest atoms" shown in green). A pump laser pulse excites the sample, and a second laser probes the NO which the pump pulse caused to desorb. Our studies proved that desorption is not caused by the accepted mechanism of carriers created in the bulk coming to the surface. Instead, light is directly absorbed by a surface band made up of the dangling bonds associated with these Si "rest atoms." Absorption of a photon creates a surface localized

Laser-Induced Desorption from Metals



1. Pump laser pulse excites Pt substrate

2. Probe pulse detects desorbed NO (gas phase)

3. Study NO (E_{Rot}, E_{Vib}, $\vec{V}$) vs. laser ø, I, ν

4. Non-thermal hot e^- mechanism (NIST, 1988)
   a) hν absorbed by Pt (bulk), creating hot e^-
   b) hot e^- + NO (s) $\longrightarrow$ NO^- (s)
   c) NO^- accelerates
   d) e^- returns to Pt (10^{-14} s)
   e) NO desorbs

5. Hot e^- mechanism now widely invoked:
   NO/Pd (IBM); CO/Cu (ATT); NO_2/Pd (Max-Planck); NO_2/Pt (Sandia)

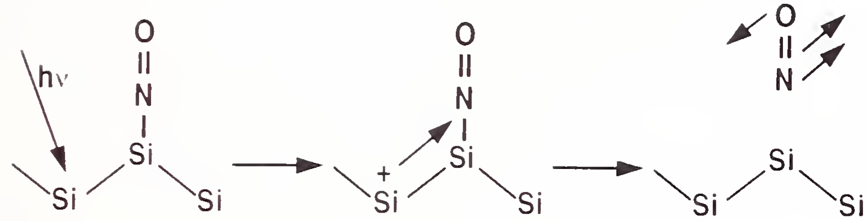
Figure 5. Laser pulse absorption by a metal substrate, causing surface molecules to desorb into the gas phase by a hot electron mechanism (NO on Pt).

hole which then takes an e^- from the NO, breaking the Si-N bond. This is a very efficient process and we expect it may be important to photochemistry on many semiconductor surfaces.

In complementary experiments, we are studying the laser-induced dissociation of $Mo(CO)_6$ on Si (fig. 7). There is lots of interest in this type of reaction because one can deposit these organometallic molecules on semiconductor surfaces and irradiate the sample with a laser which decomposes the molecules; this leaves behind the metal atoms on the surface, effectively writing thin metal lines or films on the semiconductor surface. Our approach has been to study the laser-induced dissociation of this molecule on the surface at both submonolayer and multilayer coverage. As in the preceding experiments, we use one laser to cause the decomposition reaction and another to probe the CO molecules which desorb into the gas phase. We also use IR absorption spectroscopy and other techniques to probe the molecules which did not desorb but are left on the surface.

These experiments are not finished, so there will be more of a story to tell in a few months. However, one interesting result is that there is a different mechanism for the $Mo(CO)_6$ photochemistry. As you remember, for NO on Pt, hot e^- from the bulk went to the surface

Laser-Induced Desorption from Semiconductors



1. Chemistry via bulk carriers well known
   a) photo-etching (IBM, etc.)
   b) solar energy conversion (ATT, Dupont, Exxon, etc.)

2. NIST approach: Study NO (E_{Rot}, E_{Vib}, $\vec{V}$) vs. laser ø, I, ν

3. Non-thermal surface state mechanism (NIST, 1990)
   a) hν absorbed by Si surface dangling bonds, creating surface hole (+)
   b) h^+ is captured by NO, weakening Si-N bond
   c) NO desorbs: site-specific chemistry

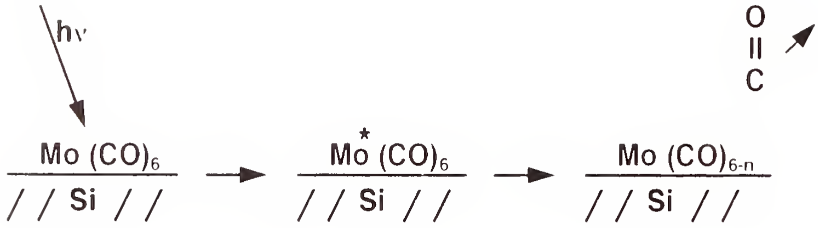
Figure 6. New mechanism for light-induced chemistry on a semiconductor surface.

and caused the reaction, while for NO on Si, direct excitation of the surface Si "rest atoms" led to desorption. For $Mo(CO)_6$ on Si, the bonds of the molecule itself directly absorb the light, so the entire photon energy is initially localized in the molecule. The presence of the surface leads to a decrease in efficiency (compared to the gas phase) of ejecting the CO ligands, because energy transfer to the Si competes with dissociation. To help develop a complete picture of photochemistry of metal carbonyl molecules on surfaces, we are doing photochemistry experiments on the same molecules, isolated in the gas phase and in liquids. It has proven extremely useful to compare reaction rates and mechanisms in all phases—gases, liquids, and on surfaces. Our group at NIST is unique in focusing so many different approaches, disciplines, and techniques—ultrahigh resolution laser spectroscopy, molecular beams, ultrafast lasers, and the UHV techniques of surface science—on problems such as energy transfer and bond-breaking reactions.

A research area we are just starting is non-linear optical studies of hot carriers at semiconductor interfaces. There are many groups throughout the world studying carrier dynamics in semiconductors by measuring the time-dependent optical absorption of laser light by bulk semiconductors. However as the packing density of devices on chips becomes higher, and operating speeds faster, the interfaces between active materials, insulators, and interconnects begin to affect device performance, as carrier dynamics are more strongly influenced by scattering from interfaces. To obtain information about very fast processes, one needs a laser technique which is sensitive to interface—as opposed to bulk—properties.

A promising technique is sum frequency generation, SFG (fig. 8), in which one laser (υ_1), resonant with

Laser-Induced Dissociation on Semiconductors



1. Much qualitative work on organometallics on semiconductors: ATT, IBM, Cornell, Harvard, Sandia, etc.

2. NIST approach: pump laser excites Mo $(CO)_6$ bonds; probe laser detects CO (gas phase)

3. Study CO (E_{Rot}, E_{Vib}, $\vec{V}$) vs. laser o, I, ν; probe Mo $(CO)_{6\text{-}n}$ on surface

4. Mechanism: excitation localized in Mo $(CO)_6$; competition between CO desorption and energy transfer to Si substrate

Figure 7. Laser-induced dissociation of $Mo(CO)_6$ on Si.

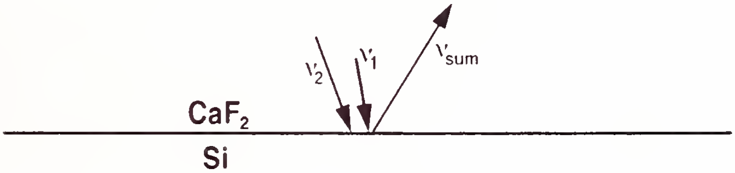
a surface state, is up-converted at the surface with photons from a second laser (ν_2) to generate new light at the sum frequency (ν_3). For a centrosymmetric medium like Si, this SFG process does not occur in the bulk but only at the surface, so it offers unique sensitivity to interfaces plus the ultrafast time resolution of femtosecond lasers. I will mention two specific experiments we are trying to do with this approach. In non-time resolved experiments, the interface between Si and the insulator calcium fluoride (CaF_2) has been studied at IBM, RIKEN (the Institute of Physical and Chemical Research in Japan), and elsewhere. It is a promising candidate for a practical epitaxial insulator required to make three-dimensional integrated circuits. Using the ultrafast pump/probe experiments, we will excite bulk carriers in the Si substrate, which will scatter from the interface. Using SFG, we will then probe the excitation and decay rates of previously unoccupied surface electronic states associated with the Ca-Si bonds.

Another type of interface of great importance is that between conducting layers and semiconductors. We believe that SFG can probe the potentials at these buried interfaces by using IR laser pulses of frequency resonant with the Schottky barrier heights associated with the interfaces. Of technical interest is the metallic cobalt disilicide/silicon, $CoSi_2$/Si, interface. This has been studied in non-time-resolved experiments by several groups, because the silicide layer can form a low dispersion interconnect for high-speed integrated circuits. We will attempt to use this nonlinear spectroscopy as a contactless probe of ultrafast circuit characteristics by measuring the time evolution of the SFG following junction current injection with a femtosecond laser pulse. No one has done SFG experiments like these before. We are developing this approach in collaboration with colleagues at IBM.

Beyond the details of the particular experiments I have described, using lasers to study these dynamical

Nonlinear Optical Studies of Semiconductor Interfaces

1. **Sum frequency generation (SFG):** $\nu_{sum} = \nu_1 + \nu_2$
   Interface only



2. **CaF_2/Si (111) static studies (ATT, IBM, RIKEN, etc.)**
   a) time-resolved SFG is new

3. **$CoSi_2$/Si static studies (ATT, RIKEN, IBM)**
   $NiSi_2$/Si
   a) Use of lasers (SFG) to probe Schottky barrier structure and dynamics is new

Figure 8. Sum frequency generation at semiconductor interfaces.

processes is important and will continue to be important. The intellectual challenge of trying to understand chemistry, energy transfer, carrier dynamics, and laser interactions at surfaces, although clearly beyond the capacity of any single group, is something to which we should continue to contribute.

Surface Force Measurements

Roger Horn
Physicist, Mechanical Properties Group
Ceramics Division
Materials Science and Engineering Laboratory

It is my privilege and my pleasure today to talk to you about some work that I and my colleagues, Douglas Smith and Alexis Grabbe, have been doing on surface forces.

What does the name "surface forces" mean? It is not really a common or familiar term to many of us, and yet I hope to convince you that it describes a very important phenomenon that deserves a lot of study. It refers to the forces acting between microscopic or even macroscopic bodies, usually when they are in close proximity. These are the forces resulting from interatomic and intermolecular forces between the atoms and molecules of the materials involved, and they include van der Waals forces, electrostatic forces, and Born repulsions [1,2].

The name "surface forces" comes from the fact that the force between two bodies depends, primarily, on the atoms and molecules that come closest together as the bodies approach, namely the atoms and molecules at the surface. For this reason, the force between the two bodies is generally a function of the separation between their surfaces.

Where do we find surface forces acting? In a word: everywhere! We are very familiar with the notion that the properties of substances—for example, whether they are solid, liquid, or gas, whether they conduct electricity, what their elastic properties are, and so on—are determined to a large extent by the interatomic bonding of those substances.

But many of the materials around us are not so simple. They have some granularity, or texture, or microstructure, on a scale much larger than atoms. Some are composites or laminates. The properties of those materials are determined by the interactions between larger elements, for example micrometer-sized or even millimeter-sized grains, crystals, layers, fibers, cells, or other components. We do not need to look very far to see examples of these materials: the floor that I am standing on is one. The seats that you are sitting on is another. This podium is another. My body is another. Everywhere around us are materials whose properties depend less on interatomic bonding than on the interactions between larger-scale elements, i.e., on the surface forces that are the subject of this talk.

Colloid science is the area in which surface forces are best known, best appreciated and best understood. Historically, most studies of surface forces have been conducted by colloid scientists. However, there is a growing awareness of the importance of surface forces in other areas of materials science. Table 1 gives a partial list of processes, products, and phenomena in which surface forces play an important role. Examples include ceramic processing, adhesion and bonding, and several aspects of tribology. There are other areas shown that are equally interesting scientifically, and vitally important for the future of the human race, but beyond the immediate interests of the Materials Science and Engineering Laboratory here, and so I am not going to dwell on them. Nevertheless, I hope to have made it clear that surface forces affect many things around us, and for this reason alone they constitute an important area of investigation.

Table 1. Some of the areas in which surface forces play an important role

COLLOID SCIENCE	• Paints and inks • Dispersions, slurries • Foodstuffs • Pharmaceuticals • Mineral separation • Ceramic processing
MATERIALS SCIENCE	• Adhesion and bonding • Processing • Fracture • Composites, coatings, thin films • Electronic packaging
TRIBOLOGY	• Friction and wear • Boundary lubrication • Flow in thin films
ENVIRONMENTAL AND EARTH SCIENCES	• Clay swelling, agronomy • Drilling muds, enhanced oil recovery • Solid waste retention • Waste water treatment
BIOLOGY	• Cell-cell interactions and recognition • Cell adhesion and fusion • Connective tissue
MEDICINE	• Drug delivery systems • Implant materials, biocompatibility

One interesting feature about surface forces I would like to point out is that they depend very much on the medium between two bodies. Furthermore, since they depend so much on the atoms right at the surfaces of the bodies, they depend on the *surface chemistry* of the materials involved. We might therefore expect to be able to exert some control over surface forces by varying the surface chemistry and the nature of the intervening medium [1]. As we go along I will show you some examples where we get dramatic effects on the surface forces by modifying those two factors.

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Our approach to studying surface forces is an experimental one. We use a commercial apparatus called the Surface Force Apparatus, which is designed to measure the force between two solid surfaces immersed in any liquid or vapor medium [3], and is illustrated schematically in figure 1. Surface forces act at very short range—typically we will be talking in terms of nanometers—and so the first requirement for accurate measurements is to have solid surfaces that are smooth on this scale. Mica is eminently suitable in this regard, and it is the usual choice of material for these measurements.

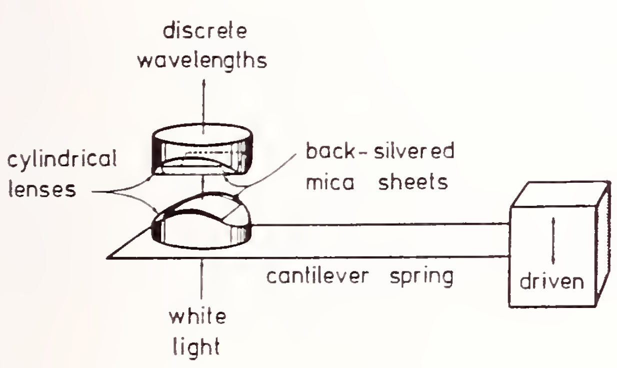

Figure 1. A schematic picture of the heart of the Surface Force Apparatus. Two solids with smooth surfaces, such as mica, are mounted as crossed cylinders having a radius of a centimeter or two. One cylinder is attached to a cantilever spring, whose deflection measures the force between the two surfaces. Surface separation is controlled by driving the remote end of the spring, and measured by optical interference between two silver layers on the outer surfaces of the two solids.

The second requirement is to have a sufficiently large area of surface interacting with the opposite surface, so that the total force between them is large enough to be measured. One way to achieve that is to use curved surfaces with a large radius of curvature, and an experimentally convenient arrangement is to use crossed cylinders. The total force turns out to be proportional to the radius of the cylinders, and a value of one or two centimeters is suitable. Thin flat sheets of a material such as mica can easily be bent into cylindrical form, and this arrangement has the considerable advantage of avoiding edge effects and problems of flatness and parallelism that would arise in a flat geometry.

The separation between the mica sheets is measured using an optical technique. We put a silver coating on the outer (or remote) surface of each mica sheet, then shine white light through the two surfaces. The two silver layers form an optical interferometer—a resonant cavity for light—so that the only light that passes through the system is a set of discrete wavelengths. By measuring the wavelengths that are passed, we can compute what the interferometer thickness is, and after subtracting the thicknesses of the two solids, we can compute the separation between the front surfaces.

In order to measure the force, we mount one surface at the end of a cantilever spring, and we control the position of the other end of the spring using some clever mechanisms for moving it up or down with very fine resolution. The optical method measures separations, on a good day, with a resolution of 0.1 nanometer, i.e., an Ångstrom. Because we can measure that very accurately, we can also measure very small deflections of the spring and, hence, very small forces. The principle, incidently, of measuring forces with a cantilever spring is identical to what is used in an atomic force microscope, which you may have read something about.

I have spoken already about mica, which is the most common material for these experiments. The idea of using mica and of using crossed cylinders goes back to David Tabor in Cambridge (U.K.) in the 1950's, and the Surface Force Apparatus was brought to its present level of sophistication by a former student of Tabor's, Jacob Israelachvili, working in Australia in the mid-1970's [3].

Many, many experiments have now been done with mica. It is an ideal material for these measurements; the only problem that we have run into is that there seems to be a limit to the world's interest in this material for technological applications.

Thus it has been a challenge for a number of years to try and find some other materials to study with this technique. We have taken a very significant step in that direction in the last few years at NIST by finding a method of preparing *silica* with a very smooth surface and in a form suitable for use in the surface force apparatus [4].

Silica, of course, is highly important in its own right. We also believe that these measurements will tell us something about surface properties of silica which will relate to other silicious materials—silicon, silicon nitride, silicon carbide—because all of those materials have a native oxide layer after exposure to air, and thus their surface properties will bear some resemblance to those of silica.

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Before I show you some results of force measurements, let me just quickly say a few words about colloid science. If I consider a canonical colloid as a suspension of small, solid particles in a liquid medium, Brownian motion will keep those particles suspended for a very long time, so long as the particles remain isolated from each other. Thus if the forces between them are repulsive, we will have a very long-lived colloid, which is called a stable colloid.

If, on the other hand, the particles attract each other, when two particles collide they will stick together. A third particle could subsequently stick to the first two, and a fourth, and so on, thereby building up an aggregate of particles. Eventually that aggregate will become heavy enough to sink out of suspension, and we will no longer have a stable colloid. That may be desirable or it may be undesirable, according to the circumstances.

The standard theory of colloid science is called DLVO theory, after the four people who concocted it (Derjaguin, Landau, Verwey, and Overbeek), about the time of World War II. Simply stated, the theory says that the net force between two particles in a polar liquid, such as water, is given by the sum of an electrostatic force and a van der Waals attraction.

The electrostatic force, which is repulsive between like particles, occurs because most solids acquire a surface charge when immersed in water. This comes about because ions either absorb to the solid or they desorb from it, with the result that two particles of a particular solid are going to repel each other. However, the range of the repulsion is affected by how much electrolyte is in the water, because ions of opposite sign to the surface charge are attracted towards the surface and concentrate near it, forming a so-called diffuse double-layer. This has the effect of screening the electrostatic repulsion. The repulsion turns out to be an exponential function of surface separation, while the van der Waals attraction is always an inverse power law [1].

The result of adding these two forces together is illustrated schematically in figure 2. The power-law attraction always dominates over the exponential repulsion at short distance, meaning that the solids will stick together if they come close enough. However, at longer distances there is a repulsive barrier, and two colliding particles must have sufficient kinetic energy to overcome this barrier if they are to come into adhesive contact. When the barrier is very high, as it would be when the solid surfaces are highly charged, particles are kept apart by the double-layer repulsion, and under these conditions a colloid remains stable.

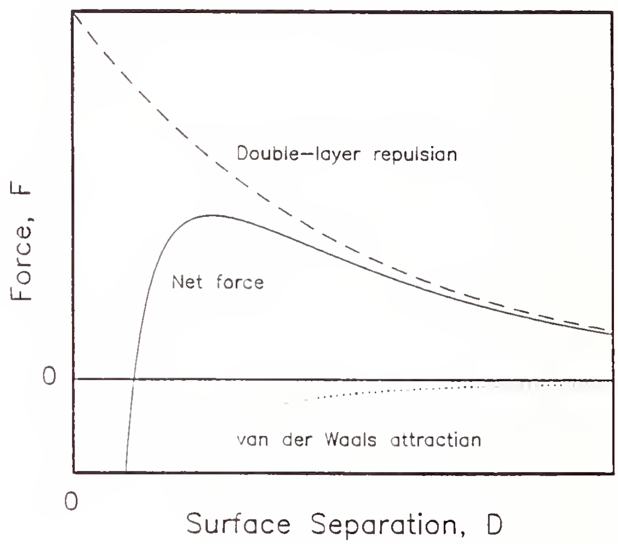

Figure 2. Schematic illustration of the DLVO theory. Repulsion is plotted as a positive force; attraction as $F < 0$. The net force is given by the sum of an electrical double-layer repulsion, which is a quasi-exponential function of surface separation (dashed curve); and a van der Waals attraction (dotted curve), which is an inverse power law.

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How well does the DLVO theory work in practice? It has had many successes in colloid science, but it has also encountered some difficulties. Figure 3 shows typical measurements of the force between mica surfaces in water at two fairly low concentrations of electrolyte, both a few times 10^{-5} moles of sodium chloride per liter. The data are shown by the symbols, and the two solid lines are DLVO theoretical fits to the data, with one adjustable parameter (the amount of surface charge) for each curve. You can see that there is very satisfactory agreement between the theory and the experiment, including the fact that the force has a maximum at a separation of about 2 nano-meters. The theory looks to be in good shape.

Figure 4 shows some comparable data for silica surfaces, again in sodium chloride solutions [4]. At long range, we see a double-layer repulsion whose range decreases as the concentration of salt increases, exactly as predicted by the theory. The solid lines in this figure again represent the DLVO theory, and again, the fits look rather good at long range.

However, at short distances something goes wrong. The measured forces keep going up and up, i.e., they become more and more repulsive as we try to push these surfaces together. The theory, as I have noted, always predicts a maximum in the force at some small but finite separation, and it predicts that if we could get these two surfaces close enough together, they should stick. There should be a van der Waals attraction between them which will cause adhesion. Experimentally, that does not happen.

Clearly, there is an additional short-range repulsive force between the surfaces, which is called a *hydration repulsion*. The hydration repulsion arises because the surface of silica has silanol groups on it, and water molecules like to stick to those groups

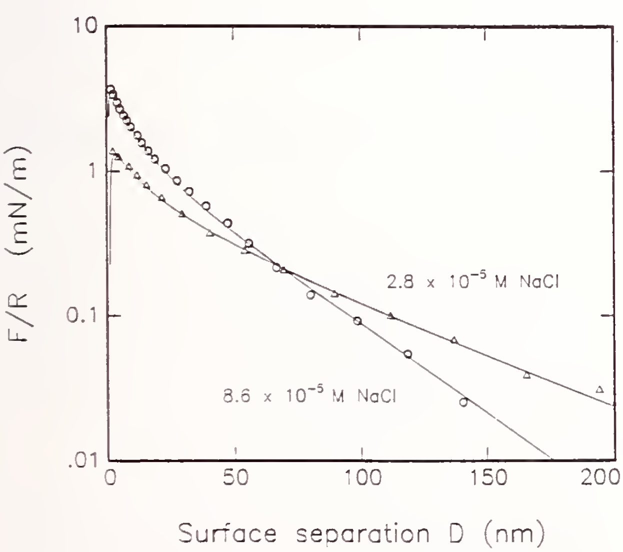

Figure 3. Typical surface forces measured between two sheets of mica immersed in water with a small amount of electrolyte present. (The force has been normalized by the radius of curvature of the mica cylinders, because that allows comparison between different experiments in which the radii might be different.) As predicted by DLVO theory, there is a double-layer repulsion whose range decreases as electrolyte concentration increases. At short range, van der Waals attraction pulls the surfaces into adhesive contact at D = 0.

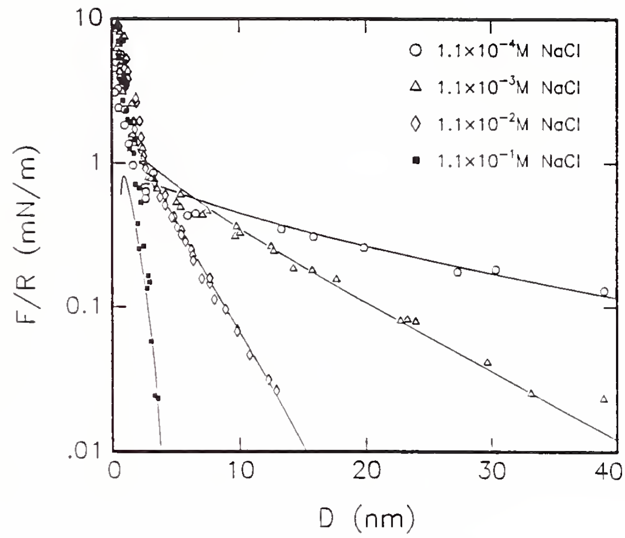

Figure 4. Force curves measured between *silica* surfaces in aqueous solutions of sodium chloride at various concentrations [4]. The range of double-layer repulsion varies as expected. However, at short range there is a strong repulsion which is not accounted for in the standard DLVO theory. This so-called *hydration force* prevents the surfaces from adhering.

through hydrogen bonding. When two surfaces are pushed together, the water between them gets squeezed out of the gap. However, the hydrogen-bound water does not want to go: it prefers to remain close to the surface. We have to push harder and harder to squeeze out those water molecules—the water of hydration—between the surfaces when they are just two or three nano-meters apart.

The consequence is very dramatic. Where DLVO theory predicts that under appropriate electrolyte conditions a colloid of silica particles would be unstable, i.e., the particles would stick together and sink to the bottom of the container, this never happens. The hydration repulsion prevents aggregation, and the behavior of the colloid does not follow the theoretical prediction. Hydration forces are also known to play a dominant role in the behavior of several other systems, including many biological materials and the swelling of clays.

Another feature of silica is that the surface is somewhat reactive, allowing us to play certain chemical tricks with it. We can take small molecules of a certain type and chemically bond them to the surface, thereby changing the surface chemistry of the silica. As an example, let us do that with a simple molecule which is hydrophobic. That is, it is an "oily" molecule that does not like water, and water does not like it. The force measured between two surfaces coated with this molecule is shown in figure 5.

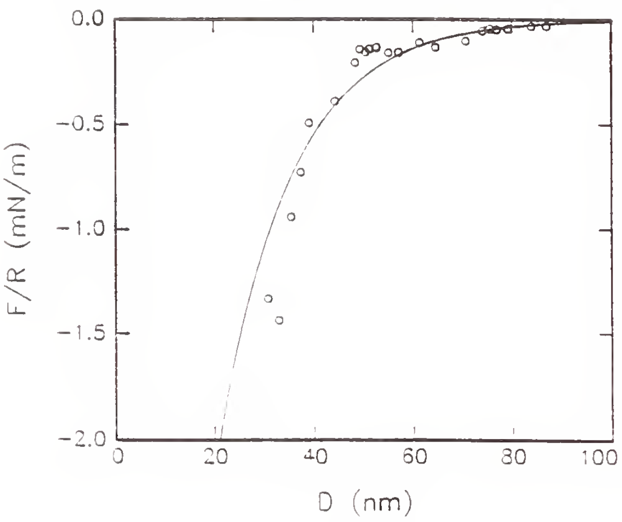

Figure 5. When a chemical treatment is used to coat the silica surfaces with a monolayer of hydrophobic material before immersing them in water, the surface force changes dramatically. Instead of a double-layer repulsion, we now measure a long-range attraction called the *hydrophobic force* (o), and a strong adhesion at contact. The hydrophobic force is much stronger than the van der Waals attraction, and so far it defies any theoretical explanation. The solid line is simply a guide to the eye.

Now we see nothing but an attraction at quite large distances. The two silica surfaces, which have no more than a monolayer of hydrophobic material on them, are now attractive at all separations, whereas bare silica surfaces repel each other at all separations. We have turned night into day with a very simple chemical treatment of this material.

This is not a van der Waals attraction. The van der Waals attraction would be right up in the top left corner of figure 5, one or two orders of magnitude weaker than the measured force. The solid line is just a guide to the eye. It happens to be an exponential curve, but it has no theoretical basis at all for the simple reason that there is no generally-accepted theory of this force. The force—dubbed a *hydrophobic attraction*—was unknown a decade ago, but has now been measured in several different systems [5]. It is a very dramatic effect, completely outside the bounds of DLVO theory, and totally lacking in any explanation right now.

— — —

As well as silica we also have available to us some thin single crystals of sapphire which we can use to make these force measurements. Sapphire is interesting because at a neutral pH or low pH it has a positively charged surface in water, whereas at high pH, i.e., alkaline conditions, it becomes negatively charged. Silica is negatively charged except under extremely acid conditions. Thus, if we measure the force between a piece of sapphire and one of silica at approximately neutral pH, the surfaces are oppositely charged and so they attract [6]. This is illustrated in figure 6 (lower curve) for a pH of 6.5. However, when the pH is increased to 11, the sapphire surface becomes negative. The force becomes repulsive (upper curve in figure 6), and it also becomes shorter-ranged due to the higher concentration of ions at pH 11. This demonstrates once again that we can make a dramatic change in the force between two materials, this time affecting their surface properties by making a very simple change in the surrounding medium.

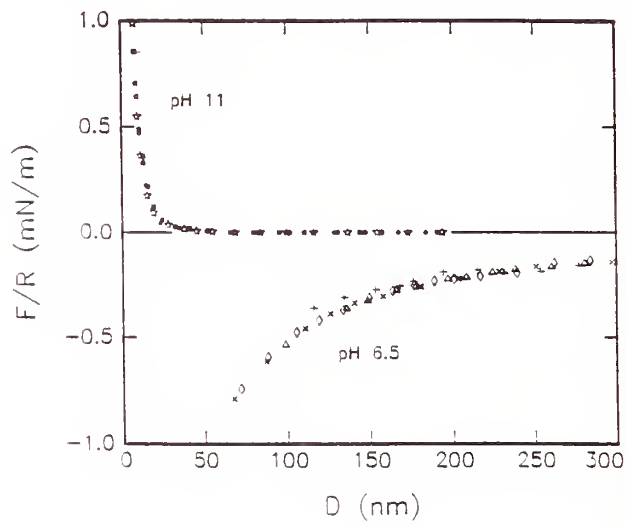

Figure 6. The electrical double-layer force between two *different* materials immersed in water, in this case *silica* and *sapphire*, can be either repulsive or attractive. Under alkaline conditions (pH 11, upper curve) both surfaces are negatively charged and so the force between them is repulsive, whereas in neutral or slightly acidic conditions (pH 6.5, lower curve) sapphire becomes positively charged (silica remains negative) and the double-layer force is attractive [6].

— — —

Now, I want to show you something entirely different, which is that the same apparatus can be used to measure *dynamic* forces. The procedure is to measure the rate of approach of the two surfaces as they are driven towards each other. The rate is affected by the viscosity of the medium between them, because there is a hydrodynamic force between the surfaces when they are in relative motion. It turns out that the hydrodynamic drag becomes progressively stronger as the surfaces approach contact.

The experiment involves driving the remote end of the cantilever spring carrying the lower surface (see fig. 1) upwards at a constant speed. If there were no viscous fluid between the two surfaces, then the surface separation would follow the dashed line shown in figure 7. With hydrodynamic drag, the approach of the surfaces is slowed down, to an extent that can be calculated from classical hydrodynamic theory. The hydrodynamic prediction, based on assuming that the liquid has a constant and uniform viscosity throughout its thickness and obeys no-slip boundary conditions at the solid-liquid interface, is shown by the solid line in figure 7.

Figure 7 also shows that experimental data for two silica surfaces separated by water conform to that prediction extraordinarily well [4]. The conclusion is that the hydrodynamic model and the assumptions on which it is based remain valid even down to very small separations. In particular, the viscosity of water shows no departure from its bulk value even in films as thin as 3 nanometers. Earlier experiments using mica surfaces separated by a silicone oil [7] revealed the liquid film thinning one molecular layer at a time when the film was only a few molecular diameters thick.

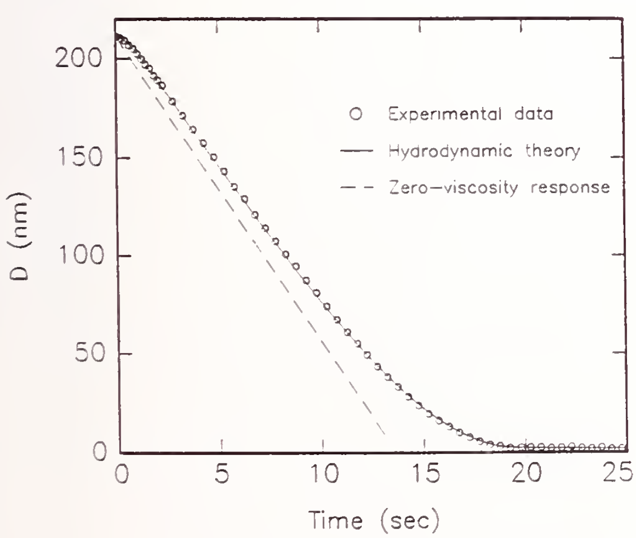

Figure 7. Dynamic forces can be measured by monitoring the rate of approach of two surfaces when the remote end of the spring bearing the lower surface (see figure 1) is driven at a constant speed towards contact (dashed line). Because of viscous coupling between the surfaces, the surface separation actually lags behind, by an amount that can be predicted from classical hydrodynamic theory (solid line). The measured response of two silica surfaces separated by a thin film of water (o) follows the theoretical prediction almost exactly [4]. This supports the validity of the hydrodynamic model, including the assumption that the *viscosity* of water remains constant and independent of film thickness, even when the film is only a few nanometers thick.

In the last part of my talk I want to discuss some measurements of adhesion. The same apparatus, designed to bring solids together and measure the forces between them, is capable of measuring two quantities related to adhesion. The first is the maximum force required to pull two materials apart, called the *pull-off force*. The second is the total work required to pull the materials from contact to a very large separation. That is called the *work of adhesion*.

For two sheets of mica in dry nitrogen gas, we would typically measure a pull-off force of 12 millinewtons. (Do not be too concerned about the absolute numbers because our interest here is in the relative values.) Silica-silica contact gives a similar pull-off force (9 mN). The work of adhesion is about 0.1 joules per square meter of surface for both of those materials. Given that similarity, what do we expect if we bring one surface of mica up to one surface of silica and then pull them apart? The first guess would be that we are going to get a comparable number. What I am going to show you, however, is that we measure something quite different.

The top curve in figure 8(a) shows the force between a sheet of silica and a sheet of mica in an atmosphere of dry nitrogen gas, measured as the two materials approach for the first time. The only force is a van der Waals attraction, which is rather small on this scale, but it is enough to pull the surfaces into adhesive contact (corresponding to a minimum in the force at zero separation). A certain force is then required to pull the two surfaces apart. If they were two sheets of silica that force would be at -9 on this scale; if they were two sheets of mica, it would be at -12. However, in the silica-mica experiment the force required to pull the two out of contact is way down at -67 millinewtons (fig. 8(a), lower curve). Furthermore, there is a rather long-ranged attractive force persisting even when the materials are far from contact (up to several micrometers, which is a much larger separation than we usually encounter in surface force experiments, e.g., figs. 3-6). Clearly, there is a dramatic hysteresis in this system between bringing the surfaces towards contact and separating them again, and the pull-off force is much stronger than it is between either of the materials paired with itself [8].

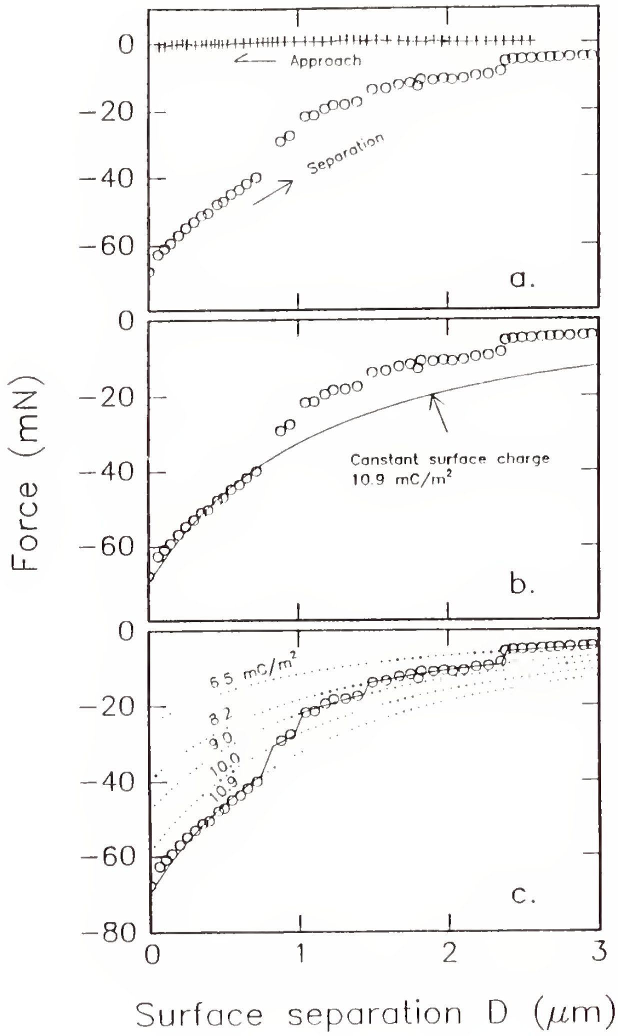

Figure 8. Forces measured between dissimilar materials, *mica* and *silica*, in an atmosphere of dry nitrogen gas [8]. (a) On the first approach to contact there is very little force between the two surfaces (+). However, after contact, the force measured during separation (o) is a very strong, long-ranged attraction. The force is attributed to electrostatic attraction following contact charge transfer between the dissimilar materials. (b) shows the same separation data, together with the electrostatic force calculated for our experimental configuration, with two surfaces each bearing an equal and opposite charge. Part (c) shows that the full set of data can be fitted by a *sequence* of curves calculated for successively smaller charge densities (dotted lines), separated by abrupt transitions from one charge to the next at certain distances. Electrical *discharges* across the nitrogen gap were observed at the same distances.

Where does this large post-contact force come from? We soon discovered that what is happening is a transfer of electrical charge from one material to the other when they are in contact. This is the same phenomenon that gives rise to static electricity, and from these measurements it appears also to be a very significant factor in determining the adhesion between dissimilar materials.

We built two small *in situ* electrometers into the surface force apparatus to measure the amount of charge transferred between the two materials [9]. The electrometer measurements showed, first of all, that the charge is equal and opposite on the two surfaces when they are separated. Silica acquires a negative charge, mica becomes positive, and the charge densities are in the range of 5 to 20 millicoulombs per square meter of surface (or one electronic charge for every 8–32 square nanometers), which is quite a high charge density.

Since we now know that opposite charges reside on the two materials as they are separated, it is clear that the strong, long-ranged attraction is an electrostatic force. We can then proceed to make a prediction of how the force should vary with separation, using an appropriate model of the experimental configuration.

The result is shown in figure 8(b), where the solid line shows the distance dependence of the force predicted for a constant charge on both surfaces of 10.9 millicoulombs per square meter, which is within the range measured with the electrometer. You can see that it gives a reasonable account of the data at comparatively short distances. However, it does not do so well at longer distances. Why not?

Close examination of the "separation" data in figure 8(a) or (b) reveals certain places at which the curve is not smooth. Those regions do not correspond to poor data or to random noise. In the experiment we actually observed that the attractive force decreases abruptly at certain separations (0.75, 0.97, 1.44 and 2.36 micrometers, in this case). With the electrometers, we also observed sudden reductions in the amount of charge on each surface at precisely the same separations. We concluded that *discharges* occur at these distances, and certain simple tests have shown that the discharges occur across the nitrogen gap between the two materials. The discharges are evidently only *partial*, in that only a fraction of the surface charge disappears each time. The most important thing to note is that the discharges only occur when the gap increases to about a micrometer, and not across smaller gaps [8].

Taking these discharges into account, it is possible to fit the entire set of force data with a *series* of constant-charge curves, as shown in figure 8(c). Each of the dotted lines in this figure is a curve of the type you have already seen in figure 8(b), but each corresponding to a different surface charge (as indicated on the figure). The solid lines are sections of those curves, joined together at the discharge separations. Thus the force corresponds to surfaces separating initially with a fixed charge, then the charge dropping abruptly to a lower value, separating a bit further at that fixed charge, dropping to the next lower value, and so on. In this way, we can get a very nice description of how the force is decreasing with separation.

One of our main interests is to know what the work of adhesion is. How much did it take to pull the materials all the way from contact out to a very large separation, given that we have a large force and rather large separations compared to the normal surface forces that we are accustomed to measuring? The total work is just the area between the $F = 0$ axis and the solid line segments in figure 8(c). Computing that area from $D = 0$ to 3 micrometers gives a value of more than 6 joules per square meter; the value would be greater if the integration were continued beyond 3 micrometers. As shown in table 2, this value is much larger than typical values for work of adhesion measured between two surfaces of mica or two surfaces of silica under the same conditions. In fact, it is comparable to the *cohesive* strength of mica, or of silica (1–2 and 8.7 joules per square meter, respectively).

Table 2. Measured adhesion between smooth solids brought into contact in dry nitrogen gas

	Mica-mica	Silica-silica	Mica-silica
Pull-off force (mN)	12	9	67
Work of Adhesion (J/m^2)	0.11	0.08	>6

The adhesion between mica and silica is clearly much greater than the adhesion of either material to itself. The reason is that electrical charge transfers *spontaneously* between the two materials when they are in contact, and we suggest that this will be a general phenomenon occurring between dissimilar materials. No systematic charge transfer occurs between two surfaces of silica or two of mica.

It is worth noting that the total work of adhesion depends on the series of discharges that occur as the materials are separated. About half of the work has been done by the time the first discharge occurs, so even if the exact sequence of discharges varies, the adhesion is still substantial. We are currently exploring the discharges in more detail, and their dependence on the environment. In particular, we would like to know how the discharges (and adhesion) are affected by humidity, which is well known to reduce static electrical effects.

I have shown you three samples of our work. In the first, my main point was to try and demonstrate to you how the surface force can be affected by a liquid environment between two materials and by surface treatment of the materials. Our interest in this is based largely in colloid science, in controlling how a colloid behaves, and in particular in controlling the stability of colloids. I also showed you a sample of some novel measurements between dissimilar materials. These are of interest for heterocoagulation, where the particles in a mixed colloid (having two or more different types of particle present) might stick to each other but not to themselves, for example.

The second sample was just a brief illustration of the fact that we can measure dynamic forces resulting from liquid viscosity. We can investigate whether hydrodynamic theory works in ultra-thin liquid films, and we can measure the viscosity of those films. If the hydrodynamic theory does break down, we can explore the flow mechanisms that occur when the films are down to molecular dimensions. These studies have obvious applications in lubrication, and in understanding flow through porous media. In the future we will extend them to more complicated liquids, and also to experiments in which the two surfaces are moved laterally over one another to explore friction and sliding lubrication.

The final sample concerned adhesion between dissimilar materials. Here we observed spontaneous contact electrification, and saw that it resulted in a very large work of adhesion. Some interesting discharges across narrow gas gaps were observed, and we are very interested in studying those further. We think that these measurements could have significant implications for interfacial bonding and fracture. Our observations could be particularly important in the areas of electronic materials and electronic packaging, because they concern the interplay between adhesion, charge distribution and possible discharges, all of which are important considerations in these areas.

Overall, what I have tried to show you is some work which is quite basic in its approach. We try and understand the fundamental mechanisms of surface forces, where they come from, and how they are effective. However, while basic, the research does not remain aloof from the real world. If we can understand the fundamentals, then we can start to control surface forces. With control of surface forces we will be able to control certain processes and, ultimately, properties of materials. That is the current state of the art in colloid science. I think the same approach will soon be followed in other areas of materials science. And, as I stated at the start of my talk, there are many, many different areas all around us where surface forces have a major role to play. That alone gives us ample reason to continue studying them.

And now, to see how much progress has been made in understanding and applying our knowledge of surface forces to produce better materials, I suggest we adjourn the morning session to investigate some of the colloids that are served in the NIST cafeteria.

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Predicting Fire Hazards to Building Occupants

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Chief, Fire Measurement and Research Division

I'm going to show you some of the progress we've made in establishing an organized body of knowledge, which we call fire science, and how this technology benefits both American society and American industry.

As John Lyons mentioned in his opening remarks yesterday, the Bureau of Standards goes back to 1901. Our involvement in fire research goes back almost that far, to 1904, when a fire erupted on the west side of the City of Baltimore and spread steadily to the east, destroying some 25 percent of the city (fig. 1). It finally was stopped by the local fire department, while the fire departments from surrounding cities and counties stood by and watched. They had arrived at the scene with their equipment, but their hoses wouldn't connect to the Baltimore City water supply.

Shortly thereafter, the Bureau was asked to develop standard threads so that one could make adaptors for connecting foreign hoses to local water supplies. It turns out this played a significant role in eventually controlling the large Berkeley Hills fire just a few weeks ago.

Since then, there have been a number of pieces of legislation which installed at this location a variety of duties involving various aspects of fire, the latest of those being the Fire Safe Cigarette Act of 1990.

While the history of fire studies at NBS/NIST goes back to some fairly routine determinations some 87 years ago, the scientific quality of the work required to do the more recent legislative challenges has been

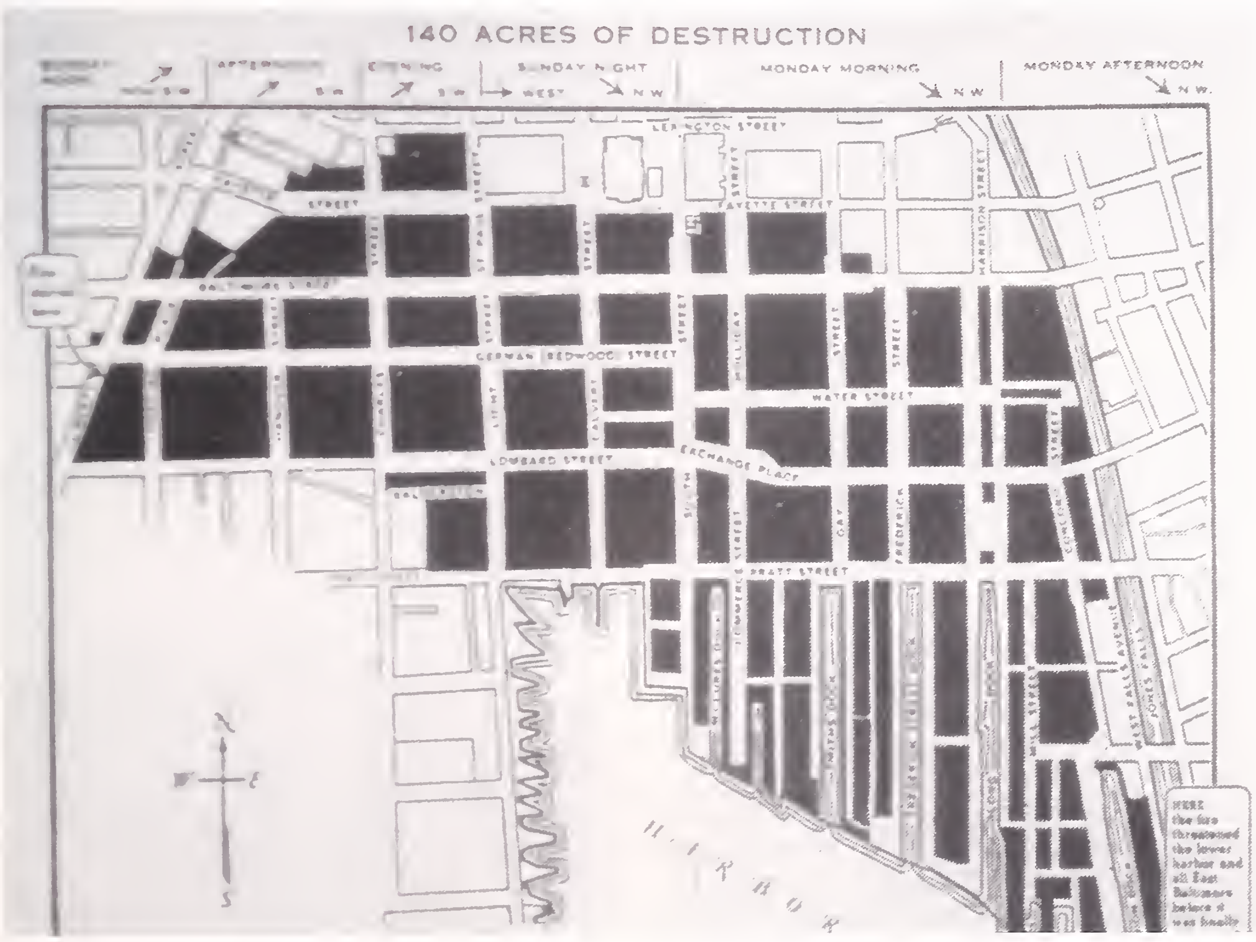

Figure 1. Fire in Baltimore, MD, in 1904. The fire spread from the west side of the city (left) to the east. Reprinted with permission from the National Fire Protection Association [1].

remarkably higher, and I'd like to give you a flavor of some of that today.

At this point the NIST organization is, in fact, the main source worldwide for new science and methods for understanding the phenomenology of fire.

The reason for the continued legislative activity is that the costs of fire in this country are extremely high. In 1990, over 4,000 people died and 125,000 were seriously injured [2]. To put this in perspective, during the course of the Vietnam War more people died and were injured in fires stateside than were killed or injured in combat.

The other component of the profile is even more startling. A recent survey of the totality of fire costs and losses showed that annually we ring up a burden on the economy of $128 billion or so (Table 1). In remarks at a meeting of the National Fire Protection Association, John Lyons pointed out that this is approximately 2.5 times the total world semiconductor market. One could also say that this amounts to a savings and loan bailout every year.

Table 1. Effects of fire on the U.S. population [3]

ANNUAL ECONOMIC COSTS OF FIRE ($ Billions)	
Losses	31
Insurance Premiums	6
Fire Service	43
Preventative Measures	48
	128

For industrial firms this takes a variety of different forms. Obviously there are direct losses—plants destroyed, stock damaged and so forth. Inevitably, when there is a fire of even modest size, immense amounts of litigation ensue and, in the course of that, enough mud gets slung back and forth so it's not uncommon for the firm involved to also suffer a loss of public image, which often has a negative impact on sales in the future. There is certainly a loss of competitive position while a firm gets back on its feet again, and there are documented cases where, as a result of single fire, even medium-sized companies have been forced into total bankruptcy [2].

Perhaps the best example of this kind of industrial deterioration comes from a fire about two years ago in Pasadena, Texas, in which a high-density polyethylene plant went up in flames—a plant that produced approximately one-fifth of the nation's output of that material. The direct fire losses for that were of the order of $750,000. The total cost, some of which includes the fact that the owner of the plant had to give away certain proprietary information to its competitors in order to meet their customers' needs, the total cost is estimated to run upwards to the order of $3 billion. That's a single incident.

There are multiple contributions to this kind of fire loss. The first is the design of the building. Figure 2 presents a dizzying view from the top of the Empire State Building looking down the side, and the crunched-up foreign object you see is a B-25 bomber that on a foggy day in 1945 parked itself in the 78th and 79th floors, dumping over a thousand gallons of aviation fuel. The fire that resulted was incredibly intense, but because the Empire State Building is built of what we refer to as fire-rated, or fire-resistive, construction, the fire was contained and there was limited loss of life. The rest of the building resumed business shortly thereafter.

By contrast, much more recently, there was a fire in the Dupont Plaza Hotel in San Juan, Puerto Rico. The fire resistance barriers were not present in all places. The fire spread quite rapidly and there were 96 fatalities (fig. 3).

Compliance with the general guidelines for fire-resistive construction, the basis for which was done here at NBS, at the old Van Ness Site, isn't enough.

In 1946, there was a classic example of a hotel fire, the LaSalle Hotel in Chicago, which met all the fire-resistive construction requirements. However, the fuel-loading of interior finish materials was sufficiently high that despite this kind of highly efficient evacuation, some 61 people didn't get to evacuate (fig. 4).

Figure 5 is a nighttime picture of the First Interstate Bank Building in Los Angeles in 1988. It provided a beacon that could be seen for long distances. This fire erupted on the 12th floor of the building. The main fuel for this was the furnishings and the building contents—the work stations, paper, et cetera. This fire was sufficiently intense that it blew out windows on the 12th floor and spread through the outside to the next, and the next, and the next floor, before it was finally controlled.

Add to these physical factors the human behavior aspects—that is, the actions that people take or are able to take—which often affect survivability, and one has an extremely complex process to be mitigated. And yet it makes good sense, in hindsight in 1991, that if we could predict the outcome of a fire, for instance in this room, and the changes in the outcome of that fire that might result if we made some changes in this room, we would, in fact, be in an ideal position to make intelligent decisions that would reduce the losses and reduce the burden, both on the occupants and on the commercial entities involved in the structure.

Figure 2. Crash of a B-25 bomber into the Empire State Building. Reprinted with permission from NFPA [1].

The technique for making these analyses we refer to as "fire hazard analysis," in which is included fire hazard modeling. As recently as 1988—that's 3 years ago—top-line professionals in the fire protection community were not making decisions to move ahead with this, because "it was a technology that would not be available until the next century." Approximately 1 year after those pronouncements were made, NIST released *Hazard I*, the first computer-based fire hazard assessment methodology [5]. It was developed by a team here within the Building and Fire Research Lab. It was recognized worldwide very rapidly. Over 400 copies are now in distribution around the world, and that work has been recognized by the award of a Department of Commerce Silver Medal for the team.

As complex as it is—and the complexity of the phenomena in this rivals the complexity of the analyses for the safety of nuclear power plants—this type of analysis is runable on a desktop computer.

The response to this has been remarkable. The EC-92 commission, putting together the unified fire criteria for the European Community, perhaps in 1992, perhaps at some later date, set an early goal that all fire tests selected should be consistent with fire hazard analysis and should provide the data needed for that kind of modeling.

The Japanese Building Research Institute of their Ministry of Construction has also established such a policy and even some procedures.

The Australians are moving in a similar direction, and other countries are also moving likewise. This is, in fact, the way of the future.

What we have, then, is a complex new technology that combines the elements of fundamental understanding of fire phenomena with some engineering-based estimation and the most modern of computerization techniques in modeling of those phenomena. It's going to allow us to move from a situation like the one shown in figure 6, where we have a sofa just barely ignited, developing to

Figure 3. Dupont Plaza Hotel fire, San Juan, Puerto Rico. Reprinted with permission from NFPA [4].

Figure 4. LaSalle Hotel fire, 1946, Chicago, IL. Reprinted with permission from NFPA [1].

the condition shown in figure 7, and being able to predict the outcome and the impact of this degree of complex burning.

In laying out what a fire hazard model or fire hazard analysis entails, let's first take a quick look at the kinds of hazards that we're interested in.

The first and the most obvious is that which results from heat—burn injuries, buildings being burned to the ground, and so forth. In reality, however, some 70 percent of fire deaths result from the inhalation of smoke and toxic gases, a very interesting result that was established not that many years ago by a team from the Johns Hopkins University Applied Physics Lab based on an extensive study of State of Maryland fire fatalities. There have been other studies elsewhere in the world that have confirmed that general conclusion [6].

The smoke that's produced not only has this potential impact on people; it also has potential impact on things. Imagine a warehouse full of electronic equipment being blanketed with a very permeating smoke that has an acid character to it and a lot of warm moisture. It's not too hard to imagine that there could well be significant damage to electronic components, connectors and so forth.

In addition, the smoke, by dint of the very blackness that we saw in figure 7, provides a barrier to people getting out of buildings and also to the fire service coming in to do their job at locating the fire and quenching it.

The prediction of these kinds of hazards requires a systematic approach so that various people—corporate entities, regulators, scientists and building and product specifiers—all use the same approach towards reaching their decision as to what constitutes a worthwhile thing to do, a worthwhile product to buy, or a worthwhile product to sell.

And so, working with our colleagues, we have arrived at a four-step process.

The first step is to be very explicit about defining the problem that you're interested in. For the sake of discussion let's presume that I'm a manufacturer of upholstered furniture, and I'm interested in whether or not my new design is going to be sufficiently less fire-prone and contribute sufficiently less to a fire, should there be one, that in fact it's worth selling as such a product.

Figure 5. First Interstate Bank Building fire, Los Angeles, in 1988.

Figure 6. Sofa igniting (far right). NIST photo.

Figure 7. Same sofa with developed fire. NIST photo.

I've now defined the kind of problem that I'm interested in, in my terms. I now have to define it in terms that allow me to do this calculation. Where are my chairs going to be used? Auditoriums? Homes? Hotel rooms? Office buildings? Who are the people who are likely to be there? Are they likely to be awake, asleep, handicapped? At what time of day might I expect these fires to be present and to be of serious concern? (Obviously some office buildings, not like the laboratories at NIST, are unoccupied at night.)

Having now defined my problem and the situations that I'm interested in, I now proceed to the software, the equations, and I calculate the outcome of the fires for the products as they exist now and my comparative product that I'm either dreaming of or that maybe I've worked up in my pilot area.

Having done that, I now compare the results and I'm in a position to make a decision. The decision may be to go ahead, or it may be to drop this whole idea.

Now, it sounded very simple to just calculate the outcome of the fire. In fact, that is a massive undertaking if one tries to do this by hand. The software, which combines the best in fire phenomenology to date with some truly innovative computational techniques and some pretty nice graphics, requires that one do a certain amount of input to represent the fire phenomena.

Figure 8 is a pretty simple sketch. We've got, at the bottom right of this figure, some fairly benign flows coming in, but they still have to be treated quite accurately. The fluid mechanics change abruptly when one gets in the vicinity of the flames; and when one gets into the post-flame region, there is an immense amount of chemistry going on. The effect of the turbulence on that chemistry, at this point, is known to be important, but we don't know how to do it.

Down at the bottom of the figure we've got this fuel that's represented by a funny-looking arrow. There are real materials that are burning down there, and that has to be represented somehow in this computation.

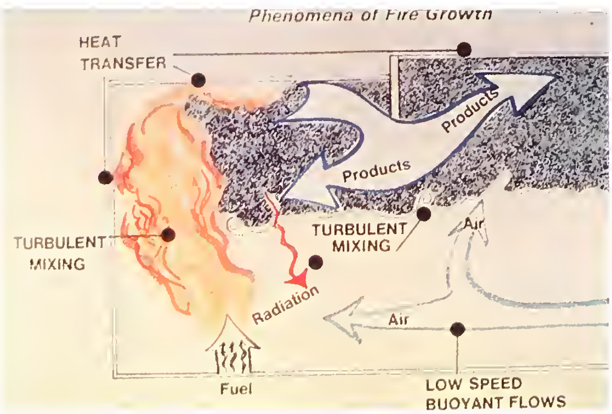

Figure 8. Preliminary sketch used for input to computerized fire analysis software.

While all this is going on, the temperature field under which the chemistry takes place and under which the fluid mechanics takes place is also changing. There are radiative losses, there are convective losses to the walls, and in some cases even conductive losses.

Therefore, to do this computation, one has to enter a description of the enclosure and, of course, the occupants who might be nearby. One has to describe at the beginning what the fuels are, where they are, and then compute as a function of time the fire growth, as the first item burns, perhaps spreads to the second, and so forth. One has to be able to compute the smoke and heat that are generated and how and where they move to, and then the impact on people.

Now, that list is overwhelming. That's a huge amount of both science and in some cases straight-out guesswork. But our capabilities over the last few years have grown remarkably. We're now in the position where we can predict a wide variety of aspects of smoke and heat movement throughout the building, and I'm going to show you some examples in a few moments. In those cases where the airflow into the fire room is insufficient for the combustion to go to completion, we have ways of approximating that vitiated burning. We can handle the rate of enthalpy transfer within the room. We can model what happens to the smoke particles after they leave the flame and as they change character when they move further and further away and cool off. And thanks to some excellent work done under grant by staff at the University of Washington, Seattle, we have a set of guidance rules for how families will behave when a fire hits their residence. And yet this still isn't enough to do the kinds of prediction that we want to be able to do. We want to be able not only to predict the course of the fire in its detail, but we also need to be able to predict what happens when you try to intervene. What happens when the sprinklers activate, and so on?

Let me give you an idea of some of the kinds of insights that are being worked on now to provide some of that future capability.

By far, the most important thing to a material or product manufacturer is to be able to predict how his product is, in fact, going to behave were it involved in a fire. Figure 9 is the output of some work by Takashi Kashawagi and his group in which they've determined what happens experimentally to the rate of flame spread as one starts to change the specific properties of the polymer, in this case the molecular weight [7].

Concurrent with that, Mark Nyden is doing some computational molecular dynamics on polymers [8]. Figure 10 shows seven ideally lined-up polyethylene molecules—red carbons, green hydrogens. He has instantaneously heated those, and he gets one of two different kinds of results depending on the chemistry and the specifics of the bonding that he's put into the model. In the upper case you can see fragments flying off into the gas phase very soon after the heat is applied. Those molecules flying off become legitimate fuel for the flames. By contrast, in the lower case, everything is still clustered together and, in fact, the white marked atoms have cross-linked, forming a char and greatly reducing the amount of fuel available for the fire.

We're also interested in and in need of a way of predicting the soot and the smoke. Kermit Smyth and his team have been looking at laminar diffusion flames, monitoring the detailed chemistry and chemical profiles enroute to a full chemical model of how soot is formed in those flames [9]. At some later date, the next move is to superimpose on that the turbulence that we saw in that earlier schematic and determine how that affects the chemistry, both the yields and the types of products coming out.

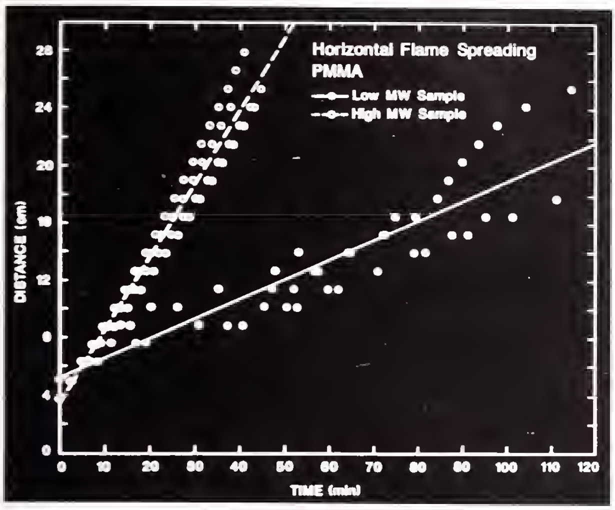

Figure 9. Effects of polymer properties on rate of flame spread.

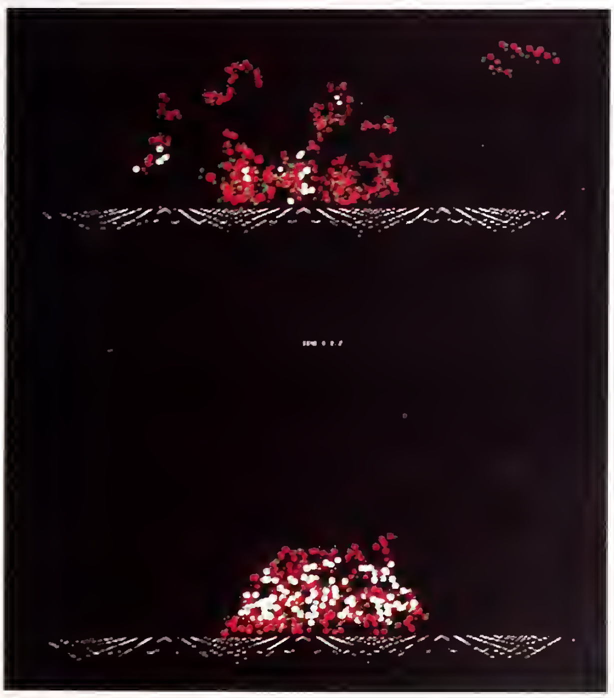

Figure 10. Effects of chemistry and bonding of polymer molecules on fire retardance.

In a particularly interesting paper, George Mulholland, Ray Mountain, and Howard Baum developed a model for the agglomeration of soot as the particles move away from the fire zone [10]. In figure 11 you can see on the right what their model predicts for arrays of small, spherical particles as they stick together. On the left are actual electronmicrographs of soot from an acetylene flame, and the similarity is remarkable.

The modeling that's been done to date generally applies to modestly sized rooms, generally the kind one finds in residences. As we go to larger structures, buildings with long corridors or large rooms, it's important to know how rapidly the smoke front, and therefore the heat and toxic gas front, moves down the corridor. What you see in figure 12 is the result of a collaboration by Howard Baum and Ron Rehm. It's a time sequence of the movement of a smoke plume down a long corridor. The colors represent different temperatures, the hot pink on the left being the warmest smoke and the light blue on the right being the coolest.

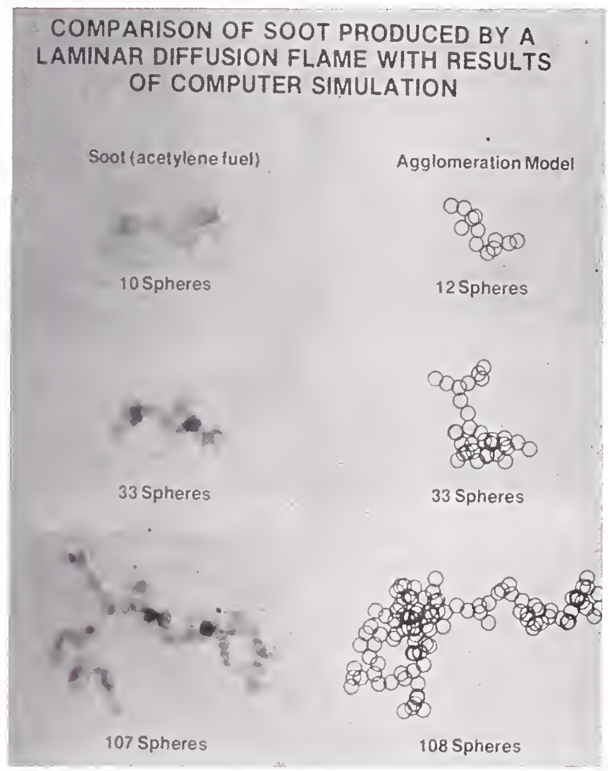

Figure 11. Predicted and actual soot agglomerates.

Experiments under grant from NIST at the California Institute of Technology have reproduced this phenomenon, and the agreement in the rate at which that smoke front moves between the model and the experiments is of the order of 2 percent.

Still on the horizon is a phenomenon that's absolutely essential, and that is, given the fact that we have a room burning like that and the sprinklers come on, how does the fire go out? We know that it doesn't go out

Figure 12. Time sequence showing movement of a smoke plume and temperature change.

Figure 13. Plaza Hotel in Washington, DC, unoccupied at the time, in which fire experiments were conducted.

immediately. But how does it go out? And if we change the way we design the waterspray, or if we substitute some other suppressant for the waterspray, what's the interaction between the suppressant, the flames and the burning combustibles underneath, leading us to be able to predict accurately the efficiency of suppression?

Let's now talk about what we can do—I'll give you some concrete examples—of what the capability of the current hazard modeling is. Figure 13 is a picture of the Plaza Hotel, an unoccupied building at the time, in Washington, D.C., not too far from the Capitol. John Klote and a team ran a series of smoke movement tests in this hotel. They burned a large fuel supply on the second floor, and made measurements at various locations both on that floor and on other floors [11].

Figure 14 is a graphical representation of what the modeling shows, where the different colors indicate different levels of threat. That's just to show you that the modeling, in a time-dependent manner and a spatially variant manner, can be done.

This is the interesting stuff. In figure 16 we have plotted a comparison of the model results and the experiments at three different locations. We're now modeling the temperature. The upper pair of curves is in the room where the fire is. As we get down lower we move successively further away. The bottom curve, which barely departs from the abscissa, is the temperature profile on the seventh floor. Now, the curve shapes aren't perfect. After all, this is a prototype model and there are a number of phenomena yet to be added. But the magnitudes are very pleasantly in agreement.

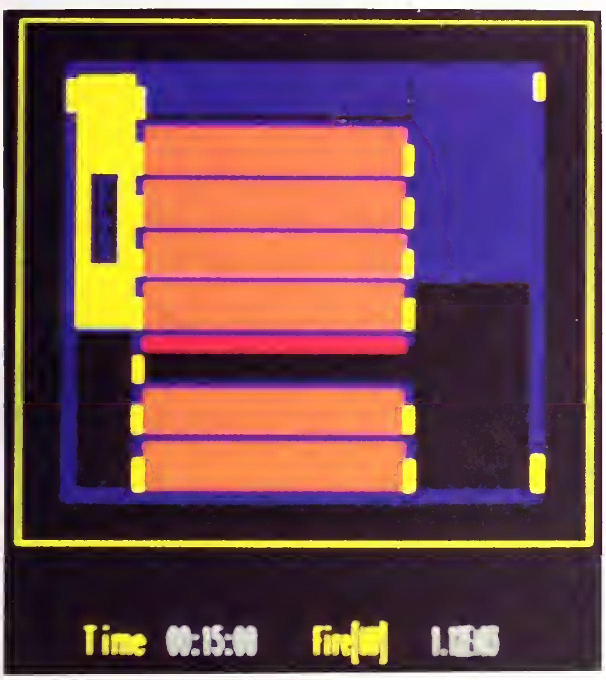

Figure 14. Conditions during the Plaza Hotel fire using a zone fire model. Colors indicate increasing levels of life hazard from blue (none), yellow, orange, and red (on the fire floor).

If we move to something that's even more sensitive, namely the prediction of carbon dioxide and carbon monoxide in those locations, it's once again gratifying that even though there are still some shape differences and some approximations that were made in the modeling, the magnitudes are, in fact, still coming out quite close.

The example I gave at the beginning of this talk on being able to compare a new product versus a currently available product is something that the modeling can also do. In this case we took a chair and burned it on the computer using experimental data representing the properties of that chair.

For the three-room "house," we modeled the carbon monoxide concentration in the room where the fire was, Room 1, and in a room two rooms away, Room 3. We then said, let's model a chair that looks the same but is constructed of materials that produce one-half the heat release and also is less prone to ignition, and one gets the second set of curves.

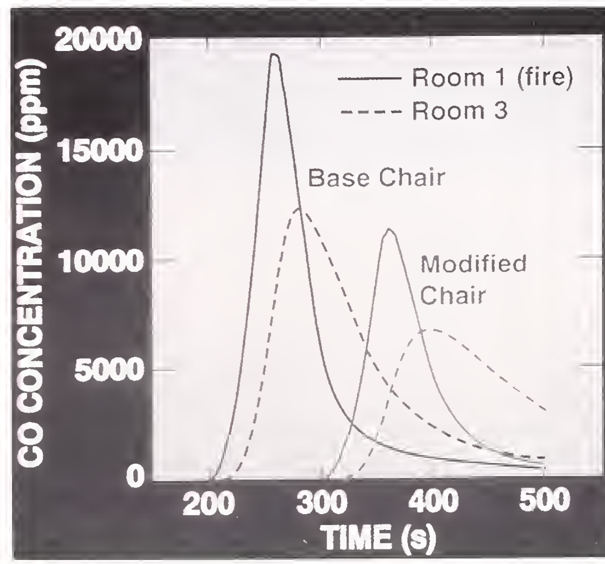

Figure 15. Comparison of modeling results from two locations.

Now, those differences are quite significant. The amount of time available to leave the room of fire origin, in the blue case, is extremely short. The time available in the orange case is quite significantly longer. That's a life-or-death difference.

We're also working with a prototype version of a model for the detailed burning of a piece of upholstered furniture, a chair. Figure 16 is a schematic of what that chair is represented to be. It consists of four panels, if you like, of fabric-covered padding, and the contours you see show the time-dependent evolution of the spread of flame across that chair. On the right-hand side, we've got the rate of heat release prediction that comes from that modeling calculation and some data from our own furniture calorimeter.

Now, I won't claim that all chairs are predicted this perfectly, but even for this chair that is remarkable agreement.

Last in my list of examples, we undertook to try to predict the national fire experience using this kind of fire hazard modeling [12]. I won't go into the details of this. But I think it's quite remarkable that for this

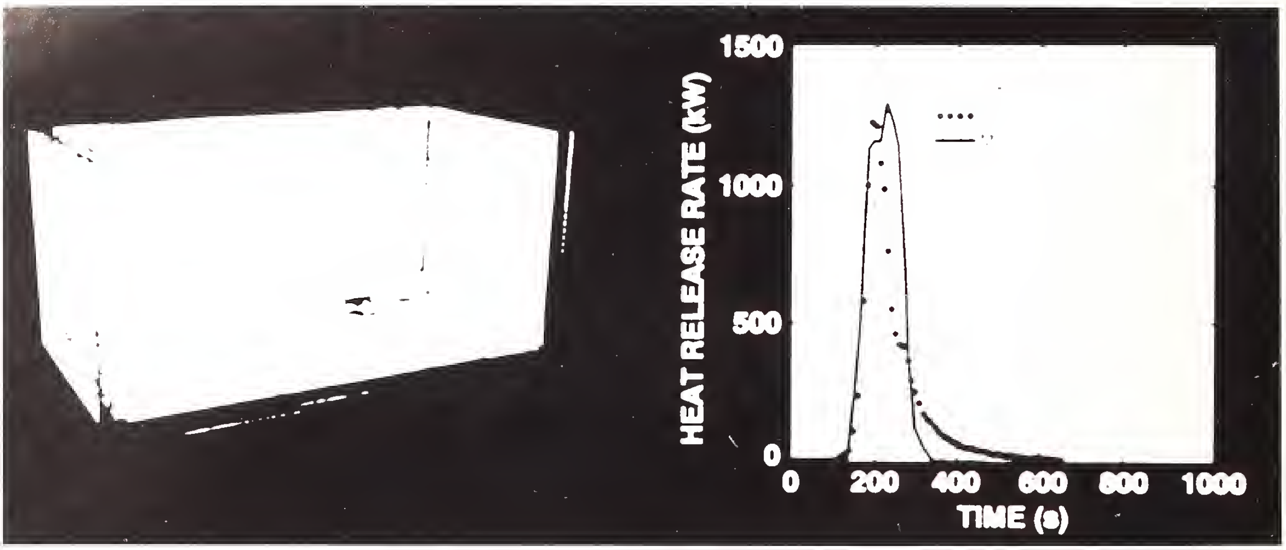

Figure 16. Representation of the time-dependent evolution of the spread of flame across that chair and the resulting rate of heat release.

particular scenario, which is upholstered furniture, in living rooms and bedrooms specifically, when that piece of furniture is the first item ignited the modeling produced an estimate that there should be in this country something on the order of 624 (a little over-precise) fire deaths per year. The actual experience is 643. That is, in my mind, a major accomplishment.

Table 2. National fire experience prediction for upholstered furniture fires: upholstered furniture in living rooms and bedrooms, first item ignited

	Statistics	Model
Total Deaths	643	624
Ignition Type		
Smoldering	498	460
Flaming	145	164
Time of Day		
Night	379	552
Evening	83	20
Day	180	52

The precision that may be implied from the totals is slightly fortuitous, as seen when one breaks down the data both in terms of type of ignition and time of day. But, nonetheless, this is the kind of thing that fire modeling is already capable doing to some degree of approximation, and soon we'll be able to do this to an even higher quality.

Fire science at NIST and in the U.S. has come a long way since the Baltimore fire of 1904. We have identified key components affecting fire initiation and growth; developed new ways of measuring those components; and established that fire models using such data can be valuable for product design, evaluation, and specification.

What lies ahead is even more exciting. Working with industrial partners, we have begun relating the chemical structure of a material to the outcome of a fire. We are probing the interaction between the time of sensing, the nature of suppression, and the level of hazard. We have begun developing techniques for evaluating the impact on a community of a large fire in its midst. As this new understanding emerges, we are using advanced electronic media to make it accessible to product designers and manufacturers, builders, engineers, and government officials, thus making true fire safety an achievable goal for the next century.

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Measuring and Characterizing Computer Performance

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Multiprocessor computers exist for only two reasons: they are either the cheapest, or the only, way to achieve the desired performance [fig. 1]. Throughout the life of our project, we have focused on the problems of performance characterization of multiple instruction, multiple data (MIMD) computers. These are multiprocessor computers in which the individual processors may be following different instruction sequences, and may be working on different pieces of data. This is the most general kind of computer organization. Single instruction, multiple data (SIMD) machines (where all processors execute the same instruction at the same time, but on different pieces of data), and single instruction, single data (SISD) machines (the traditional machine with a single central processor and a single set of data) are simpler to characterize than MIMD machines. Any measurement techniques we might develop could be applied to them as well.

MIMD machines are often split into two major subclasses: tightly and loosely coupled [fig. 2]. In tightly coupled MIMD machines all processors have very quick access to all the data memory. This architecture cannot be economically scaled to large numbers of processors. In loosely coupled MIMD machines each processor has quick access to only the data in its local memory, and much slower access to data local to other processors. These machines can be economically scaled to many thousands of processors, but it is a challenge to fit some applications to them. We have studied the characterization of, and have instrumented, both of these classes of MIMD machines.

The most recent direction in MIMD architecture is the cluster approach, wherein each node contains a small number (cluster) of tightly coupled processors, but the connection between the nodes is fairly loose [fig. 3]. This gives some of the ease of application of tight oupling, and the economical, vast scale-up potential of loose coupling. I know of at least three soon-to-be-announced massively parallel MIMD machines using this architecture. It is clearly a very important architecture for the near future.

Fortunately our experience in both tightly and loosely coupled machines has positioned us to provide measurement techniques for these cluster machines. In fact, some of our techniques have been adopted for the Intel Scientific Computers Touchstone Sigma/Paragon machines being built for the Advanced Research Projects Agency (ARPA). ARPA partially sponsors our project. We are seeking to assist other manufacturers and users.

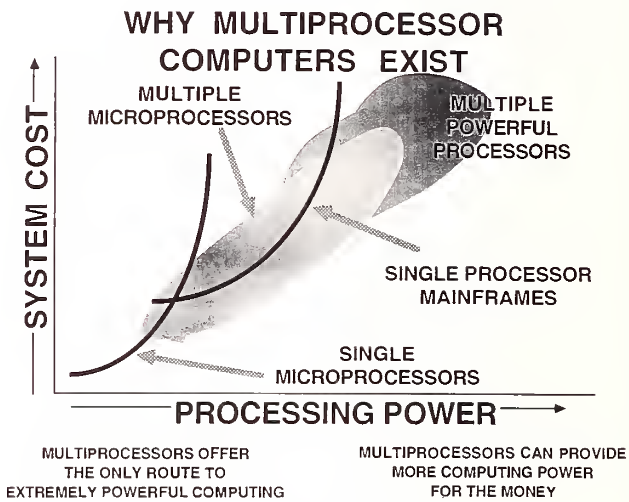

Figure 1. The reason for multiprocessor computers.

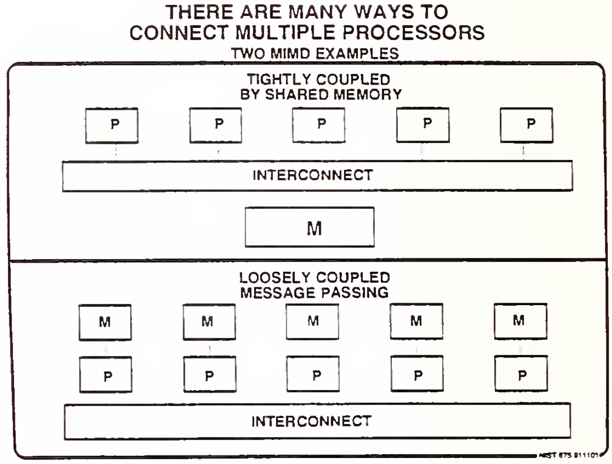

Figure 2. Tightly and loosely coupled MIMD architectures.

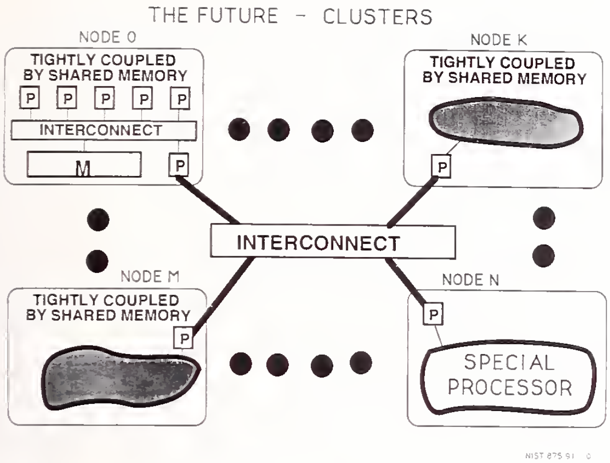

Figure 3. Cluster MIMD architecture.

WHY MEASURE ?

MULTIPROCESSOR SYSTEMS

PROMISE TO BE THE CHEAPEST SOURCE OF

COMPUTING POWER FOR MANY APPLICATIONS

BUT

>> IT IS HARD TO PREDICT HOW MUCH OF THE PROMISE CAN BE REALIZED

>> EFFICIENT USE OF MULTIPROCESSOR SYSTEMS ISN'T TRIVIAL

>> THE ARCHITECTURE MAY NOT FIT THE USE

>> AN EFFICIENT ARCHITECTURE MAY BE POORLY IMPLEMENTED

Figure 4. Why measure?

Why have a computer measurement project? The easy answer is that a fundamental function of NIST has been to support and assist American commerce, industry, and science by providing a system of reliable (standard) measurement techniques. Another answer is that the Federal Government is a very large user of computers, and NIST has a role in making the selection and use of computers within the government more effective. Measurement can contribute to the effective application of multiprocessor computers [fig. 4].

The Steps in Computer Characterization

To characterize a computer system, start with the job you need to do, or a benchmarking test routine, as a stimulus. The computer responds to the stimulus. The measurement system captures and analyzes the computer's response [fig. 5] In order to understand (and extrapolate from) the response of the computer, the characteristics of the stimulus must be known [figs. 6 and 7]. Unless care is taken, ''too much'' data may be taken about the performance of a computer. In other terms, unless you have some model of the tasks the computer accomplishes to perform its assigned work, much useless data will be taken, and this data will obscure the meaningful data. This requires a scheme for characterizing the computing demands of the job, or any job, which can be related to computational resources required to perform the job.

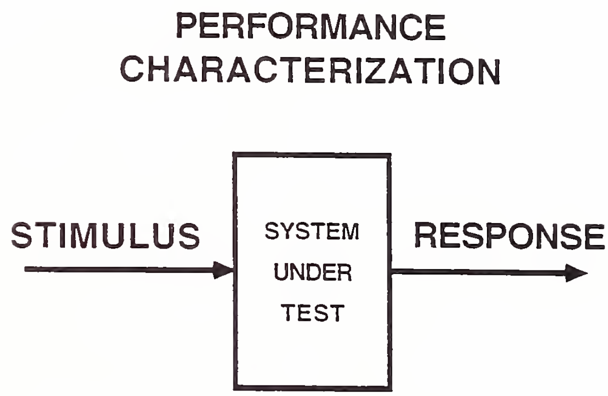

Figure 5. Stimulus-computer-response.

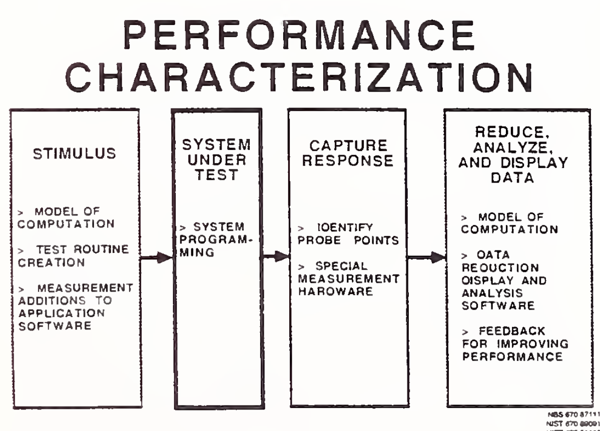

Figure 6. Stimulus-computer-capture-analyze.

BENCHMARK SIZE	IF THE RESULT IS:	
	GOOD	POOR
SMALL	- OK ALONE. BUT WHAT ABOUT COMBINATIONS? -	+ DOESN'T FIT MACHINE. AND YOU KNOW WHY. +
LARGE	+ FITS MACHINE, WHICH CAN DO PRODUCTION WORK. +	- DOESN'T FIT MACHINE. AND YOU DON'T KNOW WHY. -

Figure 7. Large and small test benchmarks.

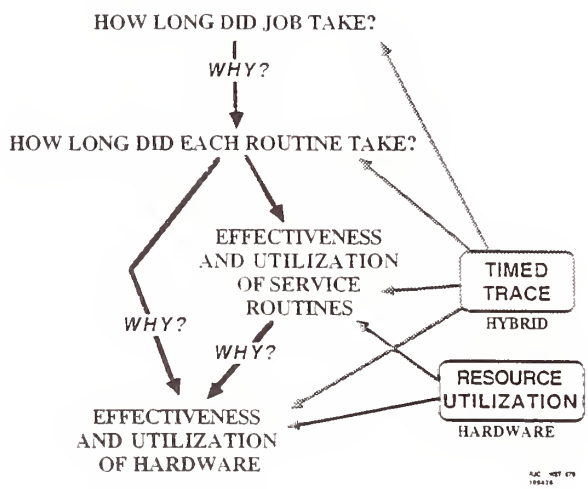

Figure 8. Trace and resource measurement.

But we have a dilemma, since there are no generally applicable units for computer performance and computing demands. The tasks that a computer performs cannot be expressed in normal physical units of force, energy, mass, etc. The only International System of Units (SI) unit that applies is *time interval*. If all jobs were alike, and all computers had the same architecture, we could use millions of instructions per second (MIPS) and millions of floating point operations per second (MEGAFLOPS)—but that is certainly not the real world. There is an almost infinite number of tasks that a computer may be asked to do, and a very large number (still expanding) of computing algorithms. However, there are relatively few types of computers actually built, and a limited number of variants of each type.

Characterization in terms of.....

Applications
> far too many different types,
> new types every day,
> what terms to use?

Machine capabilities
> limited number of architectures,
> stable architectural types.

Use machine **capabilities** to characterize the **demands** of applications.

Figure 9. Characterize in terms of machine capabilities.

The vast variety of jobs that computers are asked to perform can be broken down into intermediate-level computer performance capabilities [fig. 9]. Examples are: results per second doing arithmetic on long vectors, arithmetic on short vectors, inversion of large matrices, inversion of small matrices, string matching, overlapped vector and scalar operations; degree of parallelism; the time overhead and speed of interprocessor communication; and a dozen or so others. We now have a manageable set of computer *capabilities*, though certainly not fundamental units of measure. By actual measurement, using carefully crafted test programs, the performance of a machine can be stated in terms of these capability factors [fig. 10].

The problem is, then, to state the *demands* of the job in these same terms. This, too, can be determined by measurement during execution. Once we have determined both the demand of the job and the capabilities of a number of computers, good estimates of running time can be made for all of them. For example, experience at NIST/Boulder [1] has shown that less than a half-dozen factors can explain roughly 95 percent of the performance variation on the Livermore Loop set of benchmarks on approximately 100 different types of uniprocessor computers. But it is not as easy as this, since some multiprocessor architectures have capabilities that differ so much from others that the whole algorithmic approach to the job must be different. One may be left with the situation of having to characterize a job in terms of two, or more, different sets of capabilities. That is not really satisfying, but at least we have a better-quantified result than earlier approaches [2].

Execution time = $\sum$ (application **demands** / machine **capabilities**)

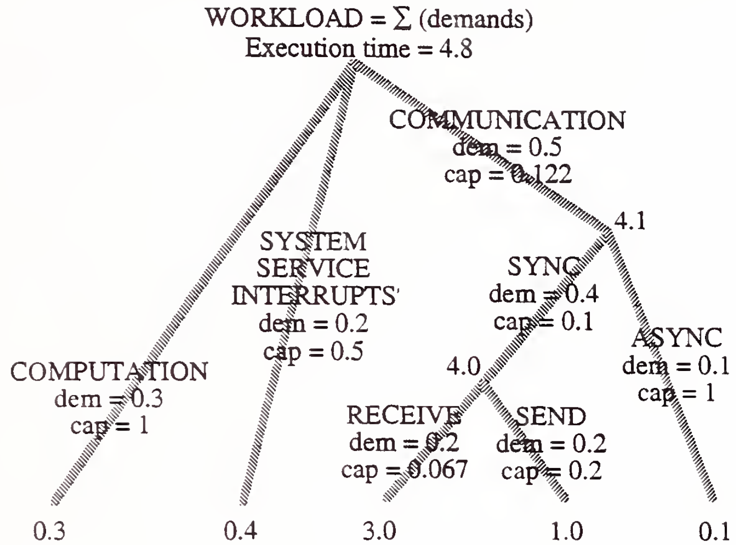

Figure 10. Capability-and-demand tree.

Taking the 'Right' Data

Measurement, in the past, has produced too much data, with few hints as to how to reduce the data to a manageable form. Our project investigates schemes intended to identify quickly the critical computing demands of real programs, with the goal of helping the programmer achieve more of the potential performance from multiprocessor computers. It can also help in configuring these systems, since most allow a building-block choice of components in buying, or allotting use of, the machine. If suitable choices are made, only the "right" measurement data need be captured, and there can even be some data reduction/analysis combined in the capture process.

When a computer is programmed to do a job, the programmer conceives of a sequence of major steps leading to the desired result. Other workers have attempted to express computer performance in terms of compiler source language instructions, but this has required over 100 factors—too many to be comprehended easily. Our approach is to characterize the work of the computer, and the demands of the job, at a higher level which roughly corresponds to the level at which the programmer thinks of program major steps, blocks, or processes. In general, the user always deals with the hardware through the intermediary of the compiler, so that we consider the interface between the user and the computer to be at the compiler source language level.

The expression of each major step may require many lines of computer source code, which is then translated into machine instructions by the compiler. In a single-processor computer, the various major steps are arranged to be executed sequentially, one after the other. The main consideration is that all the required intermediate values must be computed before the next major step is scheduled. Software called a *profiler* provides a report to the programmer of the length of time taken by each of the major steps. On a single processor machine, the execution time required by the profiler software cannot upset operation since no other software is running when it is.

On an MIMD multiprocessor machine, the goal is to do the job faster by running a number of major steps at the same time, each on its own processor. As before, each major step requires the results from other major steps before it can be run. On the multiprocessor machine they are probably on different processors. The data consuming steps must wait for their required input results to reach them. If a program step uses the results from a number of other processors, any change in the time of arrival of these results may change the performance, and even the correctness of the result. One can conceive that results could be delayed so much that a prior result was used by error. The key concept is that the time required by a single processor of a multiprocessor to execute conventional profiling software can seriously perturb the operation from the normal, and may even result in incorrect program execution.

Hardware Assistance for Measurement

The perturbation from execution-profiling measurement can be essentially eliminated by the addition of hardware. A goal of our project is to make this hardware cheap, small, and flexible. In multiprocessor machines, the user needs to know not only how much time was spent in the various major steps of the program, but also the sequence, to assure that the intended order of execution is being followed. Hardware support for event tracing makes this possible. Once the event tracing has been accomplished, the user may need to know what machine resources limited the speed of operation. For this we provide hardware support for resource utilization measurement [fig. 11].

HARDWARE ASSISTANCE TO MEASUREMENT

DETECT "EVENTS" DURING PROGRAM EXECUTION

MEASURE RESOURCE UTILIZATION BETWEEN "EVENTS"

WITH MINIMAL PERTURBATION TO EXECUTION

Figure 11. Hardware assistance to measurement.

The first measure is a trace of events that occur in the execution of the program (the job, the test routine, and major steps in them). The time at which each of these events occurred must also be captured, as well as the spot in the program at which it occurred and the processor being used in a multiprocessor computer. This is one place that the data-quantity can get out of hand. In the past people captured a trace of the execution of individual machine instructions. These come 50 million per second for each of the 1000 or more processors in a large machine, and there may be hundreds of different kinds of instructions. One comes to the conclusion that there must be a better way. Our choice is to operate at a "higher" level, nearer the programmer or source-language program. After all, to a first approximation the user cannot distinguish between the performance effects of the computer hardware and those of the language compiler; neither are user-alterable. The user must accept the compiler-hardware combination and attempt to wring maximum performance from it—or possibly obtain a different hardware configuration or improved compiler.

Our trace measurement approach involves measuring the times of user-specified events. These events are specified at the source-language level, and it is expected that hundreds or thousands of machine instructions will occur between them. This is data which can be used to identify performance at a level of detail which means something to a user. The user can identify the time taken by each subroutine corresponding to a user-defined computational step, time taken waiting for data from another program or processor, etc.

Once the overall picture of the computation has been obtained from the event trace, the user can evaluate means to improve the performance. The algorithms may not fit the architecture—a likely situation in parallel machines. But how? This is where resource utilization measure is needed. There is always some performance-limiting bottleneck. Here again traditional measurement techniques have collected overwhelming volumes of data. Computer resource utilization data often occur at the frequency of the processor clock. There is no hope of individually capturing each "tick" of this data. Some sort of preprocessing hardware is needed. This hardware could accumulate a sum of events, a peak value, or some similar simple measure. The key point is that these involve counting. These counts or tallies should be captured with key trace samples to allow resource utilization to be resolved to specific parts of the computer's work.

Taking event trace data for performance measurement must not be allowed to perturb noticeably the operation of the machine and application being characterized. In an MIMD computer system, the cooperating programs on the various processors must occasionally exchange interim results during program execution. Since the trace measurement events are confined to single processors, the program perturbation from an event must be small to avoid distorting the timing relationships between the cooperating programs. Traditional timestamping and profiling techniques call upon operating system services to capture data. Since these calls involve the execution of hundreds of extra instructions, on only the processor making the call, they can result in serious perturbation to program execution. Similarly, if the measurement data are written into the normal computer memory, they create additional memory bus traffic, and perturb contents of the memory management hardware.

Multikron

For these and other reasons, we have chosen to provide hardware support for event trace measurement [figs. 12 and 13]. When triggered by a single "write" from the executing program, our very large scale integration (VLSI) Multikron [3] hardware chip captures the event, node, processor, and process identification, and a time stamp with 100 nanosecond resolution. To further avoid perturbation to the measurement, the data are collected over a separate byte-wide network. To simplify application in cluster-architecture computers, each Multikron can automatically identify data and process from each of up to eight processors in its cluster [fig. 14].

Our approach to resource measurement involves a number of counters [fig. 15]. Each Multikron contains 16 resource counters which can be individually configured to count external events, clock frequencies, or software events. They can also be individually turned on or off at will. The contents of the resource counters can be collected with all desired trace samples, and thus resolve the accumulated counts to the desired program segments.

The Multikron chip has been designed and simulated by our group at NIST, using standard cells and the Berkeley VLSI design tools [fig. 16]. It was fabricated in 1 micrometer complementary metal oxide silicon (CMOS) through the ARPA MOSIS service. The first prototypes work at least to the 40 MHz clock frequency range.

A Bonus

With the advent of small and inexpensive facilities such as the Multikron chip, routine measurement can be applied to operational process-control computers [fig. 18]. In these systems there is an expected relationship between the offered load and computer response. Routine measurement can monitor for exception situations and provide a profile of events. This log can be used to avoid system crashes if the offered load,

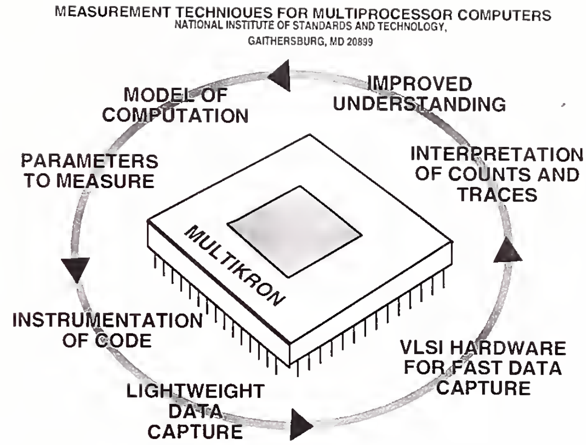

Figure 12. Multikron overview.

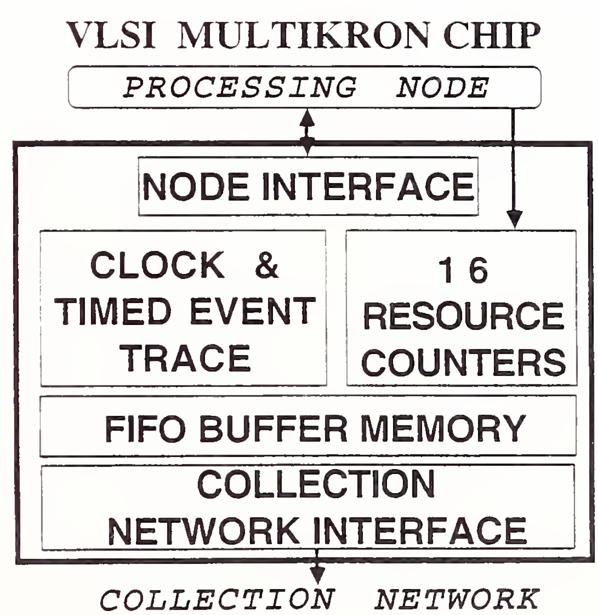

Figure 13. Multikron block diagram.

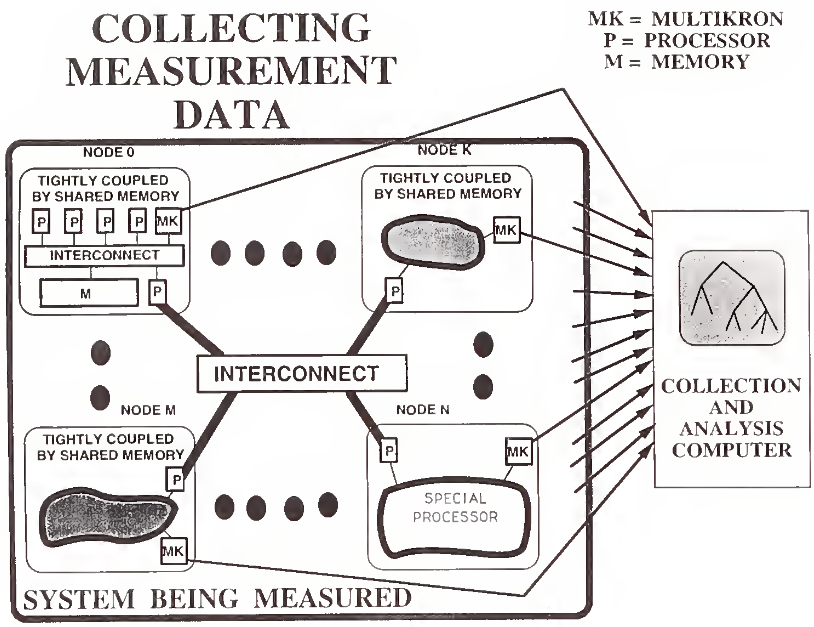

Figure 14. Multikron and collection network.

RESOURCE COUNTERS

PARAMETER	COUNTER 1 (DENOMINATOR)	COUNTER 2 (NUMERATOR)
QUANTITY	COUNT OF EVENTS	
RATIO	ALL EVENTS	SUBSET OF EVENTS
ACCESS LATENCY	NUMBER OF ACCESSES	TOTAL DELAY OF ALL ACCESSES

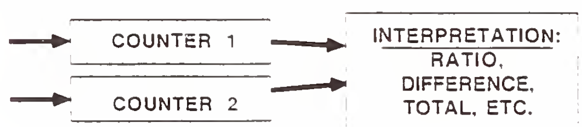

Figure 15. Use of resource counters.

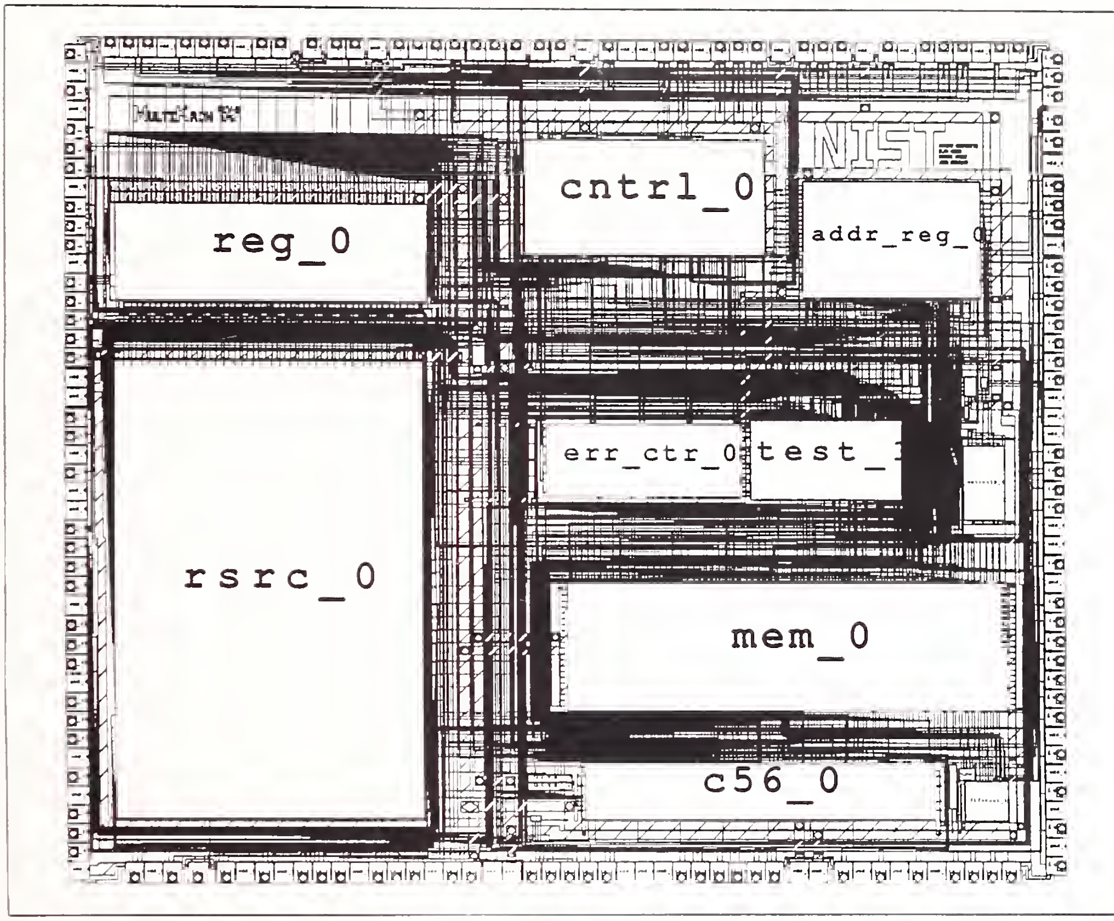

Figure 16. Multikron layout.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
MULTIKRON

OVERVIEW:

ONE VLSI MEASUREMENT CHIP PER NODE CAPTURES DATA NEEDED FOR PERFORMANCE INTERPRETATION.

- HIGH-RESOLUTION, LONG-EPOCH TIME CLOCK,
- TIMED-EVENT TRACING,
- BANK OF COUNTERS TO MEASURE RESOURCE UTILIZATION,
- COLLECTION NETWORK DOES NOT PERTURB SYSTEM.

Figure 17. Summary.

BONUS

LOW-COST, PHYSICALLY SMALL MEANS TO MONITOR OPERATIONAL SYSTEMS TO:

>DETECT BOTTLENECKS & HIDDEN FLAWS,
>ANTICIPATE CRASH SITUATIONS,
>ASSIST POST-CRASH ANALYSIS,
>DETECT MEDDLING AND VIRUSES.

Figure 18. Bonus—system monitoring.

or response, is not as predicted, and it can be used as a diagnostic tool should a system crash occur. Since our approach captures the data on a separate machine, the logged data are not lost during a crash, and the taking of data does not substantially degrade the performance of the system. With our separate-machine data collection, the temptation to turn off measurement data collection to provide more computational power under heavy loads (when measurement is most needed) will not occur.

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Applying Computational Geometry: Robustness vs. Efficiency

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Summarized by Isabel Beichl
Mathematician, Computing and Applied Mathematics Laboratory

Computational geometry is very useful in many fields, but it also presents severe challenges to those working with it. Efficiency and robustness are among these challenges and are addressed in this talk on one of the fundamental tasks in geometry, triangulation.

Triangulation is aimed at simplifying complicated structures. What is triangulation? One can triangulate an object by filling out that object with triangles in two dimensions and tetrahedra in three dimensions. Every part of the object must be covered by some triangle and the triangles must fit together in a nice way, that is they need to meet along edges or vertices or not at all. Usually, you are given what the vertices of the triangles should be.

You can use a triangulation to simplify complicated objects because the individual triangle or tetrahedron is a much simpler object in itself. In the numerical solutions of partial differential equations, people have needed a way to represent complicated objects efficiently, and using triangles and tetrahedra is often expedient. Triangulation has also been useful in giving information about points themselves. If the points were to represent the atoms in some sort of structure, then triangulating those points would give information about where the points were dense or how the points were arranged. Other researchers are interested in triangulation for free Lagrangian calculations, geometric modelling, global climate models, and particle simulations. Recently, investigators at NIST in collaboration with a group at Clark University have been using triangulation in molecular dynamics calculations to study dense, two-component liquids and glasses. The object is to relate the geometric properties of glasses to their dynamic behavior by examining defect structures and "holes." The typical simulation involves 500 particles, and one would like to generate a picture of the geometric structure after every few time integration steps. For this to be a practical possibility the triangulation should require only a few floating-point operations per particle. Now, you might say, "I can find the holes just by looking at the picture," but you aren't given a picture of the points and you would like a more scientific way to look for holes or structures beyond pictures of them. And, in practice, you are only given thousands and thousands of coordinates of points.

On top of this, the robustness of the methods is crucial. If you look at two rays coming out of a point, and if the rays are very long, then a small change in the angle will create a massive distance between the rays far away from the endpoints. Another important difficulty is that it is hard to determine when the answer you get is wrong. Unlike other numerical problems, it is hard to solve these geometric problems in terms of a converging system. So we really need some ways to check ourselves from time to time.

1. How to Triangulate

How could we find the triangles? Naively, we could try all triples of points but if we started with n points, this would at best make us go through a multiple of n^3 steps, written as an $O(n^3)$ algorithm even in 2-D; not a very satisfactory solution. Consider how many steps you would have with 1,000 points. In fact, there are well known methods for finding triangulations in 3-D in $O(n^2)$ operations. Our algorithm is more efficient than this.

In addition, there is still the question of determining that a triangulation is complete and correct. One way to help ensure completeness is to have the triangles enumerated in *shelling* order. This means that we start with one edge and find triangle number 1 and then add triangles successively so that at each stage, the set of already enumerated triangles is always simply connected, which means that you never make a loop. Intuitively, each step of a shelling is a choice of triangle in the triangulation so that no holes or bridges are formed with the set of triangles already chosen. Figure 1 is an example of a triangulation and the numbers indicate a shelling order. Note that if we had placed triangle 44 immediately after triangle 22 it would have made a bridge separating the area containing triangles 23-43. This is illegal. Specifically, a new triangle may intersect previous ones only in something homomorphic to a ball, which in the 2-D case means that it can intersect in one edge or two edges and nothing else.

Shelling has application in physical problems involving a moving front, such as simulation of self-avoiding random surfaces. It also reduces the amount

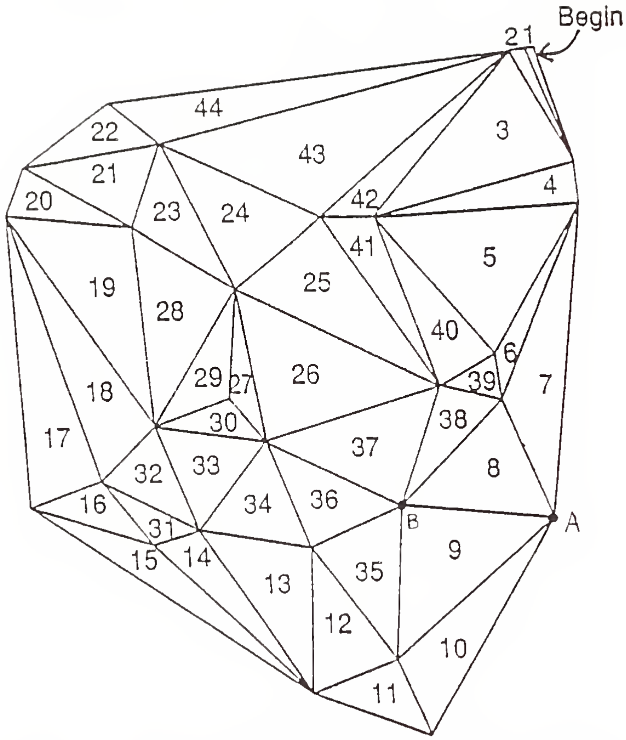

Figure 1. Example of a 2-dimensional triangulation enumerated in a shelling order.

of calculation needed in a sequential version of the algorithm, because we don't need to consider points that are behind the moving front when building new triangles. Among other things, shelling makes it easy to check that there are no more than two triangles coming out of a single edge which would obviously be wrong. Because shelling checks topological properties, it helps to ensure that numerical results are logically consistent. We use it as a check of correctness at every stage of a triangulation.

2. Empty Spheres: The Central Idea

Not all triangulations are the same. We would like to find the so-called Delaunay triangulation. This means that the circle determined by the three vertices making up a triangle contains none of the other vertices. [See *Computational geometry: an introduction* by F. P. Preparata and M. I. Shamos, 1985.]

Here is how we make a single triangle:

Suppose that we already know $\langle a,b \rangle$ is an edge of a triangle and we are looking for the third point, c. We know that if we already had c, the center of the circle determined by $\langle a,b,c \rangle$ would be somewhere on the perpendicular bisector of $\langle a,b \rangle$. (See figure 2.) So we search along the perpendicular bisector for a center of a circle that goes through a, b, and one other point c and that does not contain *any* other vertices in its interior. We start by picking any other point d and calculating ξ, the center of the circle that passes through a, b, d. Then, using a nearest neighbors algorithm, (for the moment pretend that we just try every point, but there are much faster ways) we find the nearest neighbor of ξ. If the nearest neighbor isn't a, b or d then that circle is not a Delaunay circle and $\langle a,b,d \rangle$ is not a legal triangle. Suppose the nearest neighbor is point c. We then just repeat the center calculation with d replaced by c.

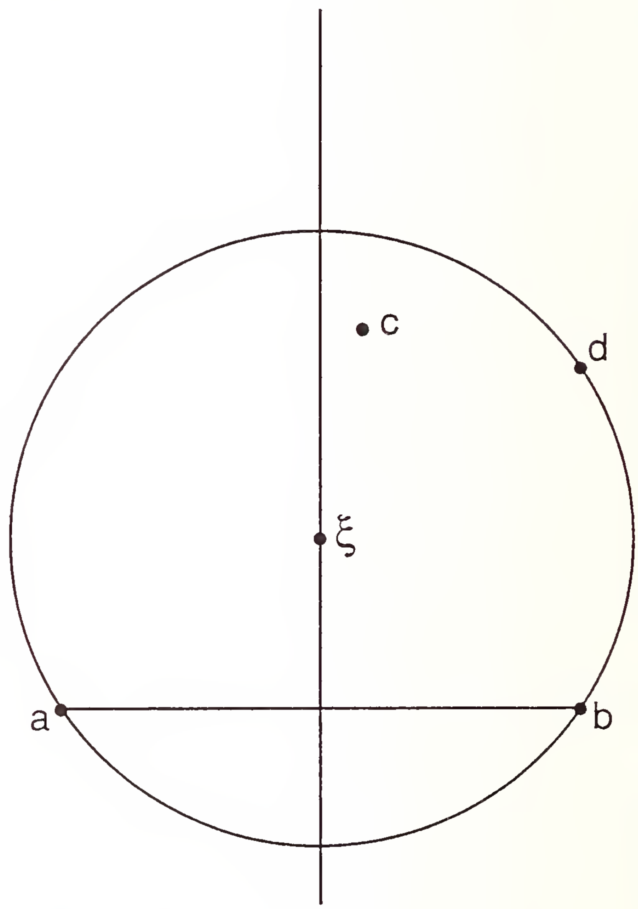

Figure 2. Triangle a, b, d, is not Delaunay because the circle contains point c, making a, b, c a more likely candidate for a Delaunay triangle.

Here is the whole procedure:

0 Choose any d different from a or b.

1 Find ξ, the center of the circle determined by $\langle a,b,d \rangle$.

2 Find the input point c closest to ξ (using a nearest neighbors algorithm). If $c \in \{a,b,d\}$, we're done. If not, repeat step 1 with d replaced by c.

We must also know when we have gotten to a boundary. This happens when there are no points on its positive side of an edge where ``positive side'' is determined by the usual right hand rule. One can use determinants to get this information but in practice we have a more complicated procedure than we can go into in this talk.

An important consideration makes this an efficient method. There is a modified nearest neighbors algorithm that works in $O(\log(n))$ time, assuming there are n input points. That is what step 2 in the above procedure costs us. The nearest neighbor algorithm only looks at the points that are close to a given query point; it doesn't have to visit every single point. We determine before we even start, which points are close by binning all of the points. So then we only look at nearby bins to a query point.

The algorithm is more stable than classical methods because distances rather than angles are compared.

3. Putting Triangles Together

We still haven't explained how to put the triangles together so that we don't get repetitions and we are sure to stop correctly. To do this we use a concise data structure to represent the triangulation: *t-lists*. We number the triangles according to the order in which we make them. We call these shelling numbers. The *t-lists* are arrays of lists, one list for each point a, and *t-list*$[a]$ is an ordered list of the shelling numbers of triangles that contain a, the same as figure 1. Here are some *t-lists* for points A and B from figure 1.

t-list$[A]$ = 8, 9, 10

t-list$[B]$ = 3, 8, 35, 36, 37, 38

If at any point *t-list*$[a]$ is empty, it means that point a has not been seen before. We can also tell the number of triangles that contain an edge <a,b> by finding $\#(\textit{t-list}[a] \cap \textit{t-list}[b])$, thatllis, the number of elements in this intersection.

Because the average number of triangles that contain a point is six, these intersections don't usually become unwieldy.

So we make triangles by the above methods and each time we make one we get two more edges to work on. Sometimes the edges have been seen before so we don't have to work on those, and sometimes we're on the boundary and we don't do anything with these either. But we do insist that the triangles come out in shelling order for the extra correctness checking that this provides.

4. Degenerate Data

Degenerate data are points that are so regular that there are choices to be made in which triangle to make either of which might be correct but not both. This situation is very common in crystal data. So in figure 3, for example, we could have triangle ABD and ACD, but ABC and ADC would also satisfy the empty sphere condition. In this case, the empty sphere condition would allow ALL of these possibilities, and that would be very wrong because the triangles would intersect incorrectly. What to do? Consistently we need to pick one of the ways to go and be consistent thereafter. Some people add ``noise'' to the data, but as can be seen in the second part of figure 3, this generates triangle $A'B'E'$ that doesn't exist in the real data. We have solved this problem by making a systematic linear perturbation of the data, as seen in the third part of figure 3, which DOES indeed choose one way to go and then stays with it consistently. The circle produced by points $A''B''D''$ clearly excludes point C'', so there is no ambiguity and consistency which exists with the other points. We can actually prove that this works on most data and doesn't lead to other problems. The proof uses tools from differential topology, and so it will be left as the subject for another presentation at another time.

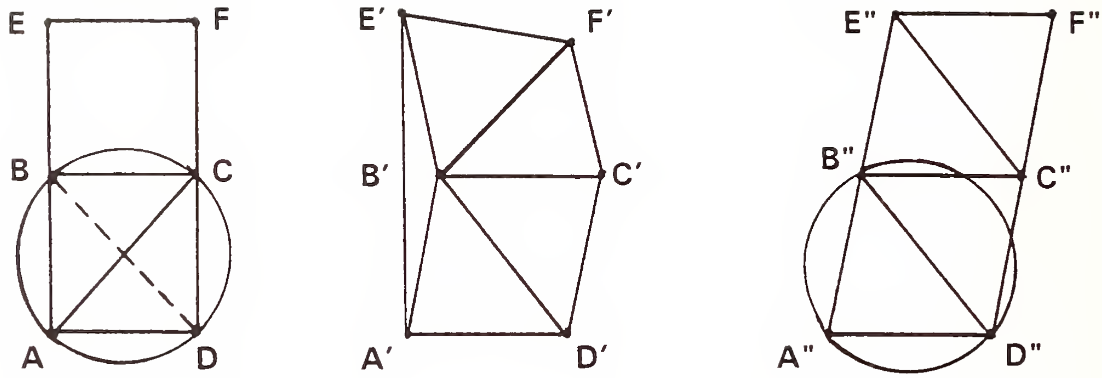

Figure 3. Perturbations of degenerate data (left drawing), by adding "noise" (center drawing), and by making a systematic linear perturbation (right drawing). Note that the creation of triangle *A'B'E'* in the center drawing is erroneous because it would indicate a triangle *ABE* in the left drawing.

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