NANOTECHNOLOGY: THE STATE OF NANO-SCIENCE AND ITS PROSPECTS FOR THE NEXT DECADE

HEARING

BEFORE THE

SUBCOMMITTEE ON BASIC RESEARCH

OF THE

COMMITTEE ON SCIENCE
HOUSE OF REPRESENTATIVES

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COMMITTEE ON SCIENCE

CONTENTS

Page

APPENDIX 3: MATERIAL FOR THE RECORD

HEARING ON NANOTECHNOLOGY: THE STATE OF NANO-SCIENCE AND ITS PROSPECTS FOR THE NEXT DECADE

TUESDAY, JUNE 22, 1999

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE,
SUBCOMMITTEE ON BASIC RESEARCH,
Washington, DC.

The Subcommittee met, pursuant to notice, at 3:00 p.m., in Room 2318, Rayburn House Office Building, Hon. Nick Smith [Chairman of the Subcommittee] presiding.

Chairman SMITH [presiding] The Science Subcommittee on Basic Research will come to order for the purpose of a hearing on nanotechnology and the state of nanoscience and its prospects for the future decades.

Today the Subcommittee is meeting to review federal funding of research into nanotechnology, to discuss the role of the Federal Government in supporting nanoscience research, and to discuss the economic implications of the scientific advances made in the field of nanotechnology.

In Fiscal Year 1999, the Federal Government will spend approximately $230 million on nanotechnology research. Eighty percent of the funding comes from the National Science Foundation, about $90 million; the Department of Defense; the Department of Energy. The remaining money comes from the National Institutes of Health, the Department of Commerce, and NASA. In addition, the private sector has shown interest in the field of nanotechnology. And the question that this Subcommittee hopes to answer is how much effort should the Federal Government be putting into taxpayer funded research in this area?

According to testimony submitted by our panelists, scientists have already learned a great deal about how to use nanotechnology. The best example of this is today's biotechnology industry. But, according to researchers, that is only the beginning. Nanotechnology holds great promise for breakthroughs in health, manufacturing, agriculture, energy, and national security. In fact, some researchers state that over the next few decades, nanotechnology will impact every aspect of our society.

Unfortunately, while progress has been made, the United States does not dominate nanotechnology. A significant amount of research is currently underway in Europe, especially Japan. In that context, it seems to me it is appropriate that we cooperate and keep abreast of the research being done in these other countries.

It is also appropriate for the Subcommittee to take a good look at the Federal Government's role in funding nanotechnology research, to discuss what can be done to help move this research from the lab to the marketplace, and to discuss where nanotechnology might be in 10, 20, 30 years from now.

I would like to thank our esteemed panelists very much for taking time out of your schedule to be here today and would ask our Ranking Member if she has a statement at this time.

Ms. JOHNSON. Thank you, Mr. Chairman. I'm pleased to join you today in welcoming our witnesses for this afternoon's hearing. The ages of civilization are designated by reference to a prominent material that could be fashioned by the prevailing state of technology. For example, the Stone Age, the Bronze Age, and the Iron Age. Now we are at the threshold of an age in which materials can be fashioned, atom by atom.

The word "revolutionary" is too overworked to have much impact anymore, but nanotechnology, which is the subject of today's hearing, truly is revolutionary. As expressed in a recent report from the National Research Council, the ability to control and manipulate atoms, to observe and simulate collective phenomenon, to treat complex material systems, and to span length scales from atoms to our everyday experience provides opportunities that were not even imagined a decade ago. Nanotechnology will have enormous consequences for the information industry, the manufacturing of all kinds of medicines and health. Indeed, one of our witnesses has written that it will leave virtually no product untouched.

I congratulate the Chairman for convening this hearing so that we may learn more about the promise of this research related to nanotechnology and about the marvels that have been accomplished thus far. We are, naturally, interested in hearing the panel's assessment of the vitality of federally supported research efforts in this field and we are aware that the planning activities are underway which may lead to research in this nanotechnology in the Administration's Fiscal Year 2000 budget request.

The views of the panel on the value, timeliness, and appropriate focus of such an initiative would be welcome. Again, I want to thank you, Mr. Chairman, for calling this hearing and I appreciate the attendance of our witnesses. Maybe in 10 years, 15 or 20 years, we will say we had that hearing and look what it brought. Thank you.

Chairman SMITH. Thank you, Representative Johnson. At this time, I would like to introduce our panelists and also, for your information, your testimony will be live because it is being webcast on our website.

First is Dr. Eugene Wong. He is the Assistant Director for Engineering at the National Science Foundation. Paul McWhorter is the Deputy Director of the Microsystems Science Technology and Components Center at the Sandia National Laboratories. Richard Smalley is Professor of Chemistry and Physics at Rice University and in 1996 was awarded the Nobel Prize in Chemistry. Ralph Merkle is a research scientist at Xerox Palo Alto Research Center. In 1998, he and NASA scientist Stephen Walch were awarded the Feynmann Prize in Nanotechnology. Esteemed witnesses today. We thank you.

It is our policy to have witnesses take the oath. If you would rise and raise your right hand.

Do you solemnly swear that the testimony that you are about to give is the truth, the whole truth, and nothing but the truth?

Mr. WONG. Yes.

Mr. MCWHORTER. Yes.

Mr. SMALLEY. Yes.

Mr. MERKLE. Yes.

Chairman SMITH. Let the record indicate that all witnesses have indicated in the affirmative. And we thank you very much.

And the spoken testimony we try to limit to 5 minutes. There is a green, yellow, and red light on the little boxes in front of you. But all testimony that you have presented to the Committee in writing, without objection, will be entered into the record of this hearing. And, hearing no objection, it's so ordered.

Dr. Wong, if you would begin.

TESTIMONY OF EUGENE WONG, ASSISTANT DIRECTOR, ENGINEERING DIRECTORATE, NATIONAL SCIENCE FOUNDATION, ARLINGTON, VA; ACCOMPANIED BY PAUL J. MC WHORTER, DEPUTY DIRECTOR, MICROSYSTEMS SCIENCE, TECHNOLOGY, AND COMPONENTS CENTER, SANDIA NATIONAL LABORATORIES, ALBUQUERQUE, NM; RICHARD E. SMALLEY, PH.D., THE GENE AND NORMAN HACKERMAN PROFESSOR OF CHEMISTRY AND PROFESSOR OF PHYSICS, RICE UNIVERSITY, HOUSTON, TX; AND RALPH C. MERKLE, XEROX PALO ALTO RESEARCH CENTER, PALO ALTO, CA

TESTIMONY OF EUGENE WONG

Mr. WONG. Yes. My name is Eugene Wong and I am the Assistant Director of the National Science Foundation for Engineering. I am pleased to come before you to testify on the great opportunities that are presented to us in the area of nanoscience and technology.

One nanometer is truly a magical point on the scale of length, for it is at this place where the smallest man-made things meet the natural atoms and molecules of the living world. Recent discoveries at this scale are promising to revolutionize biology, electronics, materials, and other applications. We are seeing inventions and discoveries that were unimaginable only a very short time ago. For example, we now have materials and electronic devices that assemble themselves and we will see an example of that in a moment and biological motors extracted from living systems and running on their own.

What is nanoscale? One nanometer is 1-billionth of a meter. To get an idea of the size, we can compare some familiar things. The diameter of an atom is about ¼ of 1 nanometer. The diameter of a human hair, on the other hand, is 10,000 nanometers. The protein molecules, which are so important, so critical to life, are several nanometers in size. Moving to man-made things. The smallest devices on commercially available chips are about 200 nanometers, whereas the smallest experimental device on experimental chips are approximately 10 nanometers in their smallest dimension. Nanoscale refers to dimensions that vary from a fraction of a nanometer to tens of nanometers.

Figure one provides a good illustration of the scale.

[Slide.]

This is an image of a pyramid of germanium atoms sitting on top of a silicon base—silicon surface. The pyramid is about 10 nanometers across its base and only 1.5 nanometers in height. Each round-looking object is a single germanium atom. This pyramid was made at the Hewlett-Packard Laboratories and was formed just a few seconds all by itself via a process called self-assembly. Self-assembly is illustrated in figure two.

[Slide.]

Here we have a collection of actual materials that were formed by self-assembly. They take different shapes and I think one of the key points about self-assembly is by properly creating the environment for assembly, these molecules and atoms actually collect themselves into the requisite shapes, as in the case of the sphere and as in the case of the pyramid that we saw on the last—in the last figure.

Over the last 20 years, a series of instruments were invented that now allows us to see, manipulate, and control objects in nanoscale. They are the eyes, fingers, and tweezers of the nanoscale world. With these remarkable tools, a new world of discovery and invention has been created. This is the world of nanoscale science and technology.

Not every piece of nanoscale science and technology is new. Photography, for example, is a relatively old nanotechnology. Most of molecular biology also works at nanoscale and some of it is clearly not new. What is new and different is the degree of understanding we are able to achieve with the new tools and the precision and control that we are able to exert on the—on molecules and devices at this scale. Because of the new techniques, we are witnessing truly an explosion of revolutionary discoveries in nanoscale.

Why is nanoscale so important? First, I think the small size itself is of critical importance. Microelectronics through successively reducing the size of devices and increasing the density of devices interconnection on chips has brought us the revolution in information technology we see today. And I think the systematic reduction to the nanoscale range will be just as important a development.

Second, with the ability to control and change nanoscale structures and materials, we can dramatically improve their properties without ever changing their chemical composition. And this is a new-found—this is a new dimension.

Third, much of molecular biology works at nanoscale. By using the techniques of nanoscale science in biology, we gain two great advantages: a deeper understanding of how nature works and ways to mimic and improve upon nature. The applications of nanoscale science and technology will lead to breakthroughs in a myriad of applications, in information technology, advanced manufacturing, medical care, the environment, energy generation, and national security.

While my written testimony contains several examples of potential applications in these areas, here I will just highlight a couple of examples. The first commercial nanoscale products are already in production. The—a magnetic rehab for disk drives with nanoscale dimensions and based on the giant magneto-resistance principle is on the market today and promises to revolutionize the computer storage market. Prototypes of memory chips using an advanced version of the same principle have also been designed and fabricated.

[Slide.]

Figure three shows an example of these memory chips. Figure three shows a design for nanoscale memory chips that will have 1,000 times the memory; 100,000 times in speed—and be 100,000 times in speed; and only 1⁄10 the size of existing memory chips.

Nanotechnology can be used to dramatically improve animal and plant genetics and better control the growing processes in agriculture. Nanofabrication of detector arrays provides the potential to do thousands of simultaneous gene experiments with very small amounts of material.

[Slide.]

Figure four shows a chip—figure four, please. Figure four is the picture of a natural nanochip with 6,400 dots, each containing a small amount of a different gene in the yeast genome. With this chip, scientists can discover which genes are being activated or inhibited during the growing process. The application of this technology to agriculture has only begun to be appreciated.

The nanochip will allow the genes to be completely characterized, molecule by molecule, in just a few hours. Only a short time ago, the same experiment would have taken dozens of scientists years to complete.

The National Science Foundation has a long history of support for research in nanoscale science and technology. Research supported by the Mathematical and Physical Sciences Directorate has culminated in two Nobel Prizes in the last few years. One of these went to Dr. Richard Smalley, who is here today testifying. NSF also funds the National Nanofabrication Users Network, which provides the primary fabrication infrastructure for chip-level nanoscale research.

Yes.

Chairman SMITH. I apologize for interrupting, but if you would sort of conclude in the next 30 seconds or so, we will have a lot of time for questions.

Mr. WONG. Yes, please. Thank you.

Despite great commercial promise, the field of nanoscale science and technology cannot advance without strong federal support because this is a basic research area in its early stages of development. That is why we are coming before you to seek your encouragement and your endorsement of this important area.

Chairman SMITH. Mr. McWhorter.

TESTIMONY OF PAUL J. MC WHORTER

Mr. MCWHORTER. I am Paul McWhorter from Sandia National Laboratories. I would like to thank the Committee for the invitation to talk to you about the role of nanotechnology in the second silicon revolution.

It is really difficult to imagine any field of science or technology that has had a more profound impact on the last half-century than microelectronics. The hallmark of the microelectronics industry has been to each year provide chips that are smaller, faster, cheaper, and better. This has revolutionized all aspect of our lives from our most advanced weapons systems to our toaster ovens.

The global microelectronics industry has vectored ahead based on a very simple metric: to make transistors smaller. As transistors become smaller, they become faster. You can pack more of them on the chip and chips are able to store and process more information. To date, this has been the silicon revolution.

Today we stand on the verge of a second silicon revolution. The metrics of the second silicon revolution will be different and more important than simply continuing to pack more transistors onto a chip. The metrics of the second silicon revolution will be the incorporation of new structures, microscopic machines, on the chip alongside the transistors, creating a whole new generation of computer chip, a chip that can not only think but sense, act, and communicate as well. These fully functional machines have feature sizes smaller than human red blood cells. This new capability will have as profound of an impact on our lives over the next 30 years as microelectronics have over the past 30 years.

The second silicon revolution has begun and a variety of commercial products exist today that contain micromachines. To fully realize the potential of the second silicon revolution, however, certain scientific hurdles must be overcome. In the 1800's, realization of high-performance, traditional industrial machines required the development of a fundamental understanding of the science of the microdomain. Similarly, to effectively design, build, and operate machines in the microdomain, we must have a fundamental understanding of the materials and surfaces in the nanodomain. Nanotechnology and nanoscience will be the key elements of fully achieving the vision of micromachines and microsystems. It will be nanotechnology that will lead to new functions, better performance, and higher reliability in micromachines and microsystems.

I have a very brief two-minute video I would like to show that just describes the state-of-the-art of microtechnology to date. If you could roll the video.

Chairman SMITH. We would note for the audience that we have three screens: one in the middle and one in——

[Video.]

Mr. MCWHORTER. This is a picture of the world's smallest machine in operation. This is a transmission. For size comparison, the gear teeth that you are looking at are the size of a red blood cell. The gear itself is the size of a grain of pollen. This transmission is used as part of a system to increase the force that you can get out of the microdevices.

This is a rack and pinion system that we demonstrated. Again, built at Sandia National Laboratories. This enables us to get large linear displacements in the microdomain.

All of these devices are built using integrated circuit fabrication technique and they're batch fabricated tens of thousands at a time on a six-inch silicon wafer. Bringing these technologies together, we create this microscopic positionable mirror with large implications for use in the global telecommunications infrastructure. You can see it switching an optical lasar at a very fast rate.

This is a prototype safety mechanism for a nuclear weapon that has been developed. The purpose of this is to work on researching ways to continue to increase the safety of the nation's nuclear weapons. This device operates by it has a 24-bit code, which means that there is less than a 1 in 16 million chance of a random occurrence causing this device to unlock. You can see the engine driving the pin structure up and down inside of a maze. This is the way the decoding function is done. There is an engine and transmission that is moving this entire platform from the right to the left.

In order to unlock or arm the weapon, the code has to be entered correctly. The two gears that you see on the platform have to come and engage the other gear train in order to pop up a mirror to arm the weapon. Remember, this entire device is microscopic in dimension and built thousands at a time.

The code's been entered correctly. The gears here engage. That completes the gear train and we're able to pop up the mirror and arm the weapon. This is just an example of the type of technology that is available today in the microdomain.

Chairman SMITH. Now is each gear the size of a red blood cell or——

Mr. MCWHORTER. Each gear is the size of a grain of pollen.

This is just another size demonstration. This is a microscopic dust mite that we were able to give a ride around on the outfit gear of the microengine.

The message I would like to leave you with today is that microtechnology is real. It is here today. But, looking towards the future, to really realize the full potential of the microtechnology, we desperately need the type of capability further described in the term nanoscience. Other people on the panel will tell you more about the broader, longer term application of nanotechnology. What I would like to tell you is there is a need for it today in the area of microsystems and there would be—in addition to the longer term applications, there would be short-term impact from this work.

Chairman SMITH. Thank you.

Dr. Smalley.

TESTIMONY OF RICHARD E. SMALLEY

Mr. SMALLEY. Mr. Chairman, I appreciate the opportunity today to present my views on nanotechnology. There is a growing sense in the scientific and technical community that we are about to enter a golden new era. We are about to be able to build things that work on the smallest possible length scales, atom by atom, with the ultimate level of finesse. These little nano things and the technology that assembles and manipulates them, what we call nanotechnology, will, I am certain, revolutionize our industries and our lives.

Everything we see around us is made of atoms, the tiny elemental building blocks of matter. From stone to copper to bronze, iron, steel, and now silicon, the major technological ages of human kind have been defined by what these atoms can do in huge aggregates, trillions upon trillions of atoms at a time, molded, shaped, and refined as macroscopic objects. And even in our vaunted microelectronics of today, 1999, and our highest tech silicon computer chip, even the smallest feature is still a mountain compared to the size of an atom. The resultant technology of our 20th century is fantastic, but it pales when compared to what will be possible when we learn to build things at the ultimate level of finesse, one atom at a time. And if you think you have seen something now, just wait. This next century is going to be incredible.

Nature has played the game at this level for billions of years, building stuff with atomic precision. Every living thing is made of cells that are chock full of nanomachines. Not quite as cute as these we just saw, but beautiful in their own way, each of them going about the business of life, rubbing up against one another. Each perfect right down to the last atom. The workings are so exquisite that changing the location or the identity of just a single atom causes the machine to change, generally to damage it.

Over the past century, we have learned about the workings of these biological nanomachines to an incredible level of detail and the benefits of this knowledge are beginning to be felt now in medicine. In the coming decades, we will certainly learn to modify and adapt this machinery to extend both the quality and the length of life. Biotechnology was the first nanotechnology and it has certainly a long, long way to go.

Let me give you just one personal example: cancer. As I sit before you today, I have very little hair on my head. It fell out a few weeks ago as a result of the chemotherapy that I have been undergoing to treat a type of non-Hodgkin's lymphoma, the same sort that recently killed King Hussein of Jordan. While I am very optimistic, this chemotherapy, frankly, is a very blunt tool. And I am sure most of you have personal awareness of this. It consists of small molecules which are toxic. They kill cells in my body and although they are meant to kill only the cancer cells, they kill hair cells, too, and cause all sorts of other havoc.

Now, I'm not complaining. Twenty years ago, without even this crude chemotherapy, I would probably already be dead. But 20 years from now, not that far in the future, I'm confident we will no longer have to use just this blunt tool. By then, nanotechnology will have given us specially engineered drugs which are nanoscale and essentially cancer-seeking missiles, a molecular technology that specifically targets just the mutant cancer cells in the human body and leaves everything else blissfully alone.

To do this, these drug molecules will have to be big enough—probably thousands, perhaps tens of thousands of atoms—so that we can code information into them of where they should go and what they should kill. They will be examples of an exquisite—a new exquisite nanotechnology, this time human-made, a technology of the future. I may not live to see it, but, with your help, I am confident it will happen and cancer, at least the type that I have, will be a thing of the past.

Powerful as it is, this bio-side of nanotechnology that works in water in the water-based world of living things will not be able to do everything. It cannot make things strong like steel or conduct electricity with the speed and efficiency of copper or silicon. For this, other nanotechnologies are being developed and will be developed in the future. It's what I call the dry side of nanotech.

My own research these days has focused on carbon nanotubes. Can we have my first slide? Or do I need to hit my laptop? Is it——

[Slide.]

This is a carbon nanotube. These nanotubes are an outgrowth of the research that led to the Nobel Prize a few years ago. These nanotubes are absolutely incredible. They are expected to produce fibers 100 times stronger than steel, but only 1⁄6 the weight. Almost certainly the strongest fibers that will ever be made out of anything, strong enough, even to build an elevator to space. In addition, they will conduct electricity better than copper and transmit heat better than diamond. Membrane made from the rays of these nanotubes are expected to have revolutionary impact in the technology of rechargeable batteries and fuel cells, perhaps giving us all-electric vehicles within the next 10 to 20 years with the performance and range of a Corvette at a fraction the cost.

[Slide.]

As individual nanoscale molecules, these carbon nanotubes are unique. Just think of one at a time. They have been shown—here you see one draped across a few electrodes. They have been shown to be true molecular wires, to conduct electricity like copper—in fact, even better—and have already been assembled into the first molecular transistor ever built; with just a single molecule, a functional transistor. Several decades from now, we expect to see—we may be able to see. We don't know yet—but it may be possible that, within several decades, our current silicon-based microelectronics will be supplanted by a carbon-based true nanoelectronics of vastly greater power and scope.

It is amazing what one can do just by putting atoms where you want them to go.

Recently an Interagency Working Group on Nano Science, Engineering, and Technology has studied the field of nanotechnology in detail and made its recommendation to OSTP on March 10 for a new initiative in this critical area. Quoting briefly from Mike Roco, chair of this working group:

> A national initiative, entitled Nanotechnology in the 21st Century Leading to a New Industrial Revolution is recommended as part of the Fiscal Year 2001 budget. The initiative will support long-term nanotechnology research and development which will lead to breakthroughs in information technology, advanced manufacturing, medicine, health, environment and energy, and national security. The impact of nanotechnology on health, wealth, and lives of people will be at least the equivalent of the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in this century.

Mr. Chairman, honorable Congressmen, I believe it is in our nation's best interests to move boldly into this new field. Thank you.

Chairman SMITH. Dr. Smalley, exciting testimony. This is the most—I want the witnesses to know, this is the most high-tech Committee room that we have in the United States Congress and we had a slight malfunction and that's—so our screen for the members sort of malfunctioned.

Dr. Merkle, please proceed.

TESTIMONY OF RALPH C. MERKLE

Mr. MERKLE. Thank you very much, Mr. Chairman. For centuries, manufacturing methods have gotten more precise, less expensive, and more flexible. In the next few decades, we will approach the limits of these trends. The limit of precision is the ability to get every atom where we want it. The limit of low-cost is set by the cost of the raw materials and the energy involved in manufacture. The limit of flexibility is the ability to arrange atoms in all the patterns permitted by physical law.

Most scientists agree we will approach these limits but differ about how best to proceed, on what nanotechnology will look like, and then how long it will take to develop. Much of this disagreement is caused by the simple fact that, collectively, we have only recently agreed that the goal is feasible and we have not yet sorted out the issues that this creates. This process of creating a greater shared understanding both of the goals of nanotechnology and the routes for achieving those goals is the most important result of today's result.

Nanotechnology, or molecular nanotechnology, to refer more specifically to the goals discussed here, will let us continue the historical trends in manufacturing right up to the fundamental limits imposed by physical law. It will let us make remarkably powerful molecular computers. It will let us make materials over 50 times lighter than steel or aluminum alloy, but with the same strength. We will be able to make jets, rockets, cars, or even chairs that, by today's standards, would be remarkably light, strong, and inexpensive. Molecular surgical tools, guided by molecular computers and injected into the bloodstream, could find and destroy cancer cells or invading bacteria, unclog arteries, or provide oxygen when the circulation is impaired.

Nanotechnology will replace our entire manufacturing base with a new, radically more precise, radically less expensive, and radically more flexible way of making products. The aim is not simply to replace today's computer chip-making plants, but also to replace the assembly lines for cars, televisions, telephones, books, surgical tools, missiles, bookcases, airplanes, tractors, and all the rest. The objective is a pervasive change in manufacturing, a change that will leave virtually no product untouched. Economic progress and military readiness in the 21st century will depend fundamentally on maintaining a competitive position in nanotechnology.

Many researchers think self-replication will be the key to unlocking nanotechnology's full potential, moving it from a laboratory curiosity able to expensively make a few small molecular machines and a relative handful of valuable products to a robust manufacturing technology able to make myriads of products for the whole planet. We know self-replication can inexpensively make complex products with great precision. Cells are programmed by DNA to replicate and make complex systems, including giant redwoods, wheat, whales, birds, pumpkins, and more.

We should likewise be able to develop artificial, programmable, self-replicating molecular machine systems, also known as assemblies, able to make a wide range of products from graphite, diamond, and other non-biological materials. The first groups to develop assemblers will have a historic window for economic, military, and environmental impact.

Developing nanotechnology will, I think, be a major project, just as developing nuclear weapons or lunar rockets were major projects. We must first focus our efforts on developing two things: the tools with which to build the first molecular machines and the blueprints of what we are to build. This will require the cooperative efforts of researchers across a wide range of disciplines: scanning probe microscopy, supramolecular chemistry, protein engineering, self-assembly, robotics, materials science, computational chemistry, self-replicating systems, physics, computer science, and more. This work must focus on fundamentally new approaches and methods; incremental or revolutionary improvements will not be sufficient.

Government funding is both appropriate and essential for several reasons. The benefits will be pervasive across companies and the economy. Few, if any, companies will have the resources to pursue this alone. And the development will take many years to a few decades beyond the planning horizon of most private organizations. We know it is possible. We know it is valuable. We should do it.

Chairman SMITH. Dr. Merkle, you still had 2 seconds to go before you finished. [Laughter.]

It would seem to me if there was—first let me introduce my professional staff assignee, Peter Harsha, who is just coming to work for the Science Committee, for the Committee members and for those in the science community that will be working with this Subcommittee.

It seems to me, listening to the testimony, that, if there was zero bias among you four gentleman that are offering this testimony, that the potential for this research in terms of what it can accomplish for humanity as well as what its potential is for industry and the economy is every bit as much or more than the silicon revolution. This Subcommittee will be looking closely at recommending that we substantially increase the government effort in terms of taxpayer dollars into this area of research as well as ways that we might encourage the private sector and industry, that might eventually benefit from such research, to have an all-out effort as the United States tries to maybe make sure that we are a lead nation.

So my first question would be how do you evaluate—can we justify that kind of effort, number one? And how do you evaluate the United States position in terms of this research effort compared to Japan and Europe? And we'll just maybe each one of you, if you could take about 35, 45 seconds and give me a quick reaction, starting with you, Dr. Wong, and——

Mr. WONG. Well, first of all, I think the benefits are obvious and very great and, as several of the panel members have already said. However great it is, the horizon is too long for private investment. But, nonetheless, any federal investment in this area will catalyze private investment. It will greatly accelerate the pace at which the benefits can be translated into real applications. I think the United States is in the forefront of this new science and technology area, but the other countries, the other developed nations, are not far behind. It is an area of great focus for all the developed countries in the world; for European countries as well as Japan.

Mr. MCWHORTER. I think this is an area that the nation must maintain a leadership role in and in order to maintain and grow our leadership role in nanotechnology, I think government investment is critical. What we find in these emerging areas of technology is that many times commercial companies can be risk-averse, but when government money can come in and catalyze and initiate an effort, then the industrial investment will follow. And so the activities that we are talking about here would be just critical to catalyzing this continued growth in our leadership position and in participation from more commercial companies.

Chairman SMITH. Dr. Smalley.

Mr. SMALLEY. Let me just add that nanotechnology of the sort that has been talked about today is different than the major scientific technological pushes the country has undergone in the past, mostly since the Second World War and including the Manhattan Project, in that nanotechnology is intrinsically small science and so it is impossible to dominate the field by a huge program in a national laboratory with major facilities because it is a place where many small laboratories are active. In fact, hundreds throughout the world.

So we are particularly—it's particularly possible for countries that are not as well-funded as the United States to be major players in this area. It is a small science initiative that needs to be treated as a big science, big technology, big impact area. Which makes its funding difficult. I mean, you can't say we are going to have a $300 million program to do this one particular thing because there are many particular things to be done. And so it brings to a focus the age-old difficulty in funding small science. Nonetheless, it is an area out of which, to many extents, all blessings will flow in this next century.

Chairman SMITH. Dr. Merkle.

Mr. MERKLE. Well, I think the benefits of this technology will indeed be very impressive and I think we need to continue and expand the base of research which has been pursued throughout the country to develop a better understanding at the molecular scale and a better ability to arrange and manipulate structures at the molecular scale.

Beyond that, I would also suggest that research in artificial self-replicating systems would be a good thing to pursue, that this is an area where we have, so far, had relatively modest amounts of effort, mostly done by individuals or small groups.

Chairman SMITH. Just a follow-up question, Dr. Smalley. So does this—is it a situation—what is our weakness in terms of aggressively pursuing this research? Is it the talent of researchers that are capable of exploring this field? Or is it simply enough money to pay for enough grants to interest enough researchers?

Mr. SMALLEY. I believe, at the moment, our weakness is the failure so far to identify nanotechnology for what it is. It is a tremendously promising new future which needs to have a flag. Somebody has to go out and put a flag in the ground and say: Nanotechnology, this is where we are going to go and we are going to have a serious national initiative in this area.

Chairman SMITH. Representative Johnson.

Ms. JOHNSON. Thank you very much, Mr. Chairman. And thank you so much for such an outstanding panel of witnesses today. I note that two of them have a Texas base. One is a University of Texas graduate and the other one is a researcher at Rice. And I am delighted.

I was here when we voted down the supercollider that smashed the atoms and I was very chagrined by that and thought that was a mistake. And most of us here that were here during that time thought so. The ones who didn't think so are not here right now.

And hopefully we won't do that again in research, because we all now realize the value of that kind of basic research.

Tell me a bit about how—what is our standing—I know you commented on that earlier—in terms of funding this basic research? Because it is clear to me that this is really a government responsibility more than anything else. Private businesses just don't have the dollars nor do they feel the keen responsibility to do such basic research, not knowing what the future might bring. Most of them are directed toward a certain product when they are researching. And though we know a bit about the product—you just, Dr. Smalley, you mentioned some of the possibilities for the future that might come, but there are other things that might come that we don't know about yet.

And I wonder, did we lose ground when we stopped putting as much into basic research here several years ago? We are trying to catch up now. And what are some of the possibilities, you think, for the future? And how do we stand with other countries in funding our basic research?

Mr. WONG. I think the nanoscience and technology represents an exemplar of how basic research really pays off. I think basic research in our areas have been one of the best investments the country has ever made. And I think we have seen an example of that. I think we have found enough in this sector to know what the future—how brilliant the future is going to be, how bright it is going to be.

But I think we need to continue to invest in that area. There is a timing area. I think the particular thing about nanotechnology and nanoscience is the timing. The timing is right for a major advance, I think, in this area because we have so many, as Dr. Smalley has said, there are just so many things to be found, so many things to be investigated. This is truly a wonderful area for national investment.

Mr. MCWHORTER. I really agree with the comment about timing, that there's been a lot of research that's been going on in the area of nanotechnology. I think that research has shown much promising results to where you can start seeing a glimmer of the future and a glimmer of what's going to be possible. I think one of the real opportunities with the program as you're considering it is that there has been a lot of research in a lot of different areas and such a program would have the capability of unifying and providing some vision and unification to the research that's going on. Because I think that, you know, the putting a man on the moon was mentioned earlier, that that was a single-minded goal, but many people lined up behind. And I think that that's one of the needs of nanotechnology is to have the big picture goal and the national initiative to energize the people working in the area.

Mr. SMALLEY. Concerning our competitive situation vis-a-vis the rest of the world, as you know, coming out of the Second World War, the United States was premier in the world in the research that was done, both from native-born researchers and from European researchers that came over to get away from Hitler. And in many extents, we are running off of that wonderful time. I myself decided to go into science when Sputnik went up. I was in high school at the time. So that generation is passing now.

At Rice University, for a quarter of a century, I have taught some of the very brightest human beings I have ever met. It's a fantastic university, as you know. It's amazing the fraction of them that do not go into science. By and large science is not what American boys and girls do. They go into other fields and do very well at it.

We've managed to get this far here at the end of the century, still being pretty much as good as anybody, in many areas better than most, because of our openness, because of foreign researchers coming into work in our universities, and so forth. I don't think we should assume that will continue forever. European, Japanese, Asian universities have embraced research in very serious ways and, in many areas, are more than competitive with anything in the United States. The reason for foreign nationals to come to this country to do their Ph.D. dissertations is getting weaker and weaker. And one of these days it's going to happen that we don't do very good research in this country because we can't get good American boys and girls to get into the field.

And that's one of the reason why I emphasize this is a small science activity. This is where we are most effective. We can have a huge project like the superconducting supercollider that can be worldwide premier because of the vast investment and we can sort of capture it. But this is much more diffuse and much more sensitive to the overall well-being of American science and the way it's perceived by youngsters. Many of these bright students don't go into the field because they see graduate students not getting jobs because of the decrease in the funding for basic research. They regard it as—this isn't a serious enterprise in society.

Ms. JOHNSON. Thank you.

Mr. MERKLE. Well, I would agree with my fellow panelists that the opportunities in nanotechnology for the next few decades are absolutely remarkable and that it would be a great shame if we were to walk away from this. We must pursue this. It is essential that we pursue this in a timely fashion and, in fact, we are now seeing the major size of the opportunity.

I think that we do, absolutely, need to pay attention to the younger generation. One of the things that I see is e-mail which is sent to me by students; students who send me requests asking, I want to get into nanotechnology. What should I do? I want to get into nanotechnology. Where are the programs? I can point them at Rice. I can point them at a few others. I want to be able to point them at more programs.

Students are very quick to pick up on new ideas and new technology and they have picked on this and they are very excited. We need to provide the support and the follow-through so that they have somewhere to go so that they can learn what needs to be learned, so that they can participate in these programs, and so that we can develop the technology. Thank you.

Ms. JOHNSON. Thank you very much.

Chairman SMITH. My good friend from California, Representative Woolsey.

Ms. WOOLSEY. Thank you, Mr. Chairman. When I was reviewing this hearing, I was thinking, well, how are these brilliant doctors going to be able to talk about nanotechnology so that laypersons will understand it, so that my constituents will understand it? So that the taxpayers will think it is a good idea that they pay taxes and that we actually invest in microtechnology? You were great. Thank you. Your testimonies were terrific. Dr. Smalley, you gave me my answer.

So those are the kinds of things I think the public is going to be asking. I believe that not only the taxpayers, not only our constituents, but also our students, future students. Young people that come into your colleges are all ready to think of new technologies. We need not just boys, but girls to care about science and technology.

And I think the kinds of questions they are going to be asking— and I'm going to ask them and then I hope you'll answer. One, does length of life or quality of life, which, or is it both, that are going to be affected by nanotechnology? I also think they're going to want to know, does self-replicating mean cloning? And, if so, what are the ethics?

And, also, will the benefits of nanotechnology be used in peaceful applications or are we only looking at it so we can be bigger and better and competitive with the rest of the world? Is there a way we can all work together, globally, to improve the challenges we have for lack of food, health care around the globe? Because, first of all, that's what people in my district just north of the Golden Gate Bridge will be asking me, Marin and Sonoma counties. And, second of all, that's a good way to get girls interested in science. They have to see a real, neat, something meaningful.

So my three questions: quality of life, length of life; self-replicating; and a partnership for a peaceful benefit. So in whatever order. Dr. Merkle, you look ready.

Mr. MERKLE. Well, basically the answer to the question of will we improve the length or the quality of life, the answer is both. I think that as we see this technology mature, we will have a remarkable set of medical capabilities. Disease and ill-health are caused largely by damage at the molecular and the cellular level, and today's surgical tools are simply too big to deal with damage at that level. In the future, we'll have surgical tools that are molecular, both in their size and their precision, and they will be able to intervene directly at the level where the damage occurs and correct it. So I think that will have a remarkable impact on health care overall and will lead to a revolution in medicine.

As far as the self-replication, it's very much a non-biological kind of self-replication. And to give you an analogy, if you look at cars. Cars provide transportation, but they are very mechanical in their design style. Horses also provide transportation and they're very biological. Horses can survive on sugar lumps, carrots, straw, hay, the whole bit. A car requires a refined fuel, a single refined fuel, such as gasoline. And it really can't function without gas, oil changes, spark plugs, roads to run on. It's an artificial device. It's a mechanical device.

And in the kind of designs I've thought about for self-replicating systems, they're very mechanical. They completely lack the adaptability of living systems. They are very much machine-oriented. And the thought of them being able to function outside of a very carefully controlled environment is similar to a car running wild in the woods.

As far as the broader implications for the environment, I think that today's manufacturing methods are often too imprecise to economically avoid pollution. Because nanotechnology will be a very precise manufacturing technology, it won't pollute. As nanotechnology replaces existing manufacturing technologies, pollution from manufacturing plants will largely disappear.

Nanotechnology will also let us make inexpensive solar cells and batteries, giving us very low-cost, clean solar power. This should virtually eliminate the need for coal, oil, and nuclear fuels.

Ms. WOOLSEY. Dr. Smalley.

Mr. SMALLEY. Let me just pick up on this last point that Dr. Merkle mentioned, the energy problem. Let's suppose that halfway through this next century, we really do have a problem with burning fossil fuels. Right now, I believe there's really one alternative that could really apply to the energy needs of the entire planet, which, of course, is what you have to do if you're going to affect things like the CO_2 greenhouse effect, if it is a problem. And right now that alternative is nuclear, nuclear fission, in particular, not nuclear fusion, fission.

And while I can well imagine, I actually believe that the United States and Europe, Japan are stable enough societies that they could actually generate all their power by nuclear fission and provide the necessary stewardship to make the planet safe, I find it very hard to believe that the entire planet can operate as a nuclear power. And it is a very scary future. It would be very nice to have an alternative to fossil fuels and an alternative to nuclear fission that would be capable of providing energy for what will probably be 10 billion to 15 billion people in the middle of this next century in a way that the planet can sustain.

I believe that it's almost certain that, if that alternative exists, it has to be solar. But, right now, we do not have the solar technology that's even laughably close to being able to handle, for example, 80 percent of all the world's energy production. And if you don't do 80 percent, you're not touching the problem. And if you don't provide energy technology that is economically cheaper than any alternative, it won't be adopted any way.

Where is that solar technology going to come from? Not just improving solar cells, but something totally new that on a cloudy day in New York can take most of the photons that hit some cheap collector and store it in some useful form of energy, hydrogen or electric charge someplace. When you think about the physics that controls that, you are rapidly led to the conclusion that the physics that makes it possible happens within a little one nanometer cubic box. That's where the event occurs that the energy from a photon becomes a stored hydrogen molecule and electron.

In fact, in photosynthesis, it's about a one nanometer cubic space where, at the last moment, it becomes stored energy. I don't know what that solar energy technology is going to be, but I bet you it's a nanotechnology. That's one of the reasons why it's so important for us to invest in it now. It's so broadly disseminated. It involves so many disciplines. It is small science, thousands of laboratories. Somehow out of that, our hopes exist that that's where the solar technology comes out and we have an alternative this next century to either burning all our fossil fuels and the negative encounter that would come from that or to a nuclear fission power economy.

Chairman SMITH. The gentlelady's time has expired. The gentleman from Connecticut, Mr. Larson.

Mr. LARSON. Thank you, Mr. Smith. And I thank the panelists as well for this interesting and informative discussion. The one thing that I come away with is that all of you are absolutely sure that nanoscience and nanotechnology is the way of the future. I think someone used the term what we need to do is plant the flag. One of the things that seems to work here in Washington is if we're planting the flag we're doing so because there's an enemy that we're dealing with or a nation at risk.

I believe—and not much has been discussed with respect to this—that on a number of technological fronts, because of advancing technology and competing nations that do not lag that far behind us, that we're in a unique position of seeing this nation leapfrog with its own technology. Witness the individual, you know, traveling on bicycle in Burma with a cell phone, communicating. I'd be interested in your response to the potential for leapfrogging and where does the scientific community come in collectively and say, hey, wake up America. This is a real problem. You're about to be leapfrogged by your own technology and your own arrogance for not having seen the opportunity to reinvest in yourself.

Whoever wants to take it.

Mr. MERKLE. Okay, well I think the potential for leapfrogging is very great, obviously, because the basic requirements for doing research in nanotechnology are relatively small. It is possible for a relatively small organization to have a big impact. Now there are some very interesting questions around that as to whether a small group can effectively leapfrog a large group. I think they boil down to understanding where you're going and having a clear and sharp focus. And I think if a small group had a sharp focus, it could be very effective. Whether or not such a small group with such a sharp focus will develop in some foreign country I really can't say. It's certainly a possibility.

Mr. LARSON. You have the opportunity to make the decision today in this country to invest X number of dollars into nanotechnology. What would that figure be and where would you direct its focus?

Mr. MERKLE. I think the focus would be directed towards research which improved our ability to manipulate molecular structure. That would include scanning, probe microscopy, and self-assembly. That would be on the experimental end. I think on the theoretical end, I would focus very clearly on what does a molecular manufacturing system look like? In other words, we have been talking about what will we be seeing in 20 years or 30 years, sometime in the next century? What will these remarkable advances look like?

We have computational capabilities today which will let us model proposed molecular machines. And we could have very strong theoretical programs aimed at describing what this future will look like so we have a better understanding of what it is and how best to achieve it.

Mr. LARSON. So help me here. As a government official, what does the government do? Put out an RFP to our universities to say, look, please respond, you know, to this money that we've set—how would you go about directing that and focusing those dollars so it gets into the hands of people that are on the cutting edge of this technology? I mean, please help me here. I'm just——

Mr. WONG. Yes, I think the National Science Foundation's in that business. It's our business to fund the most promising areas of research. And I think we believe in betting on the people; supporting the infrastructure, the research infrastructure; the universities; the highest quality peer-review process. I think these are all important parts of the infrastructure that we have built up that have made the basic research such a productive enterprise.

Speaking of leapfrogging, I think there are two points I'd like to make. One is it's easy to leapfrog in one specific aspect and that happens all the time. But in terms of an overall paradigm shift, to be able to really move, in a major way, in the sector, that requires a basic infrastructure. And I have a great deal of faith in the robustness of our infrastructure.

Mr. LARSON. How much money should the country be investing?

Mr. WONG. The—I guess—I can tell you what we are doing now. The NSF at the moment is spending $90 million a year in nanoscale funds for research.

Mr. LARSON. Is that enough, Dr. Wong?

Mr. WONG. That's not enough, but I think you are leading me to a dangerous place, which is to anticipate what the——

Mr. LARSON. That's our job. To lead you to dangerous places so we can make better decisions.

Mr. WONG. Yes. I will try to accommodate you a little bit. I think the final budget will be issued, that the Administration is going to work out, over the next few months, but, clearly, from my own vantage point, I'm eagerly advocating the cost of this very important research.

Chairman SMITH. The gentleman's time has expired. It's at $230 million governmentwide, including other agencies, in addition to the $90 million.

I think we'll do a short second round. And, Dr. Merkle, a question for you. How much can we expect the private sector to move ahead with research? Some have suggested, until they see the application within 2 to 5 years, there's not going to be an interest in the commercial sector to contribute to this kind of research. Give me—guide us in terms of what Xerox is doing and what we can expect other private sectors to do.

Mr. MERKLE. Well, Xerox, as an example, is happy to have one or perhaps ½ a researcher working in this area, but certainly would not pursue any larger effort unless there were some outside source of funding. So the idea of having a 5- or 10-person group, which is relatively modest as these things go, focus specifically on molecular and nanotechnology is not something that would be within the charter of Xerox. Similarly, I think, many other companies are relatively limited, or if they are pursuing research, are pursuing research with relatively near-term goals. So the commercial funding for long-term development is relatively modest at the corporate level. If you look at major corporations, they are not pursuing this as aggressively as they might.

Chairman SMITH. The testimony from all of you, though, seems to imply that the application is in reach in a lot of areas and, if that is true, it seems like, somehow, there's a way to harness the contribution, financial contribution, an effort of the private sector as well. Does anybody have a reaction? Yes, Mr. McWhorter.

Mr. MCWHORTER. I think the private sector will invest and will invest in a very large amount, but the issue with the private sector is risk. And, you know, the key aspect of what the investment will be is, you know, when will they see what the application is and when will they see the risk being mitigated? And so I think with a program like the NSF program that's being described, one of the key roles that that does is it shows the direction and it mitigates the risk so that you can free up and realize the private sector investment.

Chairman SMITH. Dr. Smalley, you have an answer.

Mr. SMALLEY. Well, there's a huge difference between the circumstance where you see a product in 2 to 3 years and one where you imagine one in 10 years. In the current financial enterprise, you can make a start-up for the first, but you'd be a fool to make a start-up with the second, unless you're in the biotech industry in which case you may still be a fool.

We're certainly talking about the 10-year, 20-year time horizon. And so, at the moment, this is primarily a responsibility of large organizations in societies like our Federal Government. I believe that's really the way it ought to be. I mean, I think that American industry has evolved in a healthy way and that they are much better about taking care of the short-term applications where they need to get their profits. But that devolves upon universities and federal laboratories much more the core responsibility for taking care of a longer-distance view.

Chairman SMITH. Dr. Wong, how would we manage a multi-agency nanoscience initiative? Should NSF be a lead agency? Have you done any thought on this? Has there been any talk between the agencies that are now working——

Mr. WONG. The NSF has been the coordinator of a major inter-agency effort for the last few years. There's a very active working group going on now chaired by NSF in this area. We are prepared to play that role. We've had a long history in it. We are absolutely determined and devoted to this as a major strategic direction. Since we are the primary funder of basic sciences and long-lead-time projects, I think we are probably in a position to do that.

Chairman SMITH. How about our effort of being aware of the research that's being accomplished in other countries? Do we have the—I notice we have cut way back on our science attaches even in Japan. Do we have the proper effort to observe and keep abreast of what's happening in other countries? Whoever can best answer that.

Mr. SMALLEY. Well, as an active researcher in the field, the one thing we do most of the time is worry about what other people are doing. And so there is a tremendous amount of scrutiny and, for that matter, collaboration with researchers in European and Japanese laboratories. So that aspect, I think, is well in hand.

Now, broader, on the national security level, looking at programs we may not be aware of through the published literature and at conferences and so forth, this I'm not equipped to comment on but it is, perhaps, something that needs to be looked at.

Chairman SMITH. Representative Woolsey.

Ms. WOOLSEY. Well, you stole my question. And I was going to ask Dr. Wong and Dr. McWhorter about cooperation internationally. So I suppose what I'd like to say—ask is how can we do a better job of being—of partnering with other scientists around the world so we're not reinventing the wheel if it's already invented and et cetera.

Mr. WONG. I think we've—over the last 15 years or 20 years—we really have evolved a system of international competition yet cooperation at the same time that's extremely healthy. At the basic science research level, there's open publication, there's open exchange. I think that's been a tremendous boon to the whole field and we will continue to do that.

Ms. WOOLSEY. Mr. McWhorter.

Mr. MCWHORTER. I agree. I think this is an area that we have done very well in. You know, we are a global community now and it's, you know, I think the world of scientists are much more connected these days and most of the conferences are international in nature and so there's a lot of interaction among people from different countries.

Ms. WOOLSEY. Well, where would it not be? I mean, when we talk nuclear, is that a place where we wouldn't be sharing?

Mr. WONG. I think there are at least two areas where one has to be very careful. One is national security issues, when national security issues are involved, clearly we ought to be careful. And second is when intellectual properties are involved, when the research and development have moved sufficiently downstream to have property rights. I think there we have to be careful as well unless our commercial interests be impaired.

Ms. WOOLSEY. And is it possible to be careful enough? I mean, if we are all working together globally would we maybe not have to be so careful? Oh, you know where I am. I've shown my hand.

Mr. WONG. My bias is that we can always improve, but I think we're doing pretty well. That's my bias.

Ms. WOOLSEY. Anybody else like to respond to that?

Mr. SMALLEY. I believe it's much easier to render the entire process sterile by trying to be too careful than it is to both succeed in developing an area and make sure that you've kept it all to yourself. You spend all your time trying to make sure that nobody else gets a good idea, you shut down your own intellectual activities.

So in this area of nanotechnology where it's tempting, in fact almost impossible to avoid, talking about revolutionary advances, which will have huge economic impact and national security implications, it's quite easy to get yourself in a conversation where you're saying, well, if it's that important, let's put it all behind a fence and we'll do it all ourselves and never talk to anybody. And that would be a prescription for sterility. It would not happen in the United States. And we would guarantee being a third-class player in the game.

Ms. WOOLSEY. Okay.

Mr. MCWHORTER. I think that we can keep in mind the difference between nanotechnology in general versus specific, say, national security applications of nanotechnology. And in the general case, you know, cooperation is good. And in the specific case of national security, secrecy and confidentiality is critical. And so there would be applications that, maybe at a national lab, where, you know, we wouldn't talk about the work. And so, you know, the national security issue is a very important one.

Mr. MERKLE. Yes, I think, actually, I would agree with the general comments. One of the observations is that an international cooperative effort where we are very closely involved with researchers in other countries is also a very good way of monitoring their activities so that we are not caught by surprise.

Ms. WOOLSEY. Thank you.

Chairman SMITH. Mr. Larson.

Mr. LARSON. Thank you again, Chairman Smith. And, again, my appreciation. Just a quick two questions. One will be very simple to answer, but the—in the President's proposed information technology initiative, it includes the acquisition of the terascale computing system for addressing challenging scientific computing problems. What would be the impact of that level of computational power on nanotechnology research?

Mr. SMALLEY. It's vast. The key aspect of nanotechnology is you're now dealing at the fundamental, ultimate level where you know where all the atoms are. That instantly makes it a fundamental science. So if you know where the atoms are, you can say, okay, how does it behave? And it becomes a calculatable problem. Well, not calculatable with the computers of a couple decades ago, but, interesting, calculatable now with these new incredible computers.

And I can tell you from my own research as we try to build these cables that are 100 times stronger than steel and so forth, every day there are questions: well, how can we make this work? And we'll think up some way. It'll take us months to see whether it works. And we do calculations to see whether it's feasible. And those calculations are now becoming much, much more relevant and much more fundamental.

It's a wonderful aspect about nanotechnology that hasn't been mentioned today so far is that it is simultaneously deep, fundamental true science of the true ivory tower sort and yet commercially, in some cases immediately, financially interesting. By and large the reason that biotechnology has a special flavor is that it is a nanotechnology. That you know where all the atoms are. You can calculate it. And yet you're dealing with some little nano object that suddenly has a commercial importance as a drug. And so you will find researchers in biotech industries, completely privately funded, doing research that would fit perfectly in a biochemistry department in a university and visa-versa. There's this immediacy between the ivory tower pure scientist and the technologist.

In the rest of science, by and large, that's not been the case. The pure scientists are dealing with problems and techniques that are pretty far from the commercial realm, with a few exceptions. But in nanotechnology, they will get much more together. So it will have the effect of vitalizing the American scientific establishment by getting the scientist at the most fundamental levels involved in objects of societal and commercial importance.

Mr. LARSON. What are the top 10 universities in this country dealing with this technology?

Mr. SMALLEY. Well, Rice University, clearly, is number one. [Laughter.]

By and large, they are the top 10 that you always hear mentioned, although since the 1960's and the 1970's, the strength of research in this country has broadened out dramatically from the Harvard and MIT, Cal Tech, Princeton, Yale. But those names still are up high on the list, for good reasons.

Mr. WONG. Let me mention, if I may, a topic that hasn't been raised—bioinformatics. It's a subject that's very closely connected with nanotechnology. And bioinformatics lives on terascale computers. And the computation involving the shape of molecules and their functions is a critical part of bioinformatics. And it's probably the most exciting part of biotechnology today.

Mr. LARSON. And, Dr. Merkle, you've made the distinction a couple of times here, at least—and for a non-scientist, forgive me—but you keep—when we say nanotechnology, you make a point to say molecular nanotechnology.

Mr. MERKLE. Well, I think there is the idea that we'll be able to build a wide arrangement of molecular structures. And, in particular, one of the things which, of course, I've mentioned a few times is that artificial self-replicating systems will play an important role. This is an idea which I think is gaining acceptance, but is not yet fully accepted throughout the scientific community, and so I want to just say that this is an area where there are some differences in opinion about the particular routes to follow, but, nonetheless, agreement about the overall goals and objectives that we should be able to build, essentially, most of the structures that are consistent with physical law.

Mr. LARSON. Thank you, sir.

Chairman SMITH. Gentlemen, on behalf of the Committee, the Congress, the Nation, our compliments to you for what you have achieved so far. I think all of us that have heard your testimony today and will read your testimony in the transcript are going to be the flag bearers because it seems obvious that the information—there's enough information and enough justification to aggressively pursue additional research in this area. I mean, it might not culminate in what we would hope it would, but it seems obvious that the justification is there and it's a worthwhile pursuit and I think we will aggressively pursue that as we proceed with our new appropriations.

So, again, my thanks. My compliments. We would like to ask your permission to send you additional questions. One question I would like you to answer for us, if you will, is how do we best devise the kind of peer-review process that is going to help us best assure that the taxpayers' dollars is best spent? So if you'll include that in your responses.

Chairman SMITH. So, again, thank you very much and this Committee is adjourned.

[Whereupon, at 4:20 p.m., the Subcommittee was adjourned.]

APPENDIX 1: Opening Statements

THE HONORABLE NICK SMITH
CHAIRMAN, SUBCOMMITTEE ON BASIC RESEARCH

OPENING STATEMENT

HEARING ON

Nanotechnology: The State of Nano-Science and Its Prospects for the Next Decade

June 22, 1999

Today, the Subcommittee is meeting to review federal funding of research into nanotechnology, to discuss the role of the federal government in supporting nano-science research, and to discuss the economic implications of scientific advances made in the field of nanotechnology.

In Fiscal Year 1999, the federal government will spend approximately $230 million on nanotechnology research. Eighty percent of the funding comes from the National Science Foundation, the Department of Defense and the Department of Energy. The remaining money comes from the National Institutes of Health, the Department of Commerce, and NASA. In addition, the private sector has shown interest in the field of nanotechnology.

According to testimony submitted by our panelists, scientists have already learned a great deal about how to use nanotechnology. The best example of this is today's biotechnology industry. But according to researchers, that is only the beginning. Nanotechnology holds great promise for breakthroughs in health, manufacturing, agriculture, energy use, and national security. In fact, some researchers state that over the next few decades, nanotechnlogy will impact every aspect of our society.

Unfortunately, while progress has been made, the United States does not dominate nanotechnology research. A significant amount of research is currently underway in Europe and in Japan.

In that context, it is appropriate for the Subcommittee to take a good look at the federal government's role in funding nanotechnology research, to discuss what can be done to help move this research from the lab to the marketplace, and to discuss where nanotechnology might be in ten, twenty or thirty years from now.

I would like to thank our panelists for appearing before the Subcommittee today, and I look forward to hearing their testimony.

**OPENING STATEMENT
HEARING ON
NANOTECHNOLOGY: STATE OF NANO-SCIENCE AND ITS PROSPECTS FOR THE NEXT DECADE
BY
THE HONORABLE EDDIE BERNICE JOHNSON (D-TX)**

June 22, 1999

I am pleased to join the Chairman in welcoming our witnesses to this afternoon's hearing.

The ages of civilization are often designated by reference to a prominent material that could be fashioned by the prevailing state of technology: for example, the stone age, the bronze age, and the iron age. Now, we are at the threshold of an age in which materials can be fashioned atom-by-atom.

The word "revolutionary" is too overworked to have much impact anymore. But nanotechnology, which is the subject of today's hearing, truly is revolutionary. As expressed in a recent report from the National Research Council, "the ability to control and manipulate atoms, to observe and simulate collective phenomena, to treat complex materials systems, and to span length scales from atoms to our everyday experience, provides opportunities that were not even imagined a decade ago".

Nanotechnology will have enormous consequences for the information industry, manufacturing of all kinds, and medicine and health. Indeed, one of our witnesses has written that it will leave virtually no product untouched.

I congratulate the Chairman for convening this hearing so that we may learn more about the promise of research related to nanotechnology and about the marvels that have been accomplished thus far.

We are naturally interested in hearing the panel's assessment of the vitality of federally supported research efforts in this field. We are aware that planning activities are underway which may lead to a research initiative on nanotechnology in the Administration's fiscal year 2001 budget request. The views of the panel on the value, timeliness, and appropriate focus of such an initiative would be welcome.

Again, I want to thank the Chairman for calling this hearing. I appreciate the attendance of our witnesses today, and I look forward to our discussion.

Statement of the Honorable Lynn Woolsey (CA-06) on Nanotechnology: The State of Nano-Science and Its Prospects for the Next Decade

House Science Subcommittee on Basic Research
June 22, 1999

Mr. Chairman, I'm pleased we're here today to look at the fascinating possibilities of "nanotechnology." It's hard to imagine building tools or materials that are ten times the size of an atom, but it's a symbol of how large vision can create such small technology.

Nanotechnology can take us to new levels in learning, building and healing. For example, we can create new materials that are lighter and stronger than anything we've ever known. This can help with building lightweight materials to make space travel economical, efficient and accessible to anyone with a sense of adventure.

Through nanotechnology, we can also make medicine unbelievably precise. The sharpest scalpel would seem a very blunt instrument when we can treat patients at the cellular level without damaging tissue.

We can also improve learning through nanotechnology. These advancements can help develop transistors that improve computer technology by a million-fold while using less energy.

These are three examples of why I am glad the Clinton Administration is looking at developing a nanotechnology research initiative as part of the FY 2001 budget request. It is important that we maintain a competitive edge in such important technology, and we need the funding to lead this crucial research. Because I fear that if the United States won't, our international competitors will.

I look forward to hearing from our witnesses about the effects of nanotechnology-related research on our economy and the well being of society. Thank you, Mr. Chairman.

APPENDIX 2: Written testimony, Biographies, Financial Disclosures, and Answers to Post-Hearing Questions

Nanoscale Science and Technology: Opportunities for the Twenty First Century

Subcommittee on Basic Research,

Committee on Science

U.S. House of Representatives

Eugene Wong, Assistant Director for Engineering

National Science Foundation

June 22, 1999

Mr. Chairman and Members of the Subcommittee:

My name is Eugene Wong and I am the Assistant Director of the National Science Foundation for Engineering. I am pleased to have the opportunity to testify before you on the very great opportunities that are presented to us in the area of nanoscale science and technology.

What is nanoscale?

One nanometer is one billionth of a meter. It is a magical point on the scale of length, for this is the point where the smallest man-made devices meet the atoms and molecules of the natural world. To get an idea of the scale, we can compare the lengths of some familiar things. The diameter of an atom is about one quarter of a nanometer. The diameter of human hair is about 10,000 nanometers. The smallest experimental electronic devices that have been made are about ten nanometers in their smallest dimension. The smallest devices on commercially available chips are about 200 nanometers. Protein molecules, which are so critical to living things, are several nanometers in size. *Nanoscale* refers to dimensions that vary from a fraction of a nanometer to tens of nanometers.

Figure 1 provides a good illustration of the scale. This is a scanning tunneling microscope image of a pyramid of germanium atoms on top of a silicon surface. The pyramid is ten nanometers across at the base, and it is actually only 1.5 nanometer tall. Each round-looking object in the image is actually an individual germanium atom. The pyramid obtained by Stanley Williams at the Hewlett-Packard Labs was formed in just a few seconds all by itself via a process called ***self-assembly***, which is illustrated in **Figure 2.**

Over the last twenty years, a series of instruments were invented that now allow us to see, manipulate, and control objects at nanoscale. They are the eyes, fingers and tweezers of the nanoscale world. With these tools, a new world of discovery and invention has been created. This is the world of nanoscale science and technology.

What is new?

Nanoscale phenomena and objects have been around for some time. Catalysts, for example, are mostly nanoscale particles, and catalysis is a nanoscale phenomenon. Photography is another example of nanoscale technology. Most of molecular biology works at nanoscale. What is new and different now is the degree of understanding and deliberate control and precision that the new nanoscale techniques afford. Instead of discovering new phenomena by accident or by random search, we can look for them systematically. Instead of finding nanoscale particles and structures with good properties through serendipity, we now seek to design them to order. Furthermore, novel structures and fundamentally new properties and processes can be obtained. We are witnessing an explosion of revolutionary discoveries at nanoscale.

Why are nanoscale phenomena and techniques so important?

First, the small size itself is of great potential benefit. The creation of modern information technology, for example, was made possible by systematically reducing the size of devices on a chip, thereby increasing the processing capability of a single chip. Composites are mixtures of particles of different types. Because nanoscale particles have large surface-to-volume ratios, composites made of nanoscale particles can better retain the best properties of their constituents.

Second, with the ability to control and alter nanoscale structures of materials we can often improve or profoundly change the properties and phenomena in materials without changing their chemical composition. That is, the same molecules are present, but their physical arrangement is changed. Furthermore, high performance devices can be built that were not possible before.

Third, much of molecular biology works at nanoscale. By using the techniques of nanoscale science in biology, we gain two great advantages, a deeper understanding of how nature works and ways to improve upon nature. Self-assembly, for example, is an important biological phenomenon. Understanding it affords the possibility of making inorganic things through self-assembly, as we have already seen in the germanium/silicon example in Figure 2. At the same time, applying the new found techniques of manipulating molecules affords the possibility for gene and drug delivery by directly moving molecules into cells.

Multi-scale assembly and integration are critical to all functional systems, living and man-made. The lessons of microelectronics and biology are different, yet both powerful. The lesson from electronics is a top-down design that dramatically limits the increase in complexity when density of devices and interconnection increases. The lesson of biology is the power of self-assembly. Nanoscale science and technology hold the promise of combining the best of both, working both top-down and bottom-up, in producing systems of unprecedented power and elegant simplicity.

What are the applications?

The applications of nanoscale science and technology will lead to breakthroughs in information technology, advanced manufacturing, medicine and health, environment and energy, and national security. Some of these are as follows:

Materials and Manufacturing

Several possibilities for making precisely engineered materials through nanotechnology are immediate. These include new materials with vastly improved strength and wear characteristics, better catalysts for the chemical industry, new drugs and food products, and new materials for electronics and information technology.

Electronics

Electronics will be profoundly changed by nanotechnology in many ways. The invention of integrated circuits in the early sixties brought forth a technology that has proved to be the most scalable ever invented. The basic concept of "printing" circuits on a silicon base has continued to work as the density of devices increased from a few transistors on a chip to ten million transistors on a chip. However, the physical limits of the technology will soon be reached, and a new world of *nanoelectronics* will need to be invented.

The first commercial nanoscale products are already in production. A magnetic read-head (which reads information from a hard disk) of nanoscale dimensions based on the GMR (giant magneto-resistance) principle is on the market and promises to revolutionize the computer storage market. Prototypes of memory chips using an advanced version of GMR (TMR – tunneling magneto-resistance) have also been designed and fabricated. Figure 3 shows that the future magnetic random access memory chips will outperform by orders of magnitude the memory (~ 1000), response time (~ 100000), and size (~ 1/10) the chip built with the current technology in a business of $100B/year.

The basic techniques of microelectronics are being extended to a great variety of non-electronic applications. These include gene sequencing, DNA matching, combinatorial chemistry, micro-mechanical devices, optical and sensor chips, and hybrids involving electronics with any combination of the above. In all these applications, the techniques of nanotechnology are indispensable. For example, how does one place different chemicals in a million cells on a chip? The answer will have to come from nanotechnology.

Medicine and Health

Nanotechnology is so intimately associated with molecular biology that its potential application in this area is all pervasive. We have already mentioned better drug design and better drug and gene delivery. We have also discussed chip technology in biological and medical applications. Hybrid systems involving both living and artificial components such as synthetic tissues and organs for placement in cells are yet another possibility.

Biotechnology and Agriculture

The molecular building blocks of life - proteins, nucleic acids, lipids, carbohydrates and their non-biological mimics - are examples of materials that possess unique properties determined by their size, folding and patterns at the nanoscale. Imitation of biological systems provides a major area of research in several disciplines. For example, the active area of bio-mimetic chemistry is based on this approach.

Nanotechnology can be applied for improving animal and plant genetics, better control of the growing processes and use of chemicals for agriculture. Nanofabrication of detector arrays provides the potential to do thousands of experiments for simultaneous gene characterization and selection with very small amounts of material. **Figure 4** is of a chip with 6400 nanodots, each containing a small amount of a different gene in the yeast genome - and each representing a nanodetector capable of determining the amount of that gene being expressed by the yeast. The same experiment can now be performed with tens of thousands of genes, and by comparing the gene expression, scientists can discover which few genes are being activated or inhibited during growing process or disease. With the prospect of having in hand complete genome sequences, including the model plants, this information is critical to determine what genes will determine an improved production and when a plant is exposed to salt or drought stress. The application of this technology to agriculture has only begun to be appreciated. The nano-chip will allow the genes to be completely characterized molecule by molecule in just a few hours. Five years ago this same experiment would have taken dozens of scientists years to complete.

Automotive industry

Various applications are nanoparticle reinforced polymers and tires, resistant paintings, fire-resistant plastics, and increased efficiency of combustion. **Figure 5** shows A 'nano' network of polymer strings formed between nanoparticles that increases the material strength and its melting temperature. Several companies are developing practical synthesis and manufacturing technologies to enable the use of new high-performance, low-weight "nanocomposite" materials in automobiles. Proposed applications would save 1.5 billion liters of gasoline over the life of one year's production of vehicles and reduce related carbon dioxide emissions by more than 5 billion kilograms.

Energy technologies

New types of batteries, artificial photosynthesis for clean energy, quantum solar cells, safe storage of hydrogen for use as a clean fuel and savings using energy efficient processes are a few of the potential applications.

Environment

Selective membranes that can filter contaminants, nanostructured traps for removing pollutants from industrial effluents, improved control emissions from a wide range of sources, understanding the effects of nanoscale processes in environment on biodiversity and health, and maintaining industrial sustainability by significant reduction of materials and energy use, are only a few of the opportunities.

National Security

Detectors and detoxifiers of chemical and biological agents, continued information dominance, nanostructured electronics, camouflage materials, light and self-repairing textiles, use of uninhabited combat vehicles and miniaturized surveillance systems are several of critical defense applications that will depend on nanotechnology. **Figure 6** illustrates the development of new, economic detectors based on assembling of nanoparticles coated with DNA when the targeted bio-agent is present. Such detection was not possible before in the field.

Research Opportunities

The following areas of investigation were identified during a workshop convened by the Interagency Working Group on Nanoscale Science and Technology and held during January 1999:

- Long-term nano science and engineering research that will lead to fundamental understanding and to discoveries of novel phenomena, processes, experimental and simulation tools for nanotechnology.
- Synthesis and processing "by design" of engineered, nanometer-size, material building blocks and system components, fully exploiting self organization, patterning and other advanced concepts. Accelerate the application of multiscale modeling and high-performance computation to the prediction of nanostructured properties and phenomena and materials by design
- Nanodevice concepts and system architecture research to best exploit their properties in operational systems, and combining building-up of molecular structures with ultraminiaturization.
- Application of nanostructured materials and systems to manufacturing, power systems, energy, environment, national security, and health. Develop core enabling technologies such as fundamental molecular scale measurement and manipulation tools and standard methods, materials, and data that will be applied to many commercial sectors;
- Educate and train a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology;

The Federal Role, Past and Future

Nanoscale science and technology were born of basic research, much of it funded through federal support. The National Science Foundation has a long history of support for research into the fundamental physical, chemical and materials properties of nanometer-scale systems. This support has culminated in Nobel prizes in 1996 to Robert Curl, Richard Smalley and Harold Kroto for discovery of buckyballs (C60) and in 1998 to Robert Laughlin, Horst Störmer and Daniel Tsui for the discovery and explanation of the fractional quantum Hall effect.

The National Science Foundation also funds the National Nanofbrication User Network (NNUN) the primary infrastructure for chip-level nano-fabrication research. Through its recent initiatives "Functional Nanostructures,""XYZ on a Chip" and "Nanoscale Biotechnology," it is spearheading nanoscale technology activities in these important areas.

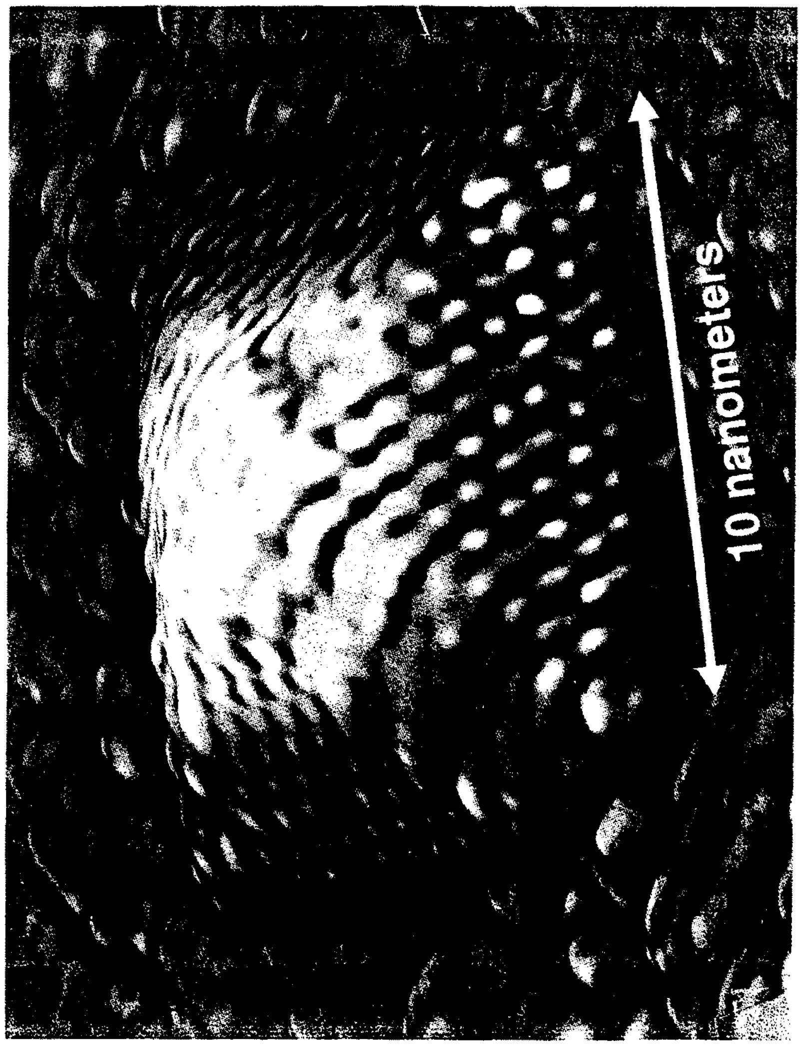
NSF has also played a lead role in coordinating interagency efforts in this area. Dr. M.C. Roco of NSF chairs the Interagency Working Group on Nanoscale Science and Technology, which operates under the auspices of the National Science and Technology Council through its Committee on Technology.

Despite its great commercial promise, the field of nanoscale science and technology cannot advance without federal support and cannot fulfill its promise in a timely way without a substantial increase in federal funding. This is so because so much of the work that is needed is fundamental research. Furthermore, even the work with targeted applications has a long lead-time. In the current competitive climate private sector investment will fall far short of what is needed and a strong federal role will be necessary for the field to advance, and to advance in a timely way.

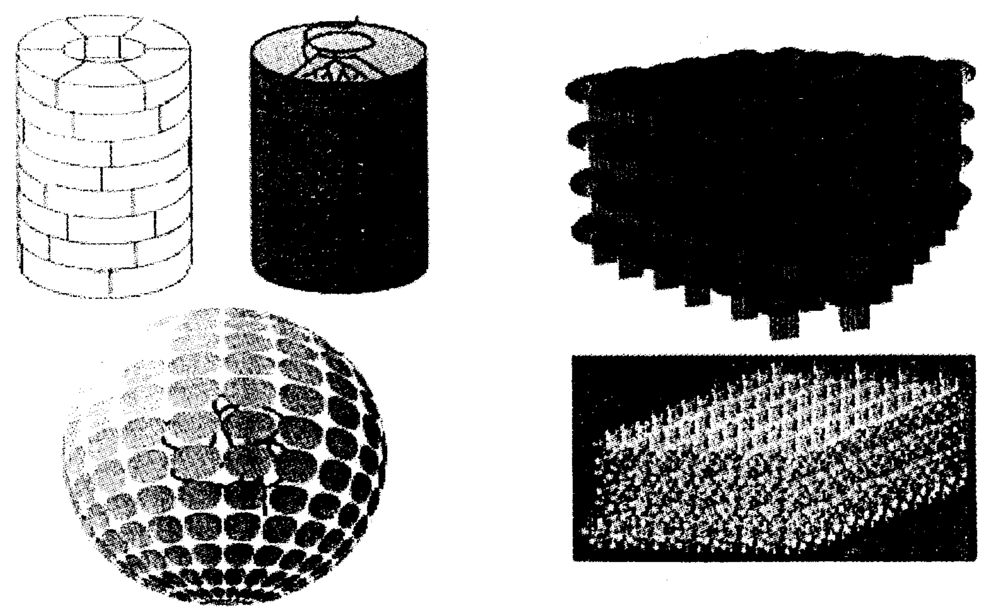
The current NSF funding is this area is approximately $90 million a year and the total funding among all agencies for FY'99 is estimated to be $240 million.

Through its role in funding research, NSF will also achieve two additional major objectives. First, the funding will catalyze private spending from industry. Second, because nearly all of NSF's funding goes to universities and because of NSF's emphasis on the integration of education with research, education in this area will benefit. Indeed, without the NSF role, it is unlikely that the trained manpower needed for this field will be available.

Nanoscale science and technology represent a major opportunity for the nation. It is a strategic area for NSF and we seek your encouragement and support.

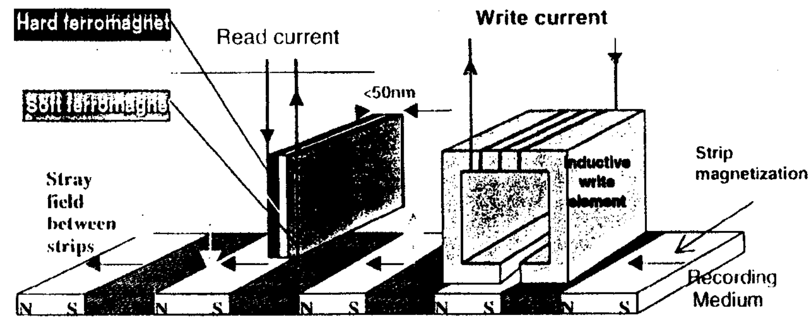

10 nanometers

NANO-SIZED POLYMERS SELASSEMBLING INTO FUNCTIONAL STRUCTURES

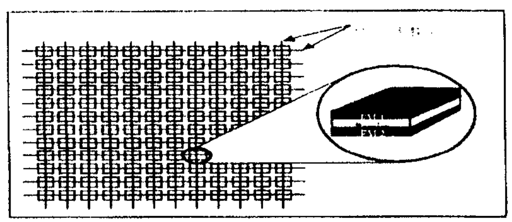


Tunneling Magneto-Resistance

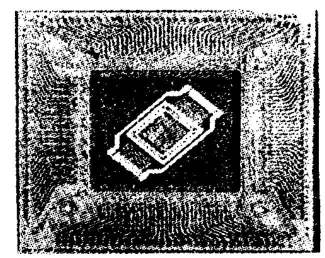
IBM in 1998:
Magnetic
nanolayers
for
hard disk
read heads



In 3-5 years:



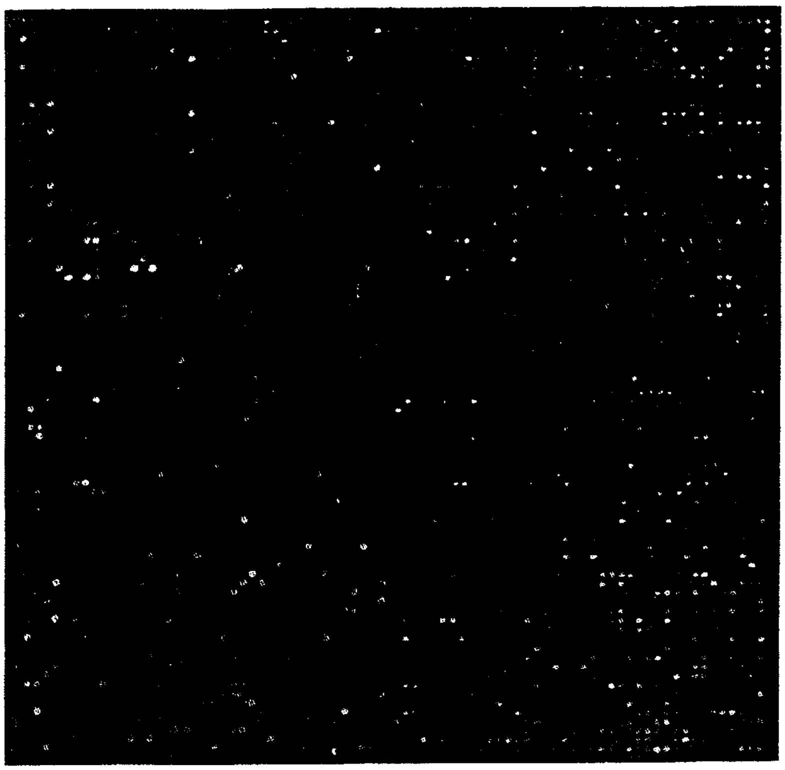
Magnetic randon access memory (MRAM)



More memory (~ 1,000),
faster (~ 100,000), smaller (~ 1/10)

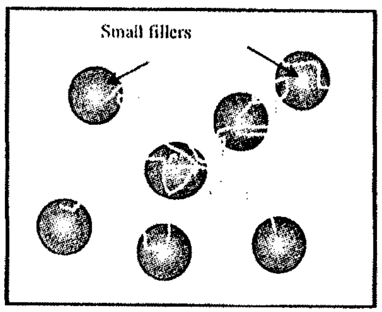
Lab-on-a-Chip with 6400 Nanodots

P. Brown at Stanford University



Nanocomposites new low-cost, high-strength materials for automotive parts

Dow Chemical Co. and Magna International of America (Troy, MI) have a joint ATP/ NIST program for manufacturing technologies to enable the use of new high-performance, low-weight "nanocomposite" materials in automobiles. Proposed applications would save 15 billion liters of gasoline over the life of one year's production of vehicles by the American automotive industry and reduce carbon dioxide emissions by more than 5 billion kilograms due to savings in replacement of other materials by nanocomposites.



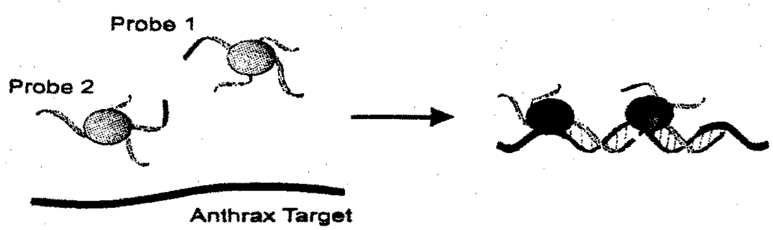
These materials are likely to find use in applications such as pipes and fittings for the building and construction industry; refrigerator liners; business, medical, and consumer equipment housings; recreational vehicles; and appliances.

Colorimetric sensor that can selectively detect biological agent DNA

(NRL/DOD)

- In commercial development with successful tests against anthrax and tuberculosis

- Compared to present technology, the sensor is simpler, less expensive (about 10 times) and much more selective (can differentiate one nucleotide mismatch in a sequence of 24)



No Anthrax Target Present

Anthrax Target Present

NATIONAL SCIENCE FOUNDATION
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ARLINGTON, VIRGINIA 22230

EUGENE WONG
ASSISTANT DIRECTOR FOR ENGINEERING

Dr. Wong was appointed to the position of Assistant Director for Engineering, at the National Science Foundation, on June 15, 1998.

Dr. Wong comes to the Foundation from the University of California, Berkeley and from Vision Software Tools, Inc. where he is Chief Scientist and a member of its Board. He has contributed extensively to research on stochastic processes in control and communication systems and was a pioneering researcher in database management systems. He was chairman of the Department of Electrical Engineering and Computer Sciences at Berkeley (1985-1989), Associate Director of the White House Office of Science and Technology Policy (1990-1993), a founder of INGRES Corporation (1980-90) and Vice President for Research and Development at Hong Kong University of Science and Technology (1994-1996).

Dr. Wong did his undergraduate and graduate work in electrical engineering at Princeton University and then continued his studies as an NSF Postdoctoral Fellow at Cambridge University. He is a member and Councilor of the National Academy of Engineering and a Fellow of the Institute of Electrical and Electronics Engineering.

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES
SUBCOMMITTEE ON BASIC RESEARCH

HEARING ON

Nanotechnology: The State of Nano-Science and Its Prospects for the Next Decade

RESPONSES TO FOLLOW-UP QUESTIONS

Dr. Eugene Wong
Assistant Director, Engineering Directorate
National Science Foundation

QUESTION 1: Several agencies have been working on the development of a new research initiative on nanotechnology for the FY 2001 budget request. The recommendation is to double current funding levels over three years.

QUESTION 1.1: What are the principal justifications for such an initiative?

ANSWER: The FY2001 budget request is currently under development. Although nanotechnology is an important topic, it is not yet clear whether there will be a new research initiative. If there is an initiative, I think there will be at least three major justifications: First, nanotechnology represents an extraordinary opportunity, one that cannot be fully realized without a significant increase in R&D investment. The essence of nanotechnology is the ability to work at the molecular level atom by atom. Acquiring this ability has profoundly changed the vision in every one of the major technology areas: materials, electronics, biotechnology, and information technology. Science fiction has become science reality. The potential to transform nearly every aspect of human existence is almost without parallel.

Second, the field is ripe for accelerated advances in both discovery and major applications. This point will be expanded in response to the question on "timeliness."

Third, the exciting promise of nanotechnology will not be realized without major *federal* support. This is so for a number of reasons. The tools of nanotechnology are necessarily ones of utmost sophistication. Sharply focused beams of light, electrons, atoms and molecules represent the principal agents of manipulation and control. Instruments that produce and control such beams are sophisticated and expensive. Nanotechnology is in early-stage research so that it is difficult to predict the pace of commercialization. In addition, there is a limited pool of trained people in nanotechnologyso that substantial investment in education will have to be made. These factors render it likely that there will be substantial under-investment by the private sector, at least initially.

QUESTION 1.2: Why is this timely?

ANSWER: The initial discovery of nanoscale techniques has been followed by a fifteen-year period of fundamental discoveries and tool development. We are seeing a veritable explosion of major discoveries. One indication is the fact that three Nobel Prize awards in the past five years were related to nanoscale science and technology, two directly. This is a clear indication that the time is ripe for a significant step-up in investment. Another reason why timing is right is related to developments in microelectronics. The incredible scalability of the integrated circuit technology is finally reaching its limit. To extend "Moore's Law" beyond its sixteen or seventeen cycles of doubling will require a new underpinning technology. Nanotechnology promises to do exactly that. Further, the "micro chip" technology is being extended with great effectiveness to a myriad of non-electronic applications such as genomics, biology, chemistry, sensors and mechanics. In nearly all these cases, the tools and devices of nanotechnology are being used, and more are needed.

QUESTION 1.3: What is the evidence that research ideas are significantly exceeding research support levels?

ANSWER: One piece of direct evidence is the response to the NSF program initiatives in this area. For example, only 13% of the proposals received in response to the 1998 NSF wide initiative on "functional nanostructures" were funded although 77% were rated as very good or excellent. This success rate would have been even lower if a limit of two proposals per university had not been imposed. A related NSF initiative "XYZ on a Chip" brought forth some 350 proposals of which only 20 are being funded.

The success rate provides only the most obvious evidence that research ideas are exceeding the research support levels. Other indicators are easy to find. First, the initial commercializations of research in nanotechnology are receiving enthusiastic market response. There is every indication that an accelerated investment in research will bring early and handsome returns. Second, some major facilities in microfabrication are quickly converting into nano facilities. This is true, for example, of the NSF micro-fabrication center at Cornell, which is now an anchor of the National Nanofabrication User Network (NNUN). Some members of the same team at Cornell have recently won a NSF competition to establish a Science and Technology Center on Nanoscale Biotechnology. The growth of these facilities will generate more ideas and fuel the demand for funding. Third, we see a significant increase in the number of academic departments that are building programs in nanotechnology. This will quickly lead to an accelerated increase of trained researchers and productive ideas. We have every reason to believe that ideas are outstripping the funding and that the situation will get worse, not better.

QUESTION 1.4: What are the main research opportunities that ought to be addressed?

ANSWER: Although this is a field with exciting promises of application, the major research opportunities are in long-term *fundamental* research that will lead to discovery of novel phenomena, processes and tools. New experimental and simulation tools probing the matter at nanoscale have fueled an explosion of fundamental discoveries at the molecular level. New discoveries are expected to lead to fundamentally new technologies. Paradigm changes are foreseen in the next 10-20 years in new nanoelectronic devices, systematic control of nanostructured materials, new targeted drug and gene delivery systems, to name the most evident. The research is crosscutting essential aspects of manufacturing, quality of life, environment and national security.

QUESTION 1.5: How would a multi-agency nanoscience initiative be managed? Of the participating agencies, which would be the "lead" agency?

ANSWER: The field of nanoscale science and technology has enjoyed a high degree of cooperation among the federal agencies. Under the auspices of the National Science and Technology Council and through its Committee on Technology, an active Interagency Working Group on Nanotechnology (IWGN) has functioned effectively for about a year. Given this history, it is likely that IWGN will form the core management team for the initiative. There will be a high degree of coordination in program and budget planning, and an equally high degree of coordination in execution, but there will also be a considerable freedom of individual decision-making in implementing agency missions and objectives. Over the past decade, we have seen a number of interagency federal science and technology initiatives launched and implemented. These will provide models and lessons in management for this initiative.

NSF has had a successful history in this emerging area. NSF is active in convening workshops to identify critical areas, formulating thematic foci through its program initiatives, promoting industry-university collaboration, and organizing coordination among federal agencies. These efforts led to the formation of the interagency working group IWGN and NSF currently chairs it. For the new initiative, both intellectual leadership and leadership in achieving a high degree of synergy among all participants, both government and private, will be required. NSF is prepared to accept any appropriate leadership role that it is called on to assume.

QUESTION 2: What are the fields in which we will see the most significant applications of nanotechnology and in what time frame do you predict we will see the full benefits?

ANSWER: The three principal categories of application are nanostructured materials, nanoelectronics together with its applications in information technology, and nanoscale biotechnology.

The fields most likely to benefit in the medium term (5-10 years) are computing and communication; pharmaceutical and medical devices; nanoparticles for colorants, sintering, catalysts, biochemical detection; various coatings for mechanical, optical, thermal, electric and magnetic effects; and nanostructured metals, ceramic and polymeric materials. The full benefits over the longer term (10-20 years) will significantly alter these fields, likely generate new industries, and impact many other areas such as the environment and space exploration.

QUESTION 3: What other nations have significant research programs on nanotechnology and how do they rank relative to the US? Are their particular subfields in which other countries are more advanced than the US?

ANSWER: Various components of nanotechnology had their origin in Europe, Japan, and the US, so it should come as no surprise that Japan and the European countries are active in this field. Focused research programs on nanotechnology have been initiated in almost all industrialized countries in the last five years. The survey made in 1997 by the World Technology Evaluation Center with participation of seven US agencies showed that US, Europe and Japan had made about the same annual government R&D investment of approximately $120M. Currently, the US has a lead in synthesis, chemicals, and biological aspects; Japan has an advantage in nanodevices and consolidated nanostructures; and Europe is strong in dispersions, coatings and new instrumentation. The United States appears to lag in nanodevices, production of nano-instruments, ultra-precision engineering, ceramics and other structural materials. Japan, Germany, U.K., Sweden, Switzerland and EU are creating centers of excellence in specific areas of nanotechnology. For example, in 1998, the Ministry of Science, Technology and Education in Germany established a network of six multidisciplinary "centers of competency" in nanotechnology with an annual budget of over 130M DM (or about $80M/year). Japan is making a strong investment in R&D to challenge the US lead in the initial commercialization efforts. For instance, in 1998 IBM developed the first commercial giant magneto-resistance (GMR) disk-head in the US, a breakthrough in the $34B disk drive market. Japanese companies (TDK, Yamaha, Alps Electric, and Hitachi Metals, followed by Sony, and Sumitomo Metals) are responding aggressively by shifting their magneto resistance (MR) disk-head production to GMR technology.

We should note, however, that international efforts in this area involve cooperation as well as competition. Provided that we make the necessary investment to gain and keep a leadership role, we should welcome the international investments that are being made.

QUESTION 4: One reason for our country's economic strength is our ability to move science from the lab to the marketplace. What are the engineering problems that need to be surpassed in order to move nanotechnology from the lab to a state of mass production? How would the proposed Nanotechnology Initiative address these problems?

ANSWER: The field is in an early stage of technology commercialization, so that the engineering problems are only identifiable in a generic way. Problems of design and production exist in every sector. For example, to move electronics from "micro" to "nano" will mean major shifts in every phase of design and fabrication. New patterning techniques will be needed to replace lithography. New interconnect technology will be critical and does not yet exist. "Scaling up" the existing techniques based on atomic and electron beams will be necessary to move the field from laboratory experiments to production.

The nanotechnology initiative should be developed as a partnership between government, the private sector, both academe and industry. At this stage of pre-competitive development, the government role as a catalyst is of tremendous importance. This role must be played with a deft touch and be based on well-tested programs that foster technology transfer and commercialization. At NSF, for example, the Engineering Research Centers (ERC), Materials Research Science and Engineering Centers (MRSEC), the Science and Technology Centers (STC), and the Small Business Innovation Research (SBIR) are highly successful activities in serving the catalytic role.

QUESTION 5: How significant will the impact be of nanotechnology on medicine and health care?

ANSWER: The potential to characterize an individual's genetic makeup will revolutionize the specificity of diagnostics and therapeutics. Beyond facilitating optimal drug usage, nanotechnology can provide new formulations and routes for drug discovery and delivery - enormously broadening their therapeutic potential. Moreover, biocompatible, high- performance materials will result from controlling their nanostructure. Proteins, nucleic acids, and lipids, or their non-biological mimics, are example of materials that have been shown to possess unique properties as a function of their size, folding, and patterns. Potential applications in the next ten years include rejection-resistant artificial tissues and organs, and gene and drug delivery systems.

QUESTION 6: Is NIH a major participant in the planning for the nanotechnology initiative, and if not, why not?

ANSWER: NIH is a major participant in the planning of this initiative and the most recent evaluation made in July 1999 is that its nanotechnology portfolio in FY 2001 might be significant.

QUESTION 7: In a scientific field as new and diverse as nanotechnology research, how would you formulate and implement an effective peer review process for selecting which research projects will be funded? How would a peer review process for nanotechnology research funding differ from NSF's normal peer review process?

ANSWER: Some of the funding for this area at NSF will be through unsolicited individual-investigator proposals. For these, the peer review system will not be different from the existing one. However, we expect that much of new funding will be for proposals solicited through interdisciplinary *program initiatives* targeting particularly timely areas. Because such initiatives are quite focused, the peer review process will make heavy use of panels that take advantage of specific sector expertise in the technical community. In addition, the "Centers" programs require yet another form of peer review, one that deals with issues that transcend mere research quality. We believe that a balance among these modalities of funding will be required to optimize the federal investment.

QUESTION 8: Generally, are the instrumentation and fabrication capabilities at universities adequate for support of nanotechnology research? If not, what are the main kinds of deficiencies, and is this an area that resources from the new nanotechnology initiative would be directed?

ANSWER: The fabrication and experimentation facilities needed for nanotechnology are indeed expensive. A considerable share of the initiative will be devoted to enhancing these capabilities.

However, it is important that we develop effective means to allow the facilities to be widely shared. NSF has had considerable experience in this regard. Indeed, a major nanoscale facility is the National Nanofabrication Users Network (NNUN) supported by NSF. This is a distributed facility with complementary capabilities at different sites, but coordinated to avoid duplication. Distributed user facilities that exploit networking to achieve maximum sharing and integration should be a major strategy for the initiative to make expensive facilities affordable and widely available.

QUESTION 9: What is the state of the human resource base available in the US to conduct research in the field of nanotechnology, in terms of research faculty at universities, industrial researchers and graduate students?

ANSWER: Nanoscale science and technology is an emerging field of research that has to rely on the relevant parts of chemistry, physics, and engineering for its human resource in the near term. It is seen as an exciting part of these disciplines and is attracting highly talented researchers, both students and faculty. For the longer term, major investments will have to be made to address the distinct education and training requirements of this field.

QUESTION 10: How would advances in nanotechnology improve American agriculture?

ANSWER: Nanoscience will contribute directly to advancements in agriculture in a number of ways: molecular-based biodegradable chemicals for nourishing the plants and protecting against insects; genetic improvement for animals and plants; delivery of genes and drugs to animals; and array-based technologies for DNA testing. For example, such array-base technologies will allow a plant scientist to know which genes are expressed in a plant when its is exposed to salt or drought stress. The application of nanotechnology in agriculture has only begun to be appreciated.

QUESTION 11: Dr. Merkle pointed out that many researchers think self-replication will be the key to unlocking nanotechnology's full potential as a robust manufacturing technology. Could artificial self-replicating systems pose unique risks?

ANSWER: Self-replication is an important mechanism for nanoscale assembly. However, the limited degree of self-replication that has been demonstrated, mostly for inorganic materials, is a long way from cloning. For now, ethical issues have not arisen. But as self-replication becomes better understood and developed, the risks will have to be reassessed.

The Role of Nanotechnology in the Second Silicon Revolution
Paul J. McWhorter
Draft of Testimony for the Committee on Science
June 22, 1999

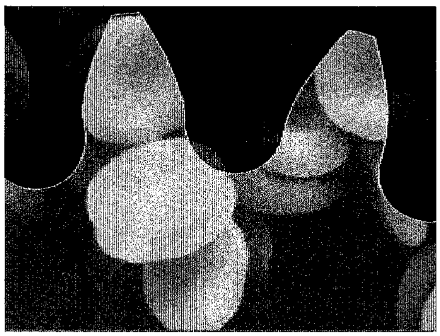

Photo of Sandia's Micro-engine Adjacent to Human Red Blood Cells.

It is difficult to imagine any field of science or technology that has had a more profound impact on the last half of this century than microelectronics. The hallmark of the microelectronics industry has been to each year provide chips that are smaller, faster, cheaper and better. This has revolutionized all aspects of our lives from our most advanced weapon systems, to our toaster ovens. The global microelectronics industry has vectored ahead based on a very simple metric; to make transistors smaller. As transistors become smaller, they become faster, you can pack more and more of them on a chip, and chips are able to store and process more information. To date, this has been the silicon revolution.

Today, we stand on the verge of a second silicon revolution. The metrics of the second silicon revolution will be different and more important that simply continuing to pack more transistors onto a chip. The metrics of the second silicon revolution will be the incorporation of new structures, microscopic machines, on the chip, alongside the transistors, creating a whole new generation of computer chip; a chip that can not only think, but sense, act and communicate as well. These fully functioning machines have feature sizes smaller than a human red blood cell. This new capability will have as profound of an impact on our lives over the next 30 years as microelectronics have had over the last 30 years.

The "Second Silicon Revolution" has begun, and a variety of commercial products exist today that contain micromachines, ranging from toys to important automobile safety devices. To fully realize the potential of the "Second Silicon Revolution", however, certain scientific hurdles must be overcome. In the 1800's, realization of high performance traditional macro-machines required the development of a fundamental understanding of the science of the micro-domain. Similarly, to effectively design, build and operate machines in the micro-domain, we must have a fundamental understanding of materials and surfaces in the nano-domain. Nanotechnology and nanoscience will be key elements of fully achieving the vision for micromachines and microsytems. It will be nanotechnology that will lead to new functions, better performance, and higher reliability in micromachines and microsystems.
[Show 2 minute video of actual micromachines in operation]

Paul J. McWhorter
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Biography

PAUL J. McWHORTER

Paul is presently serving as Deputy Director, Microsystems Science, Technology and Components Center at Sandia National Laboratories. Prior to assuming his present position, Paul initiated Sandia's Intelligent Micromachine Initiative in 1992, and has been the technical and programmatic leader of this activity. Under Paul's leadership this initiative has advanced the MEMS field by developing cutting edge technology for the integration of sensors, actuators and microelectronics on the same piece of silicon. This work has been recognized with 5 best paper awards, 2 R&D 100 awards, Industry Week's "Top Technology of the Year" Award, and Science News' Top Development of the Year Award. In 1998 Paul was named New Mexico Inventor of the Year.

Paul joined Sandia's Reliability Physics Department in 1985, developing predictive models for failure of integrated circuits. His research focused on the effects of the harsh radiation and thermal environments encountered in space and weapon applications on integrated circuits. These models are now used by Sandia and throughout industry to screen CMOS and nonvolatile memories for use in space and weapon systems.

A 1983 graduate of the University of Texas, Paul has a Bachelor of Science in Electrical Engineering. He subsequently earned a Master of Science in Electrical Engineering degree from Stanford University in 1985. He lives in Albuquerque, NM with his wife, Anna, and their eight year old daughter.

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Paul J. McWhorter, Deputy Director
Microsystems Science, Technology & Components

The Honorable Nick Smith
House Committee on Science
Subcommittee on Basic Research
2320 Rayburn House Office Building
Washington, DC 20515

Dear Representative Smith:

Thank you for the opportunity to respond in writing to the issue of improvements in the peer review process for an expanded nanoscience program. As was clear in the hearing, the development of a National Nanotechnology Initiative, led by NSF and involving centers of excellence in university, industry and government laboratories would extend the frontiers of science. Such an initiative would open broad opportunities that will impact our nation's communications, health care, energy, and national security infrastructures. The exploration and development of these broad opportunities will require an equally broad set of scientific, technological, and organizational approaches. Much of the scientific exploration needed in a nanoscience effort is well suited to small-group, university-like research environments. However, the output from these small group research efforts will, in many cases, require large-scale facilities such as synchrotron energy sources, ultra-high resolution microscopy centers, or high performance computing centers. These larger research facilities are necessary in order to synthesize, analyze, characterize, and fully explore the structure and properties of new nano-scale materials and devices that are discovered.

Yet larger scale integration of facilities, expertise and R&D environments will be required in order to move from basic science discoveries to useful nanotechnology. For example, centers where nanotechnology, microtechnology and biotechnology can be brought together will be necessary to derive the full value from basic nanoscience discoveries. Multi-disciplinary centers will build the interfaces between scientific disciplines and provide a path for new scientific discoveries to be translated into proof-of-principle technology demonstrations. As I noted in my testimony, these demonstrations help to reduce the risk in the transition from concept to commercialization and therefore are deserving of public support.

Obviously, the breadth of science and engineering that will be needed will also require a range of approaches to administer research funding and review the quality of work that is conducted. Basic research in small-group environments will be best addressed through specific peer reviewed research projects. On the other hand, larger centers, facilities and integrated efforts will require longer term, strategic investment of research funds, and an evaluation approach centered around broad expert review and advisory panels.

Please feel free to contact me for further input as the deliberations in the committee proceed. Again, thank you for the opportunity to address the committee on this exciting subject.

Sincerely,

Paul J. McWhorter, Deputy Director
Microsystems Science, Technology & Components

Copy to:
Mark Harrington
Counsel
Subcommittee on Basic Research
House Committee on Science

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Paul J. McWhorter, Deputy Director
Microsystems Science, Technology & Components

The Honorable Nick Smith
House Committee on Science
Subcommittee on Basic Research
2320 Rayburn House Office Building
Washington, DC 20515

Dear Representative Smith:

Attached is the response to your follow-up questions regarding the development of a new research initiative on nanotechnology.

Please feel free to contact me for further input as the deliberations in the committee proceed. Thank you for the opportunity to address the committee on this exciting subject.

Sincerely,

Paul J. McWhorter

Paul J. McWhorter, Deputy Director
Microsystems Science, Technology & Components

PM/cl

Enclosure with all copies: Follow-Up Questions/Response

Copy to:
Mark Harrington
Counsel
Subcommittee on Basic Research
House Committee on Science

Follow-Up Questions:

1) Several agencies have been working on the development of a new research initiative on nanotechnology for the FY 2001 budget request. The recommendation is to double current funding levels over three years.

- **Is there a need for such an initiative; is this timely; what is the evidence that research ideas are significantly exceeding research support levels?**

Impressive advances have been made in nanotechnology research over the last several years. The rate of scientific advancement and the opportunities for impacting the marketplace appear to be accelerating. However, the field of nanotechnology is presently fragmented across a wide range of disciplines. Programs in Japan and Europe are more unified and organized. Increased funding is needed in order to help unify the disparate efforts and to help build the Science and Technology infrastructure that would enable nanotechnology research breakthroughs to be incorporated into practical applications. Investment is needed in nanotechnology centers for fabrication, characterization and technology integration. These centers would enhance scientific discovery and provide the infrastructure to realize practical benefits from nanotechnology research.

- **What are the main research opportunities that ought to be addressed?**

Important opportunities exist in the areas of Nano-biotechnology, Nanoscale Structures/Quantum Control, Nanoscale Integration, and Nanoscale Interfaces.

2) What are the fields in which we will see the most significant applications of nanotechnology and in what time frame do you predict we will see the full benefits?

With proper balance between research and applied development we should expect to see benefits from nanotechnology in the 5-20 year time frame. Fruitful areas for application include Biomedical, New Materials, Energy, Environment and National Security. An early area of impact will be the application of nanoscale science to microtechnology, enabling new functionality in microelectronic and micromachine devices.

3) What other nations have significant research programs on nanotechnology, and how do they rank relative to the US? Are there particular subfields in which other countries are more advanced than the US?

In their combined programs, Europe and Japan are currently spending over twice as much as the U.S. in nanotechnology. Although all three of the major players appear to be on equal footing in addressing the scientific issues, Japan appears to be leading in the development of new devices from nanoscience discoveries.

4) One reason for our country's economic strength is our ability to move science from the lab to the marketplace. What are the engineering problems that need to be surpassed in order to move nanotechnology from the lab to a state of mass production? How would the proposed Nanotechnology Initiative address these problems?

In many cases, nanotechnology will not be the product that a consumer buys or sees. Nanotechnology will be a capability that enhances the cost, performance and reliability of products built using micro or macro technology. Some of the present challenges in realizing practical benefits from nanotechnology include:

- Characterization of nano-scale materials and structures
- Integration of nano-science into micro or macro products

By investing not only in basic research, but also in efforts to integrate nanotechnology into applications, significant practical benefits could be achieved.

5) How significant will the impact be of nanotechnology on medicine and health care?

Of all the fields perhaps medicine and health care stand to benefit the most from advances in nanotechnology. New nanometer probes and imaging tools will increase our knowledge and understanding of molecular, genomic and cellular processes that control disease and aging. Nanotechnology will provide new formulations and routes for drug delivery. The development of biocompatible materials for bone, tissue and organ replacement will result from new nanostructured materials.

6) In a scientific field as new and diverse as nanotechnology research, how would you formulate and implement an effective peer review process for selecting which research projects will be funded? How would a peer review process for nanotechnology research differ from NSF's normal peer review process?

The breadth of science and technology involved in the nanotechnology initiative will require a range of approaches to evaluate and review the quality of work that is conducted. Basic research in small-group environments will be best addressed through a strict peer review process. On the other hand, larger centers, facilities and integrated efforts will require a different evaluation approach, possibly centered around broader expert review and advisory panels.

7) What is the state of the human resource base available in the US to conduct research in the field of nanotechnology, in terms of research faculty at universities, industrial researchers and graduate students?

Currently the human resources available to conduct research in nanotechnology are fragmented across various science and engineering disciplines. As these resources are brought together under the nanotechnology initiative, new scientists and engineers will receive the multidisciplinary training needed to extend and integrate scientific discovery into market driven applications.

8) How would advances in nanotechnology improve American agriculture?

Agriculture is not my area of expertise, so I should probably not speculate on this.

9) Dr. Merkle points out that many researchers think self-replication will be the key to unlocking nanotechnology's full potential as a robust manufacturing technology. Could artificial self-replicating systems pose unique risks?

In my opinion, the idea of self-replicating nanodevices is still very much in the speculative stage. There is not necessarily a consensus that self-replication will be the direction that the field goes.

NANOTECHNOLOGY

Prepared Written Statement and Supplemental Material of R. E. Smalley, Rice University, June 22, 1999

Mr. Chairman, I appreciate the opportunity today to present my views on nanotechnology. There is a growing sense in the scientific and technical community that we are about to enter a golden new era. We are about to be able to build things that work on the smallest possible length scales, atom by atom with the ultimate level of finesse. These little nanothings, and the technology that assembles and manipulates them -- nanotechnology -- will revolutionize our industries, and our lives.

Everything we see around us is made of atoms, the tiny elemental building blocks of matter. From stone, to copper, to bronze, iron, steel, and now silicon, the major technological ages of humankind have been defined by what these atoms can do in huge aggregates, trillions upon trillions of atoms at a time, molded, shaped, and refined as macroscopic objects. Even in our vaunted microelectronics of 1999, in our highest-tech silicon computer chip the smallest feature is a mountain compared to the size of a single atom. The resultant technology of our 20th century is fantastic, but it pales when compared to what will be possible when we learn to build things at the ultimate level of control, one atom at a time.

Nature has played the game at this level for billions of years, building stuff with atomic precision. Every living thing is made of cells that are chock full of nanomachines - proteins, DNA, RNA, etc.- each jiggling around in the water of the cell, rubbing up against other molecules, going about the business of life. Each one is perfect right down to the last atom. The workings are so exquisite that changing the location or identity of any atom would cause damage. Over the past century we have learned about the workings of these biological nanomachines to an incredible level of detail, and the benefits of this knowledge are beginning to be felt in medicine. In coming decades we will learn to modify and adapt this machinery to extend the quality and length of life. Biotechnology was the first nanotechnology, and it has a long way yet to go.

Let me give you just one, personal, example: cancer. I sit before you today with very little hair on my head. It fell out a few weeks ago as a result of the chemotherapy I've been undergoing to treat a type of non-Hodgkin's lymphoma – the same sort that recently killed King Hussein of Jordan. While I am very optimistic, this chemotherapy is a very blunt tool. It consists of small molecules which are toxic – they kill cells in my body. Although they are meant to kill only the cancer cells, they kill hair cells too, and cause all sorts of other havoc.

Now, I'm not complaining. Twenty years ago, without even this crude chemotherapy I would already be dead. But twenty years from now, I am confident we will no longer have to use this blunt tool. By then nanotechnology will have given us specially engineered drugs which are nanoscale cancer-seeking missiles, a molecular technology that specifically targets just the mutant cancer cells in the human body, and leaves everything else blissfully alone. To do this these drug molecules will have to be big enough – thousands of atoms -- so that we can code the information into them of where they should go and what they should kill. They will be examples of an exquisite, human-made nanotechnology of the future. I may not live to see it. But, with your help, I am confident it will happen. Cancer – at least the type that I have – will be a thing of the past.

Powerful as it will be, this bio-side of nanotechnology that works in the water-based world of living things will not be able to do everything. It cannot make things strong like steel or conduct electricity with the speed and efficiency of copper or silicon. For this, other nanotechnologies will be developed – what I call the "dry side" of nanotech. My own research these days is focused on carbon nanotubes – an outgrowth of the research that led to the Nobel Prize a few years ago. These nanotubes are incredible. They are expected to produce fibers 100 times stronger than steel at only 1/6th the weight – almost certainly the strongest fibers that will ever be made out of anything. In addition they will conduct electricity better than copper. Membranes made from arrays of these nanotubes are expected to have revolutionary impact in the technology of rechargeable batteries and fuel cells, perhaps giving us all-electric vehicles within the next 10-20 years with the performance and range of a Corvette at a fraction of the cost.

As individual nanoscale molecules, carbon nanotubes are unique. They have been shown to be true molecular wires, and have already been assembled into the first single molecule transistor ever built. Several decades from now we may see our current silicon-based microelectronics supplanted by a carbon-based nanoelectronics of vastly greater power and scope.

It's amazing what one can do just by putting atoms where you want them to go.

Recently an Interagency Working Group on Nano Science, Engineering and Technology (IWGN) has studied the field of nanotechnology in detail, and made its recommendation to OSTP (March 10, 1999) for a new national initiative in this critical emerging area. Quoting from Mike Roco, chair of the IWGN:

"A national initiative, '*Nanotechnology for the Twenty-First Century: Leading to a New Industrial Revolution*' is recommended as part of the fiscal year 2001 budget. The initiative will support long-term nanotechnology research and development, which will lead to breakthroughs in information technology, advanced manufacturing, medicine and health, environment and energy, and national security. The impact of nanotechnology on the health, wealth, and lives of people will be at least the equivalent of the combined influences of microelectronics, medical imaging, computer-aided engineering and man-made polymers developed in this century. The proposed level of additional annual funding doubles (by $260M) the current level of effort, incrementally increased over three years. This initiative will focus on fundamental research on novel phenomena, processes and tools; synthesis and processing by design; nanostructured devices, materials and systems that are high-risk, broadly-enabling and are designed to have major impact; as well as on education and training of future nanotechnology workers and rapid knowledge and technology transfer."

Mr. Chairman, Honorable Congressmen, I believe it is in our Nation's best interest to move boldly into this new field.

As additional background material, the following is excerpted from *"Nanotechnology – A Revolution in the Making -- Vision for R&D in the Next Decade,"* a report of the Interagency Working Group on Nanoscience, Engineering, and Technology, presented to the OSTP Committee on Technology, March 10, 1999.

NANOTECHNOLOGY – A REVOLUTION IN THE MAKING

- VISION FOR R&D IN THE NEXT DECADE

Draft - Executive Summary - Draft

Recommendation:

As part of the fiscal year 2001 budget, the IWGN recommends a national initiative. The initiative, known as **NTR (Nanotechnology for the Twenty-First Century: Leading to a New Industrial Revolution)**, will approximately double the Federal Government's annual investment in nanotechnology research and development from its present (FY99) base of $234M per year. The increase will be incrementally grown over a three-year interval.

The NTR Initiative will address five activities:

- Long-term nano science and engineering research that will lead **to fundamental understanding and to discoveries of novel phenomena, processes and tools for nanotechnology**. This commitment will refocus the government investment beginning in the 1950s that led to today's microelectronics, microfabrication, and computer technology;

- **Synthesis and processing "by design"** of engineered, nanometer-size, material building blocks and system components, fully exploiting molecular self-assembly concepts. This commitment will generate new classes of high performance materials, bio-inspired systems, paradigm changes in device design, and efficient, affordable manufacturing of high performance products. Novel properties and phenomena will be enabled, as control of structures of atoms, molecules and clusters becomes possible;

- **Nanodevice concepts** including system architecture research to best exploit nano-derived properties in operational systems, and combining building-up of molecular structures with ultraminiaturization. The new nanodevices will cause orders of magnitude improvements in microprocessors and mass storage, create tiny medical tools that minimize collateral damage; and enable uninhabited defense combat vehicles in fully imaged battle fields. There will be dramatic payback to programs with this National priority including **information technology, nanobiotechnology and medical technology**;

- **Application of nanostructured materials and systems** to manufacturing, power systems, energy, environment, national security, and health. Areas of interest include advanced dispersions, catalysts, separation methods, and consolidated nanostructures, as well as increase the pace of knowledge and technology transfer;

- **Educate and train a new generation of skilled workers** in the multidisciplinary perspectives necessary for rapid progress in nanotechnology.

Potential for NTR impact is compelling:

- Nano science and engineering **knowledge is exploding worldwide** because of the availability of new investigative tools; maturity in the biology, chemistry, engineering, materials and physics disciplines, and interdisciplinary synergism; and financial support driven by emerging technologies and their markets. The science and engineering communities have generated a flurry of new results, doubling the publication rate each two-three years. During 1998, funding agency initiatives in nanotechnology (NSF Functional Nanostructures Initiative, and DoD Multidisciplinary University Research Initiative in Nanoscience) had success rates no higher than 1 in 6, constrained only by funding limitations;

- The nanotechnology revolution will lead to **fundamental breakthroughs** in the way materials, devices and systems are understood, designed and manufactured. Dr. Neal Lane stated at a Congressional hearing in April 1998 that, *"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."* Potential breakthroughs include orders-or-magnitude increases in computer efficiency; emergence of entirely new phenomena in physics and chemistry; nanofabrication of three-dimensional molecular architectures; novel processing architectures such as quantum computing and cellular automata; repair of human body with replacement parts; and a virtual presence in space;

- Nanotechnology is creating a **technology revolution** in the way materials, devices and systems are manufactured and perform. In the last few years, applying fundamental discoveries has developed multi-billion dollar product lines. These include: giant magnetoresistance multilayers (for computer memory), nanostructured coatings (in data storage and photographic industry), nanoparticles (colorants in printing and drug delivery in pharmaceutical field), superlattice confinement effects (for optoelectronic devices and lasers), and nanostructured materials (nanocomposites and nanophase metals). John Armstrong, formerly Chief Scientist of IBM, wrote in 1991, *"I believe nanoscience and nanotechnology will be central to the next epoch of the information age, and will be as revolutionary as science and technology at the micron scale have been since the early '70s."* More recently, industry leaders including those at the IWGN workshop on Jan. 27-29, 1999, have extended this vision by concluding that nanoscience and technology will change the nature of almost every human-made object in the next century;

- Nanoscience is an opportunity to **energize the interdisciplinary connections** between biology, chemistry, engineering, materials, mathematics, and physics in education. It will give birth to new fields that are only envisioned at this moment;

- European and Pacific countries have developed focussed programs in the science and technology of nanostructures that will provide **world-wide critical mass** to this initiative, accelerate progress, and guarantee commercial competition for the results.

NTR investment strategy:

- This initiative **builds on previous and current nanotechnology programs**, including some early investment from the Advanced Materials Processing Program, NSF instrumentation and functional nanostructures, and DoD programs supporting its Nanoscience Strategic Research Objective;

- The lead-time for science maturing into technology is approximately 10-15 years; now is a critical time for government investment in the S&T of nanostructures. The leaders from industry, academe and government present at the IWGN Workshop concluded that the Federal Government was underinvesting in **long-term nanotechnology research and development** relative to the outstanding opportunities. The private sector is unlikely to invest in nano science and engineering research until products are 3-5 years from commercialization;

- Roughly *70 percent of the funding will be for university-based research*, which will also help meet the demand for skilled workers with advanced nanotechnology skills in the next century. In the academic programs, it is anticipated that 65% of the funding will be for single investigators, 15% multidisciplinary programs and *5-10% for nanotechnology centers that will play a similar role to the supercomputer centers*, 5-10% instrumentation development and procurement, and 5% for the development of multidisciplinary educational programs. Government/industry/academic partnerships will be strongly encouraged.

Draft **NANOTECHNOLOGY – A REVOLUTION IN THE MAKING - VISION FOR R&D IN THE NEXT DECADE -** **Draft**

Interagency Working Group on Nano Science, Engineering and Technology (IWGN)
Dr. M. Roco, IWGN Chair, mroco@nsf.gov; Dr. J. Murday, IWGN Exec Sec, murday@ccf.nrl.navy.mil

Abstract:
A national initiative, "Nanotechnology for the Twenty-First Century: Leading to a New Industrial Revolution", is recommended as part of the fiscal year 2001 budget. The initiative will support long-term nanotechnology research and development, which will lead to breakthroughs in information technology, advanced manufacturing, medicine and health, environment and energy, and national security. The impact of nanotechnology on the health, wealth and lives of people will be at least the equivalent to the combined influences of microelectronics, medical imaging, computer-aided engineering and man-made polymers developed in this century. The proposed level of additional annual funding approximately doubles (by $260 M) the current level of effort, incrementally increased over three years. This initiative will focus on fundamental research on novel phenomena, processes and tools; synthesis and processing by design; nanostructured devices, materials and systems that are high risk, broadly enabling and are designed to have major impact; as well as education and training of future nanotechnology workers and rapid knowledge and technology transfer.

Contents:

1. Nanotechnology Definition

Nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomena and processes because of their small nanoscale size. Structural features in the range of about 10^{-9} to 10^{-7} m (1 to 100 nanometers) determine important changes as compared to the behavior of isolated molecules (1 nanometer) or of bulk materials. For comparison, 10 nanometers are 1000 times smaller than the diameter of a human hair.

We can exploit novel properties and phenomena of nano-based entities as we gain control of structures and devices at the atomic, molecular and supramolecular levels, and as we learn how to efficiently manufacture and use these devices. New behavior at the nanoscale is not necessarily predictable from that observed at large size scales. Important changes in behavior are caused not by the order of magnitude size reduction, but also by new phenomena such as size confinement, predominance of interfacial phenomena, quantum mechanics and Coulomb blockade. It is notable that all relevant phenomena at nanoscale are caused by the tiny size of the organized structure as compared to molecular scale, and by the interactions at their predominant and complex interfaces. Once we are able to control feature size, we can enhance material properties and device functions beyond those that we currently know or even imagine. Reducing the dimensions of structures leads to entities with novel properties, such as carbon nanotubes, quantum wires and dots, thin films, DNA based structures, and laser emitters. Such new forms of materials and devices herald a revolutionary age for science and technology provided that we can discover and fully utilize the underlying principles.

2. Revolution in the Making: Driving Forces

In 1959 Richard Feynman delivered a now famous lecture, "There is Plenty of Room at the Bottom." He stimulated his audience with the expectation of exciting new discoveries if one could fabricate materials and devices at the atomic/molecular scale. For this to happen, he pointed out the necessity of a new class of miniaturized instrumentation to manipulate and measure the properties of these small structures—nanostructures.

It was not until the 1980s that miniaturization of instruments actually surfaced in developments like scanning tunneling microscopes, force microscopies and near field microscopes. These instrument classes exploited microfabrication technology to enable nanometer resolution—a wide variety of the "eyes" and "fingers" required for nanostructure measurement and manipulation. In a parallel development, augmented computational capability now enables sophisticated computer simulations of nanostructures. These new techniques have sparked excitement in nearly all parts of the scientific community. Traditional models and theories for most material properties and device operations involve assumptions leading to "critical scale lengths" that are frequently larger than 100 nm. When the dimensions of a material structure is under the respective critical length scale, then the models and theories are not able to describe the novel phenomena. Scientists in all materials and technology disciplines are in avid pursuit of the fabrication and measurement of nanostructures to see where and what kind of interesting new phenomena occur. Further, nanostructures offer a new paradigm for materials manufacture by assembling (ideally utilizing self-organization and self-assembly) to create an entity rather than the laborious chiseling away from a larger structure.

Strong financial support for this research and development is motivated by the impressive potential for economic return, including continued improvement in electronics/electrooptics for information technology; higher performance, low maintenance materials in manufacturing, defense, space and environmental applications; and acceleration of biotechnology for medical, health and agricultural uses. John Armstrong, formerly Chief Scientist of IBM, wrote in 1991, *"I believe nanoscience and nanotechnology will be central to the next epoch of the information age, and will be as revolutionary as science and technology at the micron scale have been since the early '70s."* More recently, industry leaders including those at the IWGN workshop on Jan. 27-29 have extended this vision by concluding that nanoscience and technology will change the nature of almost every human-made object in the next century. Such significant improvements in materials performance and changes in manufacturing paradigms will lead to an industrial revolution.

Federal support of the nanotechnology infrastructure is necessary to enable the U.S. to compete in the global marketplace.

3. Nanotechnology Impact

The potential benefits of nanotechnology are pervasive:

Information Technology. The Semiconductor Industry Association (SIA) has developed a roadmap for the continued enhancements in miniaturization, speed and power consumption reduction of information processing devices—sensors for signal acquisition, logic devices for processing, storage devices for memory and displays for visualization. The roadmap projects the future to approximately

2010 and to 0.1-micron (100 nm) structures, just short of nanostructure devices. There are several reasons why it stops at 100 nm. First, it is not clear how to economically fabricate nanostructured electronics. Second, even if fabricated, the physical/chemical properties of those nanostructures are unknown; the present electronic devices are all based on models with critical scale lengths in the 100+ nm range. Third, without known properties it is impossible to design a functional device, fabricate and assemble the devices into a working system. The SIA roadmap explicitly calls for "sustained government support if this industry is to continue to provide for strong economic growth in the U.S." The lead-time for science maturing into technology is approximately 10-15 years; so now is the critical time for government investment in the science and technology of nanostructures for timely impact in information technology. Further, the investment will have spin-offs that enable the attainment (or acceleration) of the roadmap goals. The area of magnetic information storage is illustrative. Within ten years of the fundamental discovery of the new phenomenon of giant magnetoresistance, this new nanotechnology completely replaced older technologies for disk computer heads in the $34 B/yr hard disk market (1998). Other potential breakthroughs include: (a) orders of magnitude improvement in microprocessors - nanostructured transistors will continue the trend in lower cost per transistor and use less energy, thereby improving the efficiency of computers by a factor of millions; (b) changes in communications paradigms as higher frequencies (faster speeds) provide 10 times more bandwidth, with consequences in business, education, entertainment and defense; (c) expansion of small mass storage devices to multi-terabit capacities, 100 times better than today; and (d) integrated sensor systems that collect data utilizing minimal power, space and weight. Applications include: (a) affordable virtual reality stations to provide individualized teaching aids (and entertainment), (b) sufficient computational capability to enable uninhabited combat vehicles (and civilian transportation), and (c) communication capability that obviates much business travel (including commuting to a work place) in an era when transport fuels will be dramatically more expensive.

Medicine & Health. Living systems are governed by molecular behavior at nanometer scales where the disciplines of chemistry, physics, biology and computer simulation all now converge. Such multidisciplinary insights will stimulate nanobiotechnology progress far beyond its already impressive record of accomplishments in medicine and health over the last ten years. The molecular building blocks of life - proteins, nucleic acids, lipids, carbohydrates and their non-biological mimics - are examples of materials that possess unique properties determined by their size, folding and patterns at the nanoscale. We can now probe single molecule properties; this new information will complement (and largely supplant) the ensemble average techniques of present day life sciences. New analytical tools capable of probing the nanometer world will also make it possible to characterize chemical and mechanical properties of cells, of interest in cellular biology and pathology, including processes such as cell division, metabolism, regulation and locomotion. Utilization of nanofabricated surfaces and devices will increase the speed of genome sequencing by orders of magnitude, and thus our ability to probe and decode the fundamental nature of living systems. Coupling these advances in our knowledge of living systems, with the unique capabilities imparted by nanostructures and materials, we will be in a position to detect and intervene in pathology and disease using biologically inspired systems. Integration of biocompatible materials with fluidic, optic, mechanical and electronic components, all at micro to nano scale, will enable development of in vivo-implantable devices. For example, remote, non-invasive sensing systems will allow us to detect the earliest stages of emerging disease, whether caused by infection or tissue malfunction, and prevent overt disease development. Such early sensing will be coupled to better means of intervention such as coated particles to provide new routes for drug delivery, nano surgical approaches, and implantable drug synthesis and delivery systems, making prevention and therapy less costly, less traumatic for patients, and more effective. Applications include: (a) Rapid, efficient genome sequencing, which will permit the characterization of each individual's genetics, thereby enabling a revolution in diagnostics and therapeutics; (b) Intracellular sensors, which will allow for further understanding of the basic properties of living (normal and diseased) cells; (c) New formulations and routes for drug delivery, which will enormously broaden their therapeutic potential by effecting delivery of new types of medicine to sites in the body that were previously inaccessible; (d) More durable, rejection-resistant artificial organs will be developed from new biocompatible, high performance materials based on their surface nanostructure; (e) Sensing systems, which will allow the detection of emerging disease in the living body, and will ultimately shift the focus of patient care from disease treatment to early detection and/or prevention.

Materials and Manufacturing. Nanotechnology is fundamentally changing the way materials and devices will be produced in the future, including ceramics, metals, polymers, and their composites. The ability to synthesize nanoscale building blocks with precisely controlled size and composition and then to assemble them into larger structures with unique properties and functions will revolutionize segments of materials manufacturing. At present we perceive only the tip of the iceberg in terms of the benefits that nanostructuring can bring: lighter, stronger, and programmable materials, reductions in life-cycle costs through lower failure rates, innovative devices based on new principles and architectures, and use of molecular/cluster manufacturing. Molecular/cluster manufacturing takes advantage of assembly at the nanoscale level for a given purpose. Structures not previously observed in the nature can be developed. Challenges include: synthesis of materials by design, developments of bio- and bio-inspired materials, development of cost-effective and scalable production techniques, and determination of the nanoscale initiators of materials failure. Applications include: (a) net-shape manufacturing of nanostructured metals and ceramics; (b) improved printing brought about by nanometer-scale particles that have the best properties of both dyes and pigments; (c) nanoscale cemented and plated carbides and nanocoatings for cutting tools, electronic, chemical and structural applications; and (d) nanofabrication on a chip with high levels of complexity and functionality.

Aeronautics and Space Exploration. The stringent fuel constraints for lifting payloads into earth orbit and beyond, and the desire to send spacecraft away from the sun (diminished solar power) for extended missions, compel continued reduction in size, weight and power consumption of payloads. Nanostructured materials are also critical to lightweight, high-strength, thermally stable materials for planes, rockets, space station and planetary/solar exploratory platforms. The low gravity, high vacuum space environment may help develop nanostructures and assembled nanostructures that cannot be created on Earth. Applications include: (a) Low power, radiation hard, high performance computers; (b) Nanoinstrumentation for microspacecraft; (c) Avionics; and (d) Thermal barrier and wear resistant nanostructured coatings.

Environment and Energy. Nanotechnology will have potentially significant impacts on energy efficiency, storage and production. It can be used to monitor and remediate environmental problems; improve control emissions from a wide range of sources, and develop new, 'green' processing technologies that minimize the generation of undesirable by-products. The impact on industrial control, manufacturing and processing will be impressive and result in saving energy. Several technologies, developed without the benefit of the new nanoscale analytical capabilities or in development, illustrate that potential: (a) The Mobil Oil Co. long-term research program into the use of crystalline materials as catalyst supports has yielded catalysts with well defined pore sizes in the range of 1 nm; their use is now the basis of an industry that exceeds $30 B/yr; (b) The discovery of the ordered mesoporous material MCM-41 by the Mobil Oil Co., with pore size in the range 10 to 100 nm, that is widely applied in removal of ultrafine contaminants; (c) The Dow Chemical Co. has developed a nanoparticle-reinforced polymeric material that can replace metallic components in the auto industry; the wide spread use of those nanocomposites could lead to a reduction of 1.5 billion liters of gasoline consumption over the life of one year's fleet of vehicles and reduce the related dioxide emissions by more than five billion kilograms; (d) the replacement of carbon black in tires by nanometer-scale particles of inorganic clays and polymers is a new technology that is leading to the production of environmentally-friendly wear-resistant tires. Potential future breakthroughs also include use of nano-robotics and intelligent systems for environment and nuclear waste management.

National Security. The Department of Defense recognized the importance of nanostructures over a decade ago and has played a significant role in nurturing the field. Critical defense applications include: (a) Continued information dominance, identified as an important capability for the military, will depend on U.S. nanotechnology. (b) Nanostructured electronics will provide more sophisticated virtual reality systems that enable affordable, effective training. (c) Reduction in military manpower must be compensated by the increased use of nanostructure-enhanced automation and robotics, both of which will benefit from nanostructures. The use of uninhabited combat vehicles is desired, both to reduce risk to human life as well as to improve vehicle performance. For example, several thousand pounds could be stripped from a pilotless fighter aircraft, resulting in longer missions. In addition, the fighter agility could be dramatically improved without the necessity to limit g-forces on the pilot, increasing its combat effectiveness. (d) Nanostructured materials hold the promise for the high performance (lighter, stronger) needed in military platforms while simultaneously providing diminished failure rates and lower life-cycle costs. (e) Advances in medicine and health enabled by nanoscience will provide badly needed chemical/biological/nuclear sensing, protection and improvements in casualty care. (f) Changes are also possible in the design and weight reduction of nuclear weapons and systems used in non-proliferation.

Other Applications. Potential benefits from nano science and technology affect other government agency missions, including: (a) more economical and reliable transportation systems (DOT), (b) measurement, control and remediation of contaminants (EPA), (c) forensic research (DOJ), and (d) printing and engraving (BEP).

Global Trade and Competitiveness. Technology is the major driving factor for growth at every level of our economy. Nanotechnology is expected to be pervasive and ubiquitous in its applications across all technologies. Investment in nanotechnology research and development is necessary to maintain and improve our position in the world marketplace. This initiative will allow the development of critical enabling technologies with broad commercial potential. These enabling technologies include manufacturing and the measurement and standards tools necessary for U.S. industry to take advantage of nanotechnology innovations and improve our capability to compete globally.

Science and Education. The science, engineering and technology of nanostructures will require and enable advances in a fabric of disciplines: physics, chemistry, biology, mathematics and engineering. In their evolution as disciplines they all find themselves simultaneously ready to effectively address nanostructures. This provides an unprecedented opportunity to revitalize the connections between physics, mathematics, chemistry, biology and engineering in education. The dynamics of the interdisciplinary nanostructure efforts will revitalize educational connections between disciplines and will give birth to new fields that are only envisioned at this moment. This opportunity requires change in the laboratory and human resource infrastructure in universities, and in the education of nanotechnology professionals, especially for industry.

4. Investment Opportunities

Nanoscale science and engineering knowledge is exploding worldwide because of the availability of new investigative tools and interdisciplinary synergism, and is driven by emerging technologies and their applications. New experimental and modeling tools have made possible such discoveries, opening windows of research opportunities. The number of revolutionary discoveries reported in nanotechnology can be expected to accelerate in the next decade, and is likely to profoundly affect existing and emerging technologies in almost all industry sectors and application areas, including computing and communications, pharmaceuticals and chemicals, environmental technologies, energy conservation, manufacturing and healthcare-related technologies. As a result of the highly competitive and dynamic characteristic of nanotechnology and of the potential high return on investment, the opportunity to establish a special initiative is significant. There is a clear need to create a balanced infrastructure for nanoscale science, engineering, technology and human resources development in this revolutionary field.

The reported Federal Government expenditure for nanotechnology in fiscal year 1997 was $116 M (WTEC Study, 1998; Nanotechnology as defined there only included work to generate and use nanostructures and nanodevices; it did not include the simple observation and description of phenomena at the nanoscale that is part of nanoscience). It is estimated to be at over $230 M in fiscal year 1999. A much greater investment could be utilized effectively. Funding agencies and professional societies are experiencing a flurry of new results in nanotechnology, and a growing interest within the research community. The funding success rate for the small-group interdisciplinary research program, FY98 NSF "Functional Nanostructures" initiative, was about 13% (lower if one considers the limitation of two proposals per university). The success rate for the DoD 1998 MURI initiative on nanostructures was 17% (5% if one starts with the number of white papers submitted to guide proposal development).

The promise of nanotechnology must be realized through a balanced investment:

- Nanostructure Properties: develop and extend our understanding of biological, chemical, electronic, magnetic, optical, and structural properties in nanostructures.
- Synthesis and Processing: enable the atomic and molecular control of material building blocks, and engineering that provides the means to assemble and utilize these tailored building blocks for new processes and devices in a wide variety of applications. Extend the traditional approaches to patterning and microfabrication to include parallel processing with proximal probes, stamping and embossing. Particular attention must be given to the interface with bionanostructures and bio-inspired structures, multifunctional and adaptive nanostructures, scaling approaches, and affordability at commercial scales.
- Characterization and Manipulation: new experimental tools to broaden the capability to measure and control nanostructured matter, including the development of new standards of measurement. Particular attention must be given to tools capable of measuring/manipulating single macro- and supra-molecules of biological interest.
- Modeling and Simulation: accelerate the application of high performance computation to the prediction of nanostructured properties and phenomena, and materials by design.
- Device and System Concepts: stimulate the innovative application of nanostructure properties in ways that might be exploited in new technologies.

International Perspective: The U.S. does not dominate nanotechnology research. There is strong international interest, with nearly twice as much research ongoing overseas as in the United States. Other regions, particularly Japan and Europe, are supporting work that is equal to the quality and breadth of the science done in the U.S. because they have determined that nanotechnology has the potential to be a major economic factor during the next several decades. This situation is unlike the other post-war technological revolutions, where U.S. enjoyed earlier advances. The 1991 Congressional Office of Technology Assessment report, Miniaturization Technologies, states *that "the competitive position of U.S. R&D in miniaturization technology remains strong, although competition from Japanese and European industry and governments has increased."*

The international dimensions of nanotechnology research and its potential applications implies that the United States must put in place an infrastructure that is equal to that which exists anywhere in the world. This emerging field also creates a unique opportunity for the United States to partner with other countries in ways that are mutually beneficial through information sharing, cooperative research, and study by young U.S. researchers at foreign centers of excellence. A suitable U.S. infrastructure is also needed to compete and collaborate with those groups.

5. High-level Recognition of the Potential

The potential of this technology has not passed unnoticed. Then-Senator Gore held the first hearing on nanotechnology in 1992. The Defense Department identified nanotechnology as a strategic research objective in 1997, and NSF has highlighted nanoscale science and technology in its fiscal year 1999 budget. In March 1998, the President's Science Advisor Dr. John H. Gibbons identified nanotechnology as one of the six technologies that will determine economical development in the next century. Dr. Neal Lane, former NSF director, stated at a Congressional hearing in April 1998 that, *"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."*

Expert opinions in industry and academia (e.g. PCAST, National Academy, industry and professional organizations) on research needs and opportunities should be collected.

6. A National Initiative: Leading to New Industrial Revolution

Role of Government in nano science and technology: Nanotechnology research is in an early stage and has several promising results. It is clear that it can have a substantial impact on industry and on our standard of living. But investments must be made in the basic science and technologies that will enable scientists and engineers to invent totally new technologies and enable industry to produce cost-competitive products. Much of the results on nanostructures and nanoprocesses are not yet fully measurable, replicable or understood, and will require many years to develop corresponding technologies. Industry is unable in the 3-5 year industrial product time frame to effectively develop cost competitive products out of current knowledge. Fundamental nanotechnology research and development is too costly, long-term and risky for private industry to undertake. There are critical areas of research and development that are being ignored by industry or have significant underinvestment. Companies will not provide the investment needed to establish the nanoscience infrastructure and to fund long-term research needed to realize the potential. The fundamental infrastructure that industry uses to develop new products needs to be strengthened and expanded.

Nanotechnology cannot flourish without strong supporting science programs because of the scale and complexity of the nanosystems. Nanotechnology research is the USA has been developed in open competition with other research topics within various disciplines. This is one of the reasons that the USA research efforts in nanotechnology are relatively fragmented and partially overlapping among disciplines, areas of relevance, and sources of funding

Therefore, the Federal Government needs to invest in the infrastructure necessary for the United States to lead and benefit from the revolution that is coming. It needs to expand university and national laboratory facilities, build the workplace skills necessary to staff future industries based on nanotechnology, encourage cross-disciplinary networks and partnerships, ensure the distribution and spread of information, and encourage small businesses to develop the instruments and tools needed.

Nanotechnology R&D requires long-term investment: Nanoscience and engineering will need a long-term investment because of the interdisciplinary characteristic, limitations of the existing experimental and modeling tools in the intermediate range between individual molecules and bulk, and the need for technological infrastructure. The time from fundamental discovery to market is typically 10-15 years (see for instance the application of magnetoresistance by IBM, and of mesoporous silicate by Mobil Oil Co.). Historically, industry becomes a major player only in the last 3-5 years, when the investments are much larger than in the previous period but the economic return more certain. Government leadership and funds are needed to establish the infrastructure and research support in the first 7-12 years. Since major industrial markets are not yet established for nanotechnology products, the government should also support technology transfer activities to accelerate the long-term benefits.

Technological innovation and commercialization is taking place at an ever-increasing pace. The enabling infrastructure and technologies must be in place for industry to take advantage of nanotechnology innovations and discoveries. Industry is frequently reluctant to invest in risky research that takes many years to develop into a product. In the U.S., the government and university research system fills this gap. The increasing pace of technological commercialization requires a compression of past time scales and parallel development of research and commercial products and a synergy among industry, university, and government partners.

The priority research areas for additional funding in FY2001 are:

- Long-term nano science and engineering research that will lead to **fundamental understanding and to discoveries of novel phenomena, processes, experimental and simulation tools for nanotechnology**. This commitment will rival and refocus the government investment beginning in the 1950s that led to today's microelectronics, microfabrication, and computer technology; (Request $75M);
- **Synthesis and processing "by design"** of engineered, nanometer-size, material building blocks and system components, fully exploiting self organization concepts. This commitment will generate new classes of high performance materials, bio-inspired systems, changes in device design paradigms, and efficient, affordable manufacturing of high performance products. Novel properties and phenomena will be enabled, as control of organizational structures of atoms, molecules and clusters becomes possible; (Request $60M);
- **Nanodevice concepts** including system architecture research to best exploit their properties in operational systems, and combining building-up of molecular structures with ultraminiaturization. The nanodevices will cause paradigm changes such as order-of-magnitude improvements in microprocessors and mass storage, overall selective drug and gene delivery systems, use of tiny medical tools that minimize collateral damage; and uninhabited defense combat vehicles in fully imaged battle field. There will be dramatic payback to programs with National priority including information technology, nanobiotechnology and medical technology; (Request $58M)
- **Application of nanostructured materials and systems** to manufacturing, power systems, energy, environment, national security, and health. Areas of interest include advanced dispersions, catalysts, separation methods, and consolidated nanostructures; Develop core enabling technologies such as fundamental molecular scale measurement and manipulation tools and standard methods, materials, and data that will be applied to many commercial sectors (Request $58M);
- **Educate and train a new generation of skilled workers** in the multidisciplinary perspectives necessary for rapid progress in nanotechnology; (Request $10M)

Common Themes:

Funding modes:
- Need for sustained support to individual investigators and small-groups doing fundamental, innovative research; Larger investment should be given at the beginning to funding fundamental research, as well as to development of university-industry-laboratories and interagency partnerships;
- Interdisciplinary and the need for correspondingly appropriate funding modes (interdisciplinary programs, centers and networks);
- Encourage research and users' networks; The establishment of 5-10 nanotechnology research centers similar to the supercomputer centers will play an important role in development and use of the specific tools in the next decade, and in promoting partnerships. An expansion of the existing NNUN users network may be considered. Two thirds of the funds will be used for individual and small group investigators;
- Encourage university-industry-national labs and international collaborations. Knowledge and technology transfer between universities and industry will be encouraged. Develop enabling infrastructure so that new discoveries and innovations can be rapidly commercialized by U.S. industry.

Research areas:
- Nanoelectronics and information technology
- Multi-scale, hierarchical modeling and simulation of nanostructures and nanoprocesses
- Development of experimental methods and devices to measure various properties and phenomena at nanoscale; Combine measurement, manipulation and manufacturing tools;
- Connection to biology (biostructures & bio-inspired systems)
- Synthesis, assembly and processing of nanostructured materials 'by design'
- System architecture and devices
- Focus on fundamentals that are broadly enabling of many areas of technology and that help industry to develop new competitive, profitable products that industry would not develop on its own.

Partnerships:
- Among disciplines (small group research)
- Among institutions & types of institutions (e.g., universities, industry, government labs)
- Among countries
- Among U.S. government funding agencies and states; support for complementary activities
- Joint funding and use of centers (facilities)
- International collaborations to promote access to centers of excellence abroad, visits by young researchers abroad, and bilateral and multilateral agreements

Infrastructure Needs for Nanotechnology: The nanotechnology initiative requires a balanced, predictable, strong, but flexible infrastructure to stimulate the further rapid growth of the field. Ideas, concepts and techniques are moving at such an exceedingly rapid pace that the field needs coordination and focus from a national perspective. Demands are high and the potential is great for universities and government to continue to evolve and transition this science and technology to bring forth the changes in technology that will enable U.S. industry to commercialize many new products in all sectors of the economy. Even greater demands are on industry to attract new ideas, protect intellectual property, and develop appropriate products. This field has major multidisciplinary aspects, which are difficult to coordinate in a formless fashion. If these issues are not addressed, the United States will fall behind world developments and, therefore, have difficulty maintaining the economy and quality of life and security that exist today.

Tools must be provided to investigators in nanotechnology for them to carry out state-of-the-art research to achieve this potential and remain competitive. The tools will include but not be limited to such items as ion beam neutron and photon sources, instruments for manipulation, new forms of lithographs, computational capabilities and other systems to characterize the nano-scale systems. Centers, with multiple grantees or laboratories, where these tools would be available for this support should be established at a level of several million dollars annually. These centers should also have the diverse research teams that will be effective in different scientific disciplines. We should also investigate means to achieve the remote use of these facilities. Funding mechanisms that encourage centers, university, laboratory, industrial collaboration should be emphasized, as well as single investigators who are tied into these networks. One of the major potential barriers of cooperative efforts is intellectual property rights.

Support to single investigators for their competence and imaginative programs should provide a corresponding level of personnel support and equipment. University grants should encourage work among research groups to make maximum use of concepts and ideas being developed in other disciplines. The infrastructure includes building links between researchers, developers and users of nanotechnology innovations. The initiative will develop critical enabling technologies that will have significant value added in many industries. The initiative will allow U.S. industry to develop new profitable products that will maintain and improve our global competitiveness in short (3-5 years) and long term.

It will be necessary to fund training of students and support of postdocs under fellowships that will attract some of the best students available. This is extremely important considering the rapid change in the research. Students should receive multidisciplinary training in various nanotechnology fields. Both organizational attention and funding should also be devoted to ensuring the open exchange of information in multidisciplinary meetings and rapid publication of results, through, for example, workshops and widely disseminated summaries of research.

Because of the fast evolving nature of nano-technology and its importance to our society, the program management must be flexible with the capability of changes needed. Working groups to make recommendations to modify the program as it evolves should be supported.

RICHARD E. SMALLEY
Curriculum Vitae

Personal

Birth Date: June 6, 1943 U.S. Citizen
Children: Chad R. Smalley (born June 8, 1969), Preston C. Smalley (born August 8, 1997)

Education

Hope College, Holland, Michigan, 1961 - 1963
B.S. (Chem.), University of Michigan, Ann Arbor, Michigan, 1965
M.A., Princeton University, Princeton, New Jersey, 1971
Ph.D., Princeton University, Princeton, New Jersey, 1973

Industrial Position

Research Chemist, Shell Chemical Company, 1965 - 1969

Academic Positions

Graduate Research Assistant, Department of Chemistry,
Princeton University (with E. R. Bernstein), 1969 - 1973
Postdoctoral Research Associate, The James Franck Institute,
University of Chicago (with D. H. Levy), 1973 - 1976
Assistant Professor, Department of Chemistry, Rice University, 1976 - 1980
Associate Professor, Department of Chemistry, Rice University, 1980 - 1981
Professor, Department of Chemistry, Rice University, 1981 - 1982
Gene and Norman Hackerman Professor of Chemistry, Rice University, 1982 - present
Professor of Physics, Rice University, 1990 - present

Honorary Degrees

Doctor *honoris causa*, University of Liege, Liege, Belgium, 1991
Doctor of Science, The University of Chicago, 1995
Doctor of Science, The University of Michigan, 1997

Fellowships, Awards and Prizes

Harold W. Dodds Fellow, Princeton University, 1973
Alfred P. Sloan Fellow, 1978 - 1980, Fellow of the American Physical Society, 1987
Irving Langmuir Prize in Chemical Physics, 1991 (Awarded by American Physical Society)
Popular Science Magazine Grand Award in Science & Technology, 1991
APS International Prize for New Materials, 1992 (Joint with R. F. Curl and H. W. Kroto)
Jack S. Kilby Award, 1992 (North Dallas Chamber of Commerce)
Ernest O. Lawrence Memorial Award, 1992 (U.S. Department of Energy)
Welch Award in Chemistry, 1992 (Robert A. Welch Foundation)
Auburn-G.M. Kosolapoff Award, 1992 (Auburn Section of American Chemical Society)
Southwest Regional Award, 1992 (American Chemical Society)
William H. Nichols Medal, 1993 (New York Section of American Chemical Society)
The John Scott Award, 1993 (The City of Philadelphia)
Hewlett-Packard Europhysics Prize, 1994 (European Physical Society)
Harrison Howe Award, 1994 (Rochester Section of the American Chemical Society)
Madison Marshall Award, 1995 (North Alabama Section of the American Chemical Society)
The Franklin Medal, 1996 (The Committee on Science and the Arts of The Franklin Institute)
The Nobel Prize in Chemistry, 1996 (Royal Swedish Academy of Sciences)
Rice University Homecoming Queen, 1996 (Rice University Undergraduates)
Distinguished Civililan Public Service Award, 1997 (Department of the Navy)
American Carbon Society Medal, 1997
Top 75 Distinguished Contributors to the Chemical Enterprise, 1998 (Chemical & Engineering News)

Memberships

American Chemical Society, Division of Physical Chemistry
American Physical Society, Division of Chemical Physics
American Institute of Physics, American Association for the Advancement of Science
Materials Research Society, Sigma Xi
National Academy of Sciences, 1990
American Academy of Arts and Sciences, 1991

Other

Director, Rice Center for Nanoscale Science & Technology (CNST), July 1996-present
Chairman, Rice Quantum Institute, 1986 - 1996
Member Steering Committee, Rice Quantum Institute, 1979 - present
Editorial Board, *Chemical Physics Letters*, 1982 - present
Editorial Board, *Journal of Cluster Science*, 1988 - present
Editorial Board, *Molecular Physics*, June 1991 - present
Editorial Board, *Accounts of Chemical Research*, 1993
Scientific Advisory Board, Sphere Biosystems, Inc., February 1995 - present
Advisory Board, *Chemical & Engineering News*, January 1997 - present

RICE

Richard E. Smalley
GENE & NORMAN HACKERMAN PROFESSOR OF CHEMISTRY
AND PROFESSOR OF PHYSICS

June 18, 1999

Mr. Nick Smith, Chairman
Subcommittee on Basic Research
U.S. House of Representatives
Committee on Science
Suite 2320 Rayburn House Office Building
Washington, DC 20515-6301

Dear Mr. Smith:

In compliance with procedures required by the House of Representatives that each person who testifies before Congress, who is not representing a governmental entity, is to reveal resources of federal funding which directly supports the subject matter on which he or she will be testifying before the Committee, I submit the following.

For the past 3-5 years I have received federal funding for my nano research from the National Science Foundation, the National Aeronautics and Space Administration (NASA) and the Office of Naval Reseach. Further information is available upon request.

Best regards,

Richard E. Smalley

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COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES
SUBCOMMITTEE ON BASIC RESEARCH

HEARING ON

Nanotechnology: The State of Nano-Science and Its Prospects for the Next Decade

RESPONSES TO FOLLOW-UP QUESTIONS

Dr. R. E. Smalley
Center for Nanoscale Science and Technology
Rice University

QUESTION1: Several agencies have been working on the development of a new research initiative on nanotechnology for the FY 2001 budget request. The recommendation is to double current funding levels over three years.

QUESTION 1.1: Is there a need for such an initiative? Is it timely? What is the evidence that research ideas are significantly exceeding research support levels?

ANSWER: Nanotechnology is, I believe, critical to the future of most of high technology. It is the art and science of building at the ultimate level of finesse. Out of nanotechnology will come the answers, to the extent they are possible, to virtually all our technological needs. It is timely because the level of development of the underlying basic sciences of chemistry, physics, biology, electrical engineering, materials science, and computer engineering has brought us to the point that all these fields see much of their future in understanding, building, and manipulating at the nanometer scale. It is timely because it gets the juices flowing in our youngest, brightest scientists and engineers. They want to do it.

A major national initiative in nanotechnology will embolden the current generation of young American scientists and engineers, and it will inspire the next generation, the one that is now still in grade school and high school. For this reason alone, it is important that this nanotechnology initiative of our federal government be a major, bold statement. That statement has the power to inspire our youth.

QUESTION 1.2: What are the main research opportunities that ought to be addressed?

ANSWER: Nanotubes made of carbon offer amazing advantages in a wide range of technologies. In addition to their incredible strength (~ 100 stronger than steel at 1/6th the weight) and toughness, they are uniquely good as electrical conductors on a true molecular scale. As such they have the power to revolutionize virtually every technology where electrons flow – from computers, to power generation, storage and transmission, to nanoscale sensors and probes. This one topic alone, carbon nanotechnology, is of sufficient breadth and impact to justify a major national initiative at the $100M/yr level.

The general topic of assembly of functional structures on the nanometer scale is key. Carbon nanotubes, nanospheres (buckyballs) and other nano objects made of elements like silicon and cadmium selenide are fascinating, but they are themselves just building materials. They must be assembled into macroscopic 3D structures before they can have a major impact on our lives. Any new nanotechnology initiative for our country must have assembly as a central emphasis.

The interface between molecular biology and entirely artificial nanostructures is particularly fertile. In coupling to molecular biology we are joining forces with the most powerful nanotechnology yet developed, so it is reasonable to expect that much will be learned, and much that is new and powerful will be developed. The human need for cures to major diseases, for food and a clean environment will drive research on the biotechnology side of nanotechnology for many decades to come.

Molecular scale electronics -- nanoelectronics – is one of the most intriguing, potentially society-changing technologies now in its infancy. It should be included within the nation's nanotechnology initiative.

QUESTION 2: What are the fields in which we will see the most significant applications of nanotechnology and in what time frame do you predict we will see the full benefits?

ANSWER: Aside from medicine (see below, question # 5) where the effects of nanotechnology are already beginning to be apparent and will ultimately be vast, I believe we will see the following major advances.

(a) **Nanoelectronics.** In the early years (within the next 5-15 years) a major enhancement of microelectronics (computers, communication equipment of all kinds, consumer electronics, detectors, sensors, probes) will come by adding in nanoscale components. Included here will be flat panel displays for TV's etc. that are cheap and cover, if desired, an entire wall. Quite possibly these displays will be made as flexible as cloth. Also, it is likely that within the next decade nanotechnology will enable vast memories for computers and entertainment electronics (e.g. a 2 hour movie stored on a device the size of a penny). Within the next 20-30 years I expect that silicon-based microelectronics may be replaced almost entirely by a largely carbon-based nanoelectronics.

(b) **Energy storage.** Within the next 10-15 years nanostructured electrochemical batteries (particularly lithium ion batteries) are likely to be perfected to the point that all-electric vehicles will finally be economically competitive in all aspects with conventional internal combustion technologies. Within a similar period of time, the hydrogen storage problem should be solved, again critically enabled by precisely nanostructured materials. These devices will permit hydrogen to be safely used as the fuel for all sorts of vehicles and other applications. Nanotechnology is also on the critical path for the perfection of fuel cells so that this hydrogen gas can be converted cleanly and efficiently to cheap electrical power.

(c) **Electrical Power Transmission**. In the next 10-20 years nanotechnology will enable the replacement of the aluminum high-tension power transmission lines throughout our country with coaxial cables made of carbon nanotube conductors. The result will be that there will no longer be a lowering of property values for those of us who live next to power lines. There will be no more hum and buzz, and there will be no more concern that low frequency radiated power is damaging to our health. All this will be true because the great strength, light weight, and high thermal and electrical conductivity of carbon nanotubes makes practical a cable design that surrounds the high voltage core with a grounded sheath that eliminates all electric effects outside the cable. From the power industry's perspective, the new nanotech cables will be a delight, because they will enable vastly more power to be transmitted through existing corridors, thereby eliminating the huge cost and political stress of obtaining new right-of-way.

(d) **Biocompatible Membranes and Coatings**. Within the next 5-10 years nanotechnology will solve the problem of biocompatibility and long-term survivability of implanted devices. Oriented membranes of specially grown carbon nanotube fibers may turn out to be the critical breakthrough.

(e) **Sensors**. A wide variety chemical and biological sensors and analyzers will almost certainly hit the market within the next 5-10 years, all of which have nanotechnology at their core. These devices will, in many cases, comprise an entire chemical analysis laboratory on a single chip of silicon, with all the computer analysis of the data built in.

(f) **Solar Energy**. Nanotechnology will ultimately provide the answer to the question of how to make solar energy so cheap on a massive scale that it will replace oil, gas, and coal worldwide as the dominant energy source. Photovoltaics based on silicon have come a long way, but it is unlikely they can ever provide the answer on the scale that is needed to replace fossil fuels. How long it will take to make the critical breakthroughs with a true nanoscale approach, no one can yet say. Twenty years seems reasonable, if we start now. I'm betting on antenna arrays based on carbon nanotube technology, but there are many other possibilities.

(g) **Super-strong Materials** for automobiles, trucks, building construction, bridges, aircraft, rockets, spacecraft, etc. Within the next 10-20 years the amazing properties of carbon nanotubes (100 x stronger than steel at 1/6 the weight, with no corrosion) and their boron nitride counterparts will begin to hit these large volume, critically important markets. The carbon nanotubes are already being made in small amounts. Boron nitride nanotubes and fibers will be nearly as strong, and much more resistant to oxidation – a critical factor for aerospace applications in such areas as rocket and jet engine exhaust structures and the leading edges and near surfaces exposed to high temperatures on re-entry to the earth's atmosphere.

QUESTION 3: What other nations have significant research programs on nanotechnology and how do they rank relative to the US? Are there particular subfields in which other countries are more advanced than the US?

ANSWER: Japan, Korea, Taiwan, China, France, Switzerland, Holland, Germany, the United Kingdom, and the European Union all have major programs in some form of nanotechnology. At the moment I do not believe we are far behind in any critical area, but neither are we more than a few years ahead.

QUESTION 4: One reason for our country's economic strength is our ability to move science from the lab to the marketplace. What are the engineering problems that need to be surpassed in order to move nanotechnology from the lab to a state of mass production? How would the proposed Nanotechnology Initiative address these problems?

ANSWER: I believe we are doing fine in this area. The American business climate is very entrepreneurial, and very hungry for new high technology.

QUESTION 5: How significant will the impact be of nanotechnology on medicine and health care?

ANSWER: This is, at least superficially, an easy question. The high tech, high impact frontier of medicine is already rooted in nanotechnology. Ever since the middle of this century as the molecular basis of biology has become increasingly understood, we have realized that all of the mechanical aspects of how life works are due to a magnificent nanotechnology within the cell. Much of the future of medicine will be limited by just how sophisticated we can become in detecting what is going on inside and on the surface of these cells -- these wet bags chock full of nanomachines all busily going about the business of life -- and in changing what we find there. It is all nanotechnology.

Elimination of most forms of disease, and extension of the length and vitality of life for most people towards an average life span of 100 years, all seem possible to achieve within this next century.

QUESTION 6: In a scientific field as new and diverse as nanotechnology research, how would you formulate and implement an effective peer review process for selecting which research projects will be funded? How would a peer review process for nanotechnology research funding differ from NSF's normal peer review process?

ANSWER: This is a critical question. Any new funding program for nanotechnology has the danger of being absorbed by already well-funded, on-going research that is simply relabeled business as usual After all, the study of things composed of atoms is what chemistry, biochemistry, biology, medicine, materials science, atomic and condensed matter physics, geology, etc. have always been about. To minimize this problem there needs to be a clear definition of what sort of nanotechnology is to be emphasized.

Putting it in the plainest of terms, I suggest that the initiative focus on "building stuff that does stuff on the nanometer scale".

Here the key aspects are imbedded in the verbs "building" and "does". The nouns and adjectives "stuff" and "nanometer" are the parts of the definition of nanotechnology that virtually all business-as-usual science and engineering research can connect to. But the verbs carry the real story. Research funded by the new nanotechnology initiative should be focused on how to build functional nano-objects: stuff that does stuff. What we have in mind is molecularly precise engineering. In fact an interesting alternative title for the nanotechnology initiative would simply be "molecular engineering".

The new nanotechnology program should also fund work that helps us "see" what is being built on the nanometer scale, together with theoretical work that helps us understand what is happening on this length scale, and work that leads to methods of manipulating nano-objects, and assembling them into functional structures on the micron or millimeter scale.

I am not a great fan of peer review. There is too much herd mentality involved. For the people that ought to be funded, the reviewers are rarely true peers; and those that are true peers are generally too personally involved as competitors to offer an objective assessment. I believe that individual funding agents within the NSF and other agencies should be given authority to award at least 50% of their funds to which ever group they see fit, regardless of the outcome of peer review. Along with this authority should come accountability. Reward the outcomes, both for the researchers that actually make the breakthroughs, and the funding agents that picked them initially and nurtured them over the years. This system will attract a much better quality of scientist and engineer to the critical role of choosing which research to fund for our nation.

Finally, I urge that these new funds for nanotechnology not be burdened by other agendas. The new funds should be spent moving the high-tech frontier absolutely as far forward as possible. The NSF in particular has recently become a center of political correctness, to the point that many of us believe that social engineering is, *de facto*, its principal agenda. While there is nearly universal enthusiasm among scientists in the US for improving the education system, the role of minorities, the environment, and coupling with industry, the number one priority of the NSF must be the advancement of science and technology. This number one priority must not be overridden. Other agencies of the US government can address the social engineering issues.

QUESTION 7: What is the state of the human resource base available to the US to conduct research in the field of nanotechnology, in terms of research faculty at universities, industrial researchers and graduate students?

ANSWER: We are in reasonably good shape as long as the US remains in the forefront of high technology. Throughout this century US science and technology has prospered because we were open to the participation of foreign-born scientists, particularly since the Second World War. We must keep ourselves open. Science and technology move fast as a worldwide enterprise. We will stay in the forefront if we remain the most open, most collaborative, most innovative high tech society.

QUESTION 8: How would advances in nanotechnology improve American agriculture?

ANSWER: Biotechnology is already a form of nanotechnology. The new genetically engineered crops and new pesticides are examples of what should certainly be classed as nanotechnology. Beyond the continued development along these already established lines, consider the impact of, for example, a vastly cheaper desalination processes. The membrane that separates the salt works because of the way it is structured on the nanometer scale. Aside from the price of the energy needed to power the desalination plant, it is the efficiency of this membrane that determines the cost. The perfection of this membrane is a task for nanotechnology.

QUESTION 9: Dr. Merkle points out that many researchers think self-replication will be the key to unlocking nanotechnology's full potential as a robust manufacturing technology. Could artificial self-replicating systems pose unique risks?

ANSWER: Yes. Self-replication is a very powerful ability. In Nature's own nanotechnology, information-controlled replication is critical to the essence of life. As we learn to modify the machinery in living cells, hoping to make improvements, we will be making self-replicating systems that are to some extent "artificial", and we will have to be careful what sort of beast we have created.

However, I am confident that the sort of computer-controlled, self-replicating, mechanical nanoassemblers I suspect Dr. Merkle had in mind when he made his comments will never be feasible in the tiny, "artificial bacteria" form that would be dangerous.

This notion of mechanical self-replicating nanoassemblers stems back to a delightful little book written by Eric Drexler in 1986, and titled "Engines of Creation". The book makes great reading, and I recommend it heartily, together with Drexler's subsequent books, in particular his 1991 book written with Chris Peterson and Gayle Pegamit, titled "Unbounding the Future – the Nanotechnology Revolution", because they do dramatize effectively the tremendous potential technologies that will emerge as we learn to craft objects with atomic precision.

In "Engines of Creation" Drexler imagines mechanical robots the size of bacteria that can build anything on computer command, including themselves. As Drexler himself discusses even in his first book, these nanoassemblers could easily get out of hand. All they need is energy, a supply of the right kind of atoms, and information about what it is they are to build. The atoms can be provided as molecules in solution, and both the necessary energy and the information can be transmitted to each assembler by radio waves. The first instruction they are given is to build a replica of themselves. Since they, by definition, can build anything, they quickly accomplish their first assigned task, and now wherever there was one, there are now two. After many such replication cycles, there are billions of identical assemblers. Even though each one is tiny and can only produce a tiny amount of product each day, billions of assemblers working in concert can make tons – of anything. Effectively these nanoassemblers would be a new life form. If they can receive and make sense of information, there isn't much keeping them from communicating with one another, and evolving their own sort of intelligence.

Such "Drexlerian Nanotechnology" makes great reading, and neat special effects in movies, but it will always remain a fantasy. It is just a dream. There are simple facts of nature that prevent it from ever becoming a reality.

Building a molecularly perfect structure atom by atom is not like building a house brick by brick. Atoms stick to each other in complex ways that rearrange spontaneously in billionths of a second. You can't just put a new atom in and expect the other atoms in the near vicinity to stay in the same place while you go fetch another. In order to determine precisely what happens you, have to control each the typically 5-20 atoms or so in the local region (the atoms that are be bonded directly to the new atom, and the next-nearest neighbor atoms as well), roughly in the volume of a cube 1 nanometer on a side. In Drexlerian mechanical nanotechnology this would have to be done by the "fingers" of some nano-robot's arm. The fingers themselves must, of course, be made of atoms. In the vital one-nanometer cubic volume where this is to be done there simply is not enough room to fit even the tiniest of fingers, let alone the many fingers necessary to really control the assembly perfectly. In addition there is the problem of letting go of the new atom when it is in the desired place. Fingers that themselves are made of atoms are "sticky". Mechanical robots just won't work at the atomic scale as universal assemblers.

What is needed at the end of the robot arm is a catalyst—an assembly of tens to hundreds or thousands of atoms that will interact in subtle ways with all the atoms near the reaction site, and trigger just the precise chemistry that is desired, adding a new atom or small group of atoms. Far from being a universal assembler, this catalyst must be specially engineered to do just the chemistry needed at the moment. To do something else, another catalyst is necessary. This is how Nature works. The nanoassemblers inside our cells, the enzymes, are each exquisitely designed to do a certain chemistry. When the cell needs that chemistry performed, it generates the required enzyme. When they are no longer needed, they are destroyed (by other enzymes). Chemistry—the building of objects with molecular precision—is an irreductably subtle business. It needs catalysts. There is no other way.

So for a robot assembler to be truly universal for nanoscale assembly, it would need a vast array of catalyst tips that it can interchange when necessary. The result is that the size and complexity of the gadget is enormously increased. It is no longer possible (if it ever was!) to build one of these robots as small as a bacterium. Because the robot must frequently change catalyst tips, the speed at which it can work is vastly slowed. If the robot assembler is only building one atom at a time, the product of any one robot will be negligible. And now we cannot make up for this by having billions of robots working at the same time – they are just too big.

Even though Drexler's early vision of nanotechnology seems, at least to me, to be in its essential details hopelessly naïve, assemblers of some sort will certainly be built, and they will assemble wonderful things. They won't be universal assemblers, they won't self-replicate, and they almost certainly won't be as small as bacteria.

Nanotechnology: the coming revolution in manufacturing

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Abstract for testimony to the U.S. House of Representatives Committee on Science, Subcommittee on Basic Research, June 22nd, 1999.

Abstract

For centuries manufacturing methods have gotten more precise, less expensive, and more flexible. These trends are likely to culminate in the next few decades with the development of nanotechnology, a manufacturing technology able to inexpensively fabricate, with molecular precision, most structures that are consistent with physical law. Such a manufacturing technology will provide pervasive benefits across the economy and be critical to our military preparedness and economic competitiveness. Developing it will require basic research to elucidate the goals and developmental pathways. Because this research is beyond the planning horizon and resources of almost all companies government involvement could well play the critical role in its timely development.

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Available on the web at http://www.merkle.com/nanohearing1999.html

Introduction

For centuries manufacturing methods have gotten more precise, less expensive, and more flexible. In the next few decades, we will approach the limits of these trends. The limit of precision is the ability to get every atom where we want it. The limit of low cost is set by the cost of the raw materials and the energy involved in manufacture. The limit of flexibility is the ability to arrange atoms in all the patterns permitted by physical law.

Most scientists agree we will approach these limits but differ about how best to proceed, on what nanotechnology will look like, and on how long it will take to develop. Much of this disagreement is caused by the simple fact that, collectively, we have only recently agreed that the goal is feasible and we have not yet sorted out the issues that this creates. This process of creating a greater shared understanding both of the goals of nanotechnology and the routes for achieving those goals is the most important result of today's research.

The Goal

Nanotechnology (or molecular nanotechnology to refer more specifically to the goals discussed here) will let us continue the historical trends in manufacturing right up to the fundamental limits imposed by physical law. It will let us make remarkably powerful molecular computers. It will let us make materials over fifty times lighter than steel or aluminium alloy but with the same strength. We'll be able to make jets, rockets, cars or even chairs that, by today's standards, would be remarkably light, strong, and inexpensive. Molecular surgical tools, guided by molecular computers and injected into the blood stream could find and destroy cancer cells or invading bacteria, unclog arteries, or provide oxygen when the circulation is impaired.

Nanotechnology will replace our entire manufacturing base with a new, radically more precise, radically less expensive, and radically more flexible way of making products. The aim is not simply to replace today's computer chip making plants, but also to replace the assembly lines for cars, televisions, telephones, books, surgical tools, missiles, bookcases, airplanes, tractors, and all the rest. The objective is a pervasive change in manufacturing, a change that will leave virtually no product untouched. Economic progress and military readiness in the 21st Century will depend fundamentally on maintaining a competitive position in nanotechnology.

Self Replication and Low Cost

Many researchers think self replication will be the key to unlocking nanotechnologies full potential, moving it from a laboratory curiousity able to expensively make a few small molecular machines and a handful of valuable products to a robust manufacturing technology able to make myriads of products for the whole planet. We know self replication can inexpensively make complex products with great precision: cells are programmed by DNA to replicate and make complex systems -- including giant redwoods, wheat, whales, birds, pumpkins and more. We should likewise be able to develop artificial programmable self replicating molecular machine systems -- also known as assemblers -- able to make a wide range of products from graphite, diamond, and other non-biological materials. The first groups to develop assemblers will have a historic window for economic, military, and environmental impact.

What needs to be done

Developing nanotechnology will be a major project -- just as developing nuclear weapons or lunar rockets were major projects. We must first focus our efforts on developing two things: the tools with which to build the first molecular machines, and the blueprints of what we are to build. This will require the cooperative efforts of researchers across a wide range of disciplines: scanning probe microscopy, supramolecular chemistry, protein engineering, self assembly, robotics, materials science, computational chemistry, self replicating systems, physics, computer science, and more. This work must focus on fundamentally new approaches and methods: incremental or evolutionary improvements will not be sufficient. Government funding is both appropriate and essential for several reasons: the benefits will be pervasive across companies and the economy; few if any companies will have the resources to pursue this alone; and development will take many years to a few decades (beyond the planning horizon of most private organizations).

We know it's possible. We know it's valuable. We should do it.

WHITHER NANOTECHNOLOGY?

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Available on the web at http://itri.loyola.edu/nano/us_r_n_d/08_06.htm

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Introduction

A new manufacturing technology looms on the horizon: molecular nanotechnology (http://nano.xerox.com/nano). Its roots date back to a 1959 talk by Richard Feynman (http://nano.xerox.com/nanotech/feynman.html) in which he said, "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big."

In the last few years the idea that we should be able to economically arrange atoms in most of the ways permitted by physical law has gained fairly general acceptance. This can be viewed as simply the culmination of a centuries-old trend: the basic objectives of manufacturing are lower cost, greater precision, and greater flexibility in what can be manufactured: as the decades have gone by, we've gotten better and better at it. The limit of low cost is set by the cost of the raw materials and energy involved in manufacture, the limit of precision is the ability to get every atom where we want it, and the limit of flexibility is the ability to arrange atoms in whatever patterns are permitted by physical law. While it seems unlikely that we will ever completely reach these limits, the objective of molecular nanotechnology is to approach them. Manufacturing costs should be low - a dollar a pound or less - almost regardless of what is being manufactured. Almost every atom should be in the right place - while background radiation limits this, error rates of a single atom out of place among many tens of billions seem feasible in properly designed structures under "normal" conditions. And finally, we should be able to make most of the stable structures that are consistent with physical law. As structures become less stable they become more difficult and arguably impossible to make, but this still leaves a vast space of possible structures that are beyond the reach of current methods. In addition, some structures might be stable if only we could make them, but all intermediate states would be unstable. Drexler, for example, has argued that the molecular equivalent of a stone arch (http://www.foresight.org/EOC/EOC_References.html#0025) would be unstable unless all its pieces were in place. The final result would be stable, but all synthetic pathways leading to this result would have to pass through an unstable state, making synthesis impossible.

While the broad objective has gained acceptance, as a community we have still not agreed on how best to proceed, nor on what this future technology will look like, nor on how long it will take to develop. The purpose of this paper is not primarily to focus on specific technical approaches, but to ask, "What do we need to do, as a community, to speed the development of this new technology?"

The Goal

Before going further we need to make sure we are in broad agreement about the goal. Molecular nanotechnology should, by definition, permit us to manufacture (among other things) molecular computers with mole quantities of switches, connected in the intricate patterns required by today's complex computers, at a cost of perhaps a dollar a pound (or less). Today's computer - if we weigh the thin layer on top of a computer chip - costs tens of millions of dollars per pound. This thin layer, only a few microns thick, contains almost all the complexity of the modern computer. The rest of the wafer is mere sand, dragged along as a convenient mounting platform for the active region but doing little else. Viewed in this light, lithography falls woefully short of the cost goal. Molecular nanotechnology should let us extend this very thin and complex layer into three dimensions while greatly shrinking the size of the switches. It should let us position dopant atoms at specific lattice sites (chosen by design to optimize device function) while simultaneously keeping the manufacturing costs as low as the manufacturing costs of a piece of wood.

Besides computers, molecular nanotechnology should let us make inexpensive materials with a strength-to-weight ratio similar to that of diamond. These would have wide ranging applications in structural and load bearing applications. Manufactured with precisely the desired shape and structured at the molecular scale to optimize material properties, we should be able to make a jet, a rocket, a car or even a chair that would, by today's standards, be remarkably light, strong, and cheap.

The objective of molecular nanotechnology is not simply to provide a few new products nor to greatly enhance the performance of some select high-tech devices, but to replace essentially the entire existing manufacturing base with a new, radically less expensive, radically more precise, and radically more flexible way of making products. The aim is not simply to replace today's lithographic fabrication facilities to let us make better computers, but also to replace the assembly lines for cars, televisions, telephones, books, bookcases, airplanes, tractors, etc. The objective is a pervasive change in manufacturing, a change that will leave virtually no product untouched.

It Will Take a Lot of Work

It seems likely that the development of such a capability will require (a) time and (b) resources. The development of nuclear weapons took billions of dollars and a very focused development project. The Apollo program likewise took a focused effort over many years and billions of dollars in money and vast amounts of creative talent. The development of the computer industry, while following a very different pattern (private versus governmental, incremental "pay as you go" versus large up-front funding), also involved major funding and many years.

It is too early to say exactly what pattern the development of molecular nanotechnology will follow, but it is not too early to say that it is likely to require major resources. Whoever makes the decision to commit those resources is unlikely to do so unless there is a clear picture of both the goal and how to achieve it.

Suppose a hypothetical funder came to the research community today and said, "Molecular nanotechnology has a very high payoff, and I wish to start a major new program in the area.

What should I do? What should I fund?" The answer, today, would be a chorus of voices tugging in all directions.

Perhaps our hypothetical funder would fund all the different approaches. This was the basic strategy used to develop nuclear weapons. But that was a war-time effort motivated by panic and the fear of annihilation. A more likely scenario is that our hypothetical funder would say, "You are all saying different things - I won't fund a major new project until at least some substantial fraction of you have reached agreement about what to do."

What, then, is the key to developing molecular nanotechnology? Developing agreement about what it is and how to achieve it. How can we develop agreement? As a first step we must explicitly pursue research into the question, "What would a molecular manufacturing system look like?"

Self Replication and Low Cost

Take the issue of manufacturing cost. This is a primary objective of molecular nanotechnology. One way to keep manufacturing costs down would be to develop self replicating manufacturing systems (http://nano.xerox.com/nanotech/selfRep.html). The development of self replicating systems seems like a daunting task, so it is natural to ask if there are alternative ways of achieving the cost objective. To date, no alternative of similar effectiveness has been proposed. As noted earlier, lithography is perhaps seven orders of magnitude too expensive. Other approaches fall short in terms of the range of things they can make, or in terms of the precision with which they can make them. Bulk chemicals are produced today at relatively low cost, but the range of molecular structures that can be made this way is very limited. Lithography can make a great many patterns on a surface, but not with molecular precision. While self assembly is a powerful approach, the direct manufacture of (for example) a diamond rocket by self assembly seems implausible (while self assembly is likely to be important if not crucial in developing nanotechnology, it can still only make an extremely small fraction of what is possible).

It would seem that either (a) we will develop artificial self replicating systems or (b) we will not. If we do, then we can address the issue of manufacturing cost. If we do not, we must seek an alternative - and no alternative of similar effectiveness has yet been proposed.

It is worth noting that we already have self replicating systems of the biological variety. Such systems can already make desirable materials. Wood, for example, is relatively low cost and provides a reasonable strength to weight ratio. Using a programmable protein synthesizer (a.k.a. a ribosome), these self replicating cells can synthesize many compounds. Biological approaches, though, can make but an infinitesimal drop in the vast ocean of the possible. Shall we turn our backs on that ocean? Diamond semiconductors, materials that resist high temperature, structural materials with the strength to weight ratio of diamond, and a host of other examples do not seem to fall within the range of structures that biological systems can directly make.

If we pursue artificial self replicating systems, what do they look like? What are the principles on which they are based? How complex will they be? These and other questions must be systematically addressed, with a confidence and at a level of detail that lets us base major investments on the answers. (While the author has written several articles about self replicating manufacturing systems (http://nano.xerox.com/nanotech /selfRep.html) and has no doubt that they will play an essential role in future molecular manufacturing systems, the point here is that individual conclusions, regardless of how sound, aren't enough. Some substantial portion of the research community must address the issues and reach at least rough agreement about the answers).

If self replication is the right approach and we fail to pursue it, we'll make no further progress. If it's the wrong approach we must develop an alternative. No plausible alternative has been proposed which could simultaneously achieve the three objectives given above: low cost, molecular precision, and great flexibility in what can be made. Investigations to date strongly support the feasibility of programmable self replicating systems. The obvious strategy is to investigate this approach in greater depth.

Molecular Modeling

If we wish to accomplish that which is new, we must at some point discuss what we have not (yet) done. If what must be done is relatively complex (a self replicating system, for example), then we must be prepared to spend substantial time and effort discussing things that have not been made and will not be made for many years.

At the same time, we must take steps to insure that our discussions of what hasn't been done remain focused and do not drift into abstract errors and vague generalities.

Fortunately, we have a tool at hand for dealing with this: molecular modeling (http://nano.xerox.com /nanotech/compNano.html). We know the laws of physics, and we do not expect them to be substantially in error as we apply them to molecular systems under "reasonable" conditions. The applicability of Schrodinger's equation to molecular machines is unlikely to change in the next several decades. We do not need, nor do we expect, any major revolutions in physical law. Our goal and our desire is to develop molecular machines that are feasible with respect to known and well understood physical law. While physical experiments let us explore a tiny fraction of what is possible, they cannot let us investigate what we do not yet know how to make.

Molecular modeling can be used to probe systems that have already been built (allowing us to check the accuracy of the models), systems that might soon be built (letting us inexpensively explore alternatives) or systems that won't be built for many years (again letting us inexpensively explore alternatives, but on a longer time horizon).

If the key to progress is developing a shared understanding of the approach or approaches which are worth pursuing, as well as some shared vision of the goal; and if the goal cannot be achieved without many years of work, then we must adopt a disciplined method of analyzing the alternative ways of achieving the objective. Molecular modeling is a major component of that discipline.

Modeling an Assembler

To sharpen the focus on this idea of modeling future molecular machines with present molecular modeling methods, let us consider the design of an assembler (http://nano.xerox.com/nanotech/nano4 /merklePaper.html). Such a device is able to make copies of itself - hence achieving low cost - and can be programmed to build a wide range of useful structures. The term "assembler" actually encompasses a rather large family of possible designs. For our purposes, we wish to consider the simplest assembler able to achieve certain core objectives: make a copy of itself, and make a wide range of hydrocarbon structures (including diamond and graphite) under program control.

If we are to build an assembler, than at some point we must completely specify it: we must specify the location and element type of every atom. Interestingly enough, it should be possible to design and model such an assembler using computational chemistry software and computing hardware that are either presently available or could reasonably be developed in the near future (a few years). Molecular mechanics and dynamics models would be used to analyze the behavior of the mechanical components, while *ab initio* quantum chemistry models would be used to analyze the reactions involved (e.g., the making and breaking of chemical bonds). Some potential energy functions (such as Brenner's potential) are able to model bond formation and bond breaking. They would be used to do molecular dynamics on the chemical reactions where they were applicable.

Some of the reactions that will likely be involved in the synthesis of diamond have already been modeled. One example is the hydrogen abstraction tool (http://nano.xerox.com/nanotech/Habs/Habs.html), which has been modeled by several groups using both *ab initio* and molecular dynamics methods. Other components have been proposed, discussed, and modeled in varying levels of detail. This process can clearly be extended.

It is useful to emphasize that a design for an assembler is not the same as having an assembler. An assembler can build another assembler, but this presupposes the prior existence of an assembler. We must still build the first one using existing technology. This presents a separate design challenge - but a design challenge that can also be addressed by molecular modeling.

The Alternatives

If we are to develop molecular nanotechnology, it would seem that one of the significant tasks is to systematically investigate the various ways of achieving its basic objectives. Is this a reasonable course of action? Again, using self replication as an example, we need to ask: what are the available alternatives? To date, the only proposals for molecular manufacturing systems involve self replication. The obvious approach is to analyze in greater depth the proposals that have been advanced. If we hesitate to pursue this approach then we should explicitly seek alternatives and then analyze them to see if they are as effective at achieving the desired objectives.

If molecular nanotechnology is feasible within the existing framework of physical law - and that seems to be the predominant opinion - then unless (a) we expect physical law will change or (b) we expect molecular manufacturing systems will be easily developed without great effort, then the obvious strategy is to (c) begin the patient task of exploring the space of possibilities, winnowing out the approaches that either don't work or fail to achieve one (or more) of the objectives, and focus on the approaches that look like they should work. And when we've explored the possibilities, studied the alternatives, determined what is possible and rejected what is impossible - when we can see a clear path from where we are today to where we wish to be in the future - then we can begin in earnest.

Foresight Guidelines on Molecular Nanotechnology
Monterey Workshop Draft 3.2
June 17, 1999

Background

These guidelines were developed during and after a workshop on Molecular Nanotechnology (MNT) Research Policy Guidelines sponsored by the Foresight Institute and the Institute for Molecular Manufacturing (IMM). The workshop was conducted over the February 19-21, 1999, weekend in Monterey, California.

Participants included: James Bennett, Greg Burch, K. Eric Drexler, Neil Jacobstein, Tanya Jones, Ralph Merkle, Mark Miller, Ed Niehaus, Pat Parker, Christine Peterson, Glenn Reynolds, and Philippe van Nedervelde. In spite of the diversity of briefing materials and views represented at the workshop, the participants discussed the technical and policy issues with both intensity and civility. While any one participant might have preferred more or less emphasis on a particular issue, the group was able to converge on a common set of draft guidelines for the development of MNT.

The Foresight Guidelines ("the Guidelines") include assumptions, principles, and some specific recommendations intended to provide a basis for responsible development of molecular nanotechnology. The group agreed to review the Guidelines among themselves, and then release them on the WWW for review by the larger Foresight community. The intention is to eventually release the Guidelines for general distribution on the web, and in magazine and book publications. The goal is to get the Guidelines endorsed and adopted by organizations sponsoring MNT research and development projects, and to inspire effective self-regulation wherever necessary and possible.

The MNT community recognizes that the developing technology of Molecular Manufacturing will open an unprecedented new set of technical and economic opportunities. It is the considered judgment of the participants in the Foresight/IMM Workshop (the Workshop), that MNT also represents an unprecedented set of military security and environmental threats that should not be ignored.

The participants in the Workshop believe that any future discussions on this subject should include discussion of the economic and environmental benefits of MNT, as well as the potential problems. In particular, we did not want the need for some controls to prevent the responsible development of the technology. Rather than have reflexive, or poorly informed controls imposed upon the MNT R&D process at some later date, we elected to recommend a set of self-imposed controls that seem appropriate, given what we know today. The NIH Guidelines on Recombinant DNA technology are an example of a similar action taken by the biotechnology community almost 25 years ago. Those guidelines were so well accepted that the privately funded research community has continued to submit research protocols for juried review, in spite of the fact that it was optional for them to do so. In addition, although the guidelines have been progressively relaxed since they were first released, they did achieve their intended effect.

Another goal of the Workshop members was to educate MNT researchers about the potential benefits and risks of the technology, and introduce development guidelines into professional associations, such as Foresight, IMM, and possible industrial consortiums. We noted that the "moral repugnance" associated with biological weapons may have attenuated their development and use, in spite of the fact that they are relatively easy to make and deploy (Cole, 1997). Our goal was oriented towards specific development principles and guidelines that would actually prove useful to developers.

Effective enforcement will require priorities for enforcement. For example, an enforcement agency might attend to: 1) highest promise of cheap fixes, substitutions, or technological control options; 2) visible consequences to enhance agency credibility; 3) invisible consequences to ensure they get priority set by hazard level; 4) chronic long term consequences, rather than short term consequences; and 5) any theoretically possible, but unlikely catastrophic consequences.

Overall, the goal is to accelerate the development of peaceful and environmentally responsible uses of the technology. This includes capturing the environmental opportunity for designing energy efficient and zero emission manufacturing and transportation technologies.

The Guidelines must be a living document subject to modification and revision. They must also be enforced via a variety of means, possibly including quarterly lab certifications, randomized open inspections, and stiff legal and economic penalties for violations. We accept that enforcement is inherently imperfect, but the deterrent effect of unpredictable inspection, combined with predictable and swift consequences for violations, is probably better than doing nothing.

Preamble

The term "Molecular Nanotechnology" (MNT) refers to the ability to program matter with molecular precision, and scale this ability to three-dimensional products of arbitrary size. This developing technology presents an unprecedented new set of technical and economic opportunities. The opportunities include: the development of inexpensive and abundant diamondoid building materials with a strength-to-weight ratio 50 times greater than titanium, the possibility of widespread material abundance for all the Earth's people, the development of revolutionary new techniques in medicine, and the opening of the space frontier for development. Along with these new capabilities come new risks, and new responsibilities. The acceptance of these responsibilities is not optional. MNT also represents an unprecedented set of military security and environmental threats. Dealing with these concerns proactively may be critical to the positive economic development of the field.

Future discussions of this subject should include detailed consideration of the economic and environmental benefits of MNT, as well as the potential problems. In particular, the need for some controls should not prevent the responsible development of the technology. Rather than have reflexive, or poorly informed controls imposed upon the MNT R&D process, the developing MNT R&D community and industry should adopt appropriate self-imposed controls, formulated in light of current knowledge and the evolving state of the art. The possibility of the necessity for additional controls remains an open question, and its resolution may depend to some extent on the success of voluntary controls.

Experimenters and industry should have the maximum possible opportunities to develop and commercialize the molecular manufacturing industry. In addition, MNT should be developed in ways that make it possible to distribute the benefits of the technology to the four fifths of humanity currently desperate to achieve material wealth at any environmental or security cost. Providing technical abundance alone cannot make a people wealthy and secure. This also requires education, and social arrangements described as a high-trust, civil society. Technological abundance can alleviate conflicts that stem primarily from rivalry over resources. Reducing this specific cause of conflict would make the world more secure than it is today. The release from bare economic subsistence could enable billions of people to take advantage of the emerging global classroom over the World Wide Web. This education effect could compound the positive environmental and security benefits of MNT.

Effective means of restricting the misuse of MNT in the international arena should be developed. A treaty that adds MNT to the list of technologies including Chemical, Biological and Nuclear Weapons might seem appropriate, but it could lead to the unintended consequence that only the U.S. and other rule following nations would be at a competitive disadvantage for countering new weapons of mass destruction. There are reasonable arguments on both sides of the treaty question. However, at this time, the MNT community does not endorse any specific initiative to address MNT safety and security concerns through treaty arrangements.

MNT researchers and developers have an obligation to explore the potential benefits and risks of the technology, to introduce development guidelines into professional associations, such as Foresight, IMM, and possible industrial consortiums, and then to abide by those guidelines. An international MNT development consortium with shared intellectual property could be one organization that adopts the Guidelines and works by them. The consortium should require all member companies to sign and agree to enforce the consortium's adopted Guidelines for the development of MNT. The objective should be to place non-compliant companies at a competitive disadvantage with respect to intellectual property and the technology learning curve. If compliant companies and/or consortia share ideas and technology, they may be the first to implement effective MNT, discouraging non-compliant companies from following on their own. Excessively restrictive control regimes are counterproductive to this objective.

Relevant ecological and public health principles must be utilized in conducting MNT R&D. Diamondoid products or more advanced replicating devices may not break down easily in the natural environment. Furthermore, consumers may not at first have means readily available to recycle them. Thus, total "product lifecycle" considerations should be taken into consideration as the MNT industry develops. An experimental R&D program is needed to distinguish remote or theoretical ecological and public health risks from immediate and pragmatic risks.

Common public policy pitfalls must be avoided in drafting any specific new regulation. What is needed are: 1) clear guidelines and laws, 2) agencies with specific mandates and consistent roles for inspection and enforcement, 3) a focus on identifying consistent and principled classes of hazards, while ensuring that specific cases are judged flexibly. The goal is to establish the minimum necessary legal environment to ensure safety.

Principles

People who work in the MNT field should utilize professional guidelines that are grounded in reliable technology, a knowledge of and respect for the natural environment, security, ethics, and economics.

Access to the products of MNT should be distinguished from access to all forms of the underlying development technology. Access to both MNT technology and products should be unrestricted unless this access poses a risk to global security.

Accidental or willful misuse of MNT must be constrained by legal liability and, where appropriate, subject to criminal prosecution.

Ethical researchers and developers of MNT agree that governments, companies and individuals who refuse or fail to follow responsible principles and guidelines for development and dissemination of MNT should be placed at a competitive disadvantage with respect to access to technology and markets.

MNT laboratory guidelines for self-replicating machines should be analogous to those set by the United States National Institute of Health (NIH) for recombinant DNA safety levels. These guidelines should incorporate additional provisions for inherently safe designs, such as: 1) absolute dependence on a single artificial fuel source or artificial "vitamins" that don't exist in any natural environment; 2) sealed assembler labs; or 3) making devices that return to an off state, and are dependent on broadcast transmissions for replication or in some cases operation; 4) routing control signal paths throughout a device, so that subassemblies do not function independently; and 5) other innovations in safety technology developed specifically to address the potential dangers of MNT.

The global community of nations and non-governmental organizations should develop effective means of restricting the misuse of MNT. Such means should not restrict the development of peaceful applications of the technology or defensive measures by responsible members of the international community.

MNT research and development should be conducted with due regard to existing principles of ecological and public health. MNT products should be promoted which incorporate systems for minimizing negative ecological and public health impact.

Any specific regulation adopted by the researchers, industry or government should provide specific, clear guidelines. Regulators should have specific and clear mandates, providing efficient and fair methods for identifying classes of hazards and for carrying out inspection and enforcement. The community of MNT researchers and developers explicitly recognize the value of seeking the minimum necessary legal environment to ensure the safe and secure development of their technology.

Development Principles

1. Replicators must not be capable of replication in a natural environment.
2. Evolution within the context of a self replicating manufacturing system is discouraged.
3. Any replicated information should be error free.
4. Designs that limit proliferation and provide traceability of replicating systems are encouraged.
5. New experimental plans should be reviewed by a system of juried release prior to deployment.
6. Developers should attempt to consider the environmental consequences of the technology, and to limit these consequences to intended effects.
7. Industry self-regulation should be designed in whenever possible. Willingness to provide self regulation should be one condition for access to advanced forms of the technology.
8. Distribution of molecular manufacturing development capability should be restricted to responsible actors.

Design Guidelines

1. Any self-replicating device which has sufficient onboard information to describe its own manufacture should encrypt it such that any replication error will randomize its blueprint.
2. Encrypted genomes should be utilized to discourage irresponsible proliferation and piracy.
3. Mutation (autonomous and otherwise) should be discouraged.
4. Replication systems should generate audit trails.
5. MNT developers should adopt security measures to avoid unplanned distribution of their designs and technical capabilities.

A short biography of Ralph C. Merkle

Dr. Merkle received his Ph.D. from Stanford University in 1979 where he co-invented public key cryptography. He joined Xerox PARC (www.parc.xerox.com) in 1988, where he has been pursuing research in computational nanotechnology. He chaired the Fourth and Fifth Foresight Conferences on Nanotechnology, is on the Executive Editorial Board of the journal Nanotechnology, is a Senior Research Associate at the Institute for Molecular Manufacturing (www.imm.org), was corecipient of the 1998 Feynman Prize for Nanotechnology for theory, and was corecipient of the ACM's Kanellakis Award for Theory and Practice. Dr. Merkle has eight patents and has published extensively. His home page is at www.merkle.com.

June 30, 1999

Nick Smith, Chairman
U.S. House of Representatives
Committee on Science
Subcommittee on Basic Research

Dear Mr Smith:

I have received no federal funding for my research in nanotechnology

Yours truly,

Ralph C. Merkle
www.merkle.com

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES
SUBCOMMITTEE ON BASIC RESEARCH

HEARING ON

Nanotechnology: The State of Nano-Science and Its Prospects for the Next Decade

RESPONSES TO FOLLOW-UP QUESTIONS

Dr. Ralph C. Merkle
XEROX Palo Alto Research Center

QUESTION 1: Several agencies have been working on the development of a new research initiative on nanotechnology for the FY 2001 budget request. The recommendation is to double current funding levels over three years. Is there a need for such an initiative: Is this timely; what is the evidence that research ideas are signficiantly exceeding research support levels? What are the main research opportunities that ought to be addressed?

ANSWER: There is a need for such an initiative. It is timely. The magnitude of the opportunity compared with today's modest funding levels clearly supports the need for greater funding. The greatest opportunity lies in the development of assemblers: programmable self replicating systems able to manufacture both more of themselves and a wide range of other products. Manufacturing costs for assemblers and the products they make will be low, just as the manufacturing costs for potatoes, wood, or other agricultural products based on self replicating systems are low. Unlike biological self replicating systems, assemblers will make non-biological structures (e.g., computer chips, structural materials stronger than carbon fiber composites, molecular surgical tools) inexpensively and in large quantities.

QUESTION 2: What are the fields in which we will see the most significant applications of nanotechnology and in what time frame do you predict we will see the full benefits?

ANSWER: The full benefits of nanotechnology will take some decades to develop. There is no reliable way of saying how long it will take, both because of inherent difficulties in scheduling the development time for fundamentally new technologies, and also because it is difficult to project the level and focus of support. If we do little, it will take a long time. The more support we provide, and the more that support is focused on the objective, the more rapidly we will achieve the full benefits of nanotechnology.

As an example, consider the decision by John F. Kennedy to land a man on the moon. This provided two critical things: (1) support and (2) a clearly articulated goal. Absent Kennedy's decision, a lunar landing might still be in the future. The best articulated long term goal in nanotechnology is the assembler, first proposed by Drexler. After extensive discussion within the technical community, the consensus opinion is that such a device is consistent with known and well understood physical law. Initiating a well funded research program with the explicit objective of designing and building an assembler would be the single most effective action we could take to more rapidly gain the full benefits of nanotechnology.

Any forecast about how long it might take to develop applications is shrouded in qualifications, both technical and sociological. Despite this, it is plausible that we will see major applications of nanotechnology in the 2010 to 2020 time frame. Early applications are likely to include more powerful computers; stronger, lighter and less expensive materials; and molecular surgical tools. As the basic capabilities are developed, we are likely to see their application to essentially all manufactured products. Few products would not benefit from a manufacturing process that was more precise, less expensive, and more flexible.

QUESTION 3: What other nations have significant research programs on nanotechnology and how do they rank relative to the US? Are there particular subfields in which othe countries are more advanced than the US?

ANSWER: While I have some feel for specific research programs in other countries, and certainly have the general opinion that there is excellent research in this area around the world, it is difficult for me to provide a clear assessment of that research for two reasons. First, I have not explicitly reviewed the international research. There is likely much research that I am either unaware of, or whose depth is greater than I know about. Second, there is a great deal of basic research which is very good, but which is not oriented towards achieving any particular goal. Such work will be of limited effectiveness in achieving any specific objective, but the researchers and facilities could be rapidly redirected towards a specific objective once its value was recognized. By way of example, basic research in particle physics can be very good, very informative, and yet lead no closer to the construction of a nuclear bomb. The same research, when coupled with an explicit program to develop a nuclear bomb, would show great progress towards the objective.

The magnitude of the opportunity presented by nanotechnology is so great, and the means for achieving it so novel, that it is not always fully accepted. As understanding and acceptance increase, existing research programs will be retargeted to more rapidly and effectively achieve the high-payoff goals. While we can assess the quality of the research and the ability of the researchers, it is more difficult to estimate where their talents will be applied in the coming years. As an example, consider that we developed nuclear weapons while the Nazis did not even start a major program. How we came to recognize the value of the goal, while they did not, is a complex story involving many factors. How long it will take for us (or others) to recognize the magnitude of the opportunity which nanotechnology offers, and to effectively pursue that opportunity, is not clear.

QUESTION 4: One reason for our country's economic strength is our ability to move science from the lab to the marketplace. What are the engineering problems that need to be surpassed in order to move nanotechnology from the lab to a state of mass production? How would the proposed Nanotechnology Initiative address these problems?

ANSWER: At this stage of the development of nanotechnology we need to pursue fundamental research in several critical areas. Fundamentally, manufacturing requires that we assemble parts.

If the parts are molecular in scale, they must be synthesized by some existing chemical process. Therefore, research aimed at the design and synthesis of molecular building blocks is required. Such research is already being pursued, and increased funding for the Nanotechnology Initiative will increase research in this area (among many others).

Second, the assembly of parts requires that we move those parts. There are basically two ways of assembling parts: self assembly and positional assembly. Self assembly is a well understood research area, and is already being pursued. Increased funding for the Nanotechnology Initiative will proportionately increase research in this area.

Positional assembly at the molecular scale is a novel research area which lacks the long tradition of research in self assembly. To date, only relatively simple examples of molecular positional assembly have been demonstrated. The major examples come from research using Scanning Probe Microscopes (SPMs), where individual atoms and molecules have been arranged on a surface. Further research aimed explicitly at designing molecules (moleclar building blocks) that can be picked up and stacked, and research which demonstrates the ability to make simple (and increasingly complex) structures from these building blocks using SPM's is required. This area is at present underfunded relative to its importance. Research which gives us a better ability to manipulate molecular structures using SPM's should be encouraged, and the overall level of funding increased relative to other research areas funded by the Nanotechnology Initiative.

Besides parts to assemble and means to assemble them, we also need to know what to make. A pile of parts without a blueprint is just a pile of parts. The need to design and analyze what we are going to make before we actually make it requires theoretical and computational work. Fortunately, computational chemistry has reached the stage where it can accurately model molecular machines. We must design and model an assembler, the components of an assembler, the parts from which to make them, and the sequence of assembly steps involved in making the components from the parts. This will be computationally intensive. It will require research in computational chemistry (to provide appropriate computational models), the design of molecular components, system level designs for an assembler, and modeling and digital simulation of the resulting designs.

The concept of designing molecular components is still relatively new, and the concept of a system level design for a molecular machine is very new. As a consequence, both areas are underfunded. We need multiple system level designs for assemblers. These system level designs must specify the subsystems required. For example, a system level design might require a molecular robotic arm as a subsystem. The subsystems, in their turn, must be designed in molecular detail and modeled using the methods of computational chemistry. If the system level design calls for a molecular robotic arm, then we must design it in molecular detail and computationally model its behavior and characteristics. This is feasible and should be done.

Each subsystem must fit into some system level design (there is no need for a subsystem which does not fit into any system). Each system must be made from subsystems which are feasible. A system which requires an infeasible subsystem is of little interest. Thus, system designs and subsystem designs are each necessary for the other's existence. As a consequence, the development of system designs, subsystem designs, and the modeling of subsystems must be pursued in an integrated manner. This entire area is significantly underfunded. Funding for this area should be greatly increased relative to other research areas funded by the Nanotechnology Initiative.

Once we have parts, ways to assemble the parts, and designs for products made from those parts, then we can start to make the products. Early products will likely include improved SPM's (smaller, faster, more precise, more reliable, etc) which will, in turn, facilitate more rapid and reliable assembly of parts. Other products will likely include commercially useful instruments and better defined or more robust tips (higher quality SPMs with better tips will be useful in product inspection, research and low volume manufacturing). As our abilities improve the range and quality of products will increase and their manufacturing cost will decrease. At some point, we will achieve the threshold capabilities required to manufacture a self replicating system. Manufacturing costs will drop dramatically and molecular manufacturing will become the preferred way to build almost all products.

QUESTION 5: How significant will the impact be of nanotechnology on medicine and health care?

ANSWER: Disease and ill health are caused by damage at the molecular and cellular level. Today's surgical instruments are too crude to deal with this kind of damage. With nanotechnology, we will be able to make surgical tools that are molecular, both in their size and precision. By itself, this will permit unprecedented advances in diagnostics and research. Coupled with low cost, high volume manufacturing, it will usher in a revolution in medicine and health care. For example, the chemotherapy used today to attack cancer cells is imprecise and damages other tissues and organs. With molecular surgical tools, we will be able to specifically attack the cancer cells while leaving other cells unharmed.

QUESTION 6: In a scientific field as new and diverse as nanotechnology research, how would you formulate and implement an effective peer review process for selecting which research projects will be funded? How would a peer review process for nanotechnology research funding differ from NSF's normal peer review process?

ANSWER: Much of the research that is needed in nanotechnology can be funded using existing institutions and methods. Peer review, in particular, is an excellent method of funding research when the basic objectives and concepts are shared by proposers and reviewers. However, particularly in view of the new system level design efforts that are needed for the effective development of nanotechnology, some augmentation of the peer review approach is needed. An approach used effectively by DARPA, in which a program manager is given fairly free reign to fund research in a given area, would seem more effective when an integrated set of research objectives must be achieved simultaneously. NASA is also experienced in system level design efforts (e.g., for the space shuttle or Apollo program).

In view of this, some funding should be channeled through a mechanism in which specific individuals (champions) are responsible for coordinating research efforts to pursue specific approaches (such as the assembler), and are provided with control of the resources necessary to achieve significant results. As the development of integrated system designs is essential, and as such integration is unlikely to emerge from disparate peer reviewed proposals, some mechanism is needed to insure that integrated system-level approaches are advanced, analyzed, and compared with each other.

Within the framework of peer reviewed proposals, it is also essential to define the areas which need to be funded. These include:

(a) Scanning Probe Microscopy, with emphasis on building increasingly complex molecular structures.

(b) Synthesis of molecular building blocks, with emphasis on building blocks that can be manipulated and assembled using SPMs.

(c) Self assembly and supramolecular chemistry, with emphasis on the synthesis of molecular building blocks and the direct self assembly of molecular machines (molecular motors, computational components, etc.).

(d) Molecular design, with two areas of emphasis. First, designs of molecular machines and components that might reasonably be realized within a five year time frame using molecular building blocks (using either self assembly or positional assembly). Second, design of molecular machines and components that are unlikely to be realized in a 10 year time frame, but which demonstrate feasible approaches to the longer term goals of nanotechnology, particularly including self replication and the positional assembly of diamond, graphite, and materials similar to them.

(e) Computational chemistry, with emphasis on the accurate modeling of molecular machines, particularly including molecular machines made from molecular building blocks as well as molecular machines made from diamond, graphite, and similar materials.

QUESTION 7: What is the state of the human resource base available in the US to conduct research in the field of nanotechnology, in terms of research faculty at universities, industrial researchers and graduate students?

ANSWER: Whether in academia, industry, or at the graduate student level, the US has some of the finest researchers in the world. However, the number of research programs that are specifically aimed at the development of nanotechnology is still relatively limited and needs to be expanded.

QUESTION 8: How would advances in nanotechnology improve American agriculture?

ANSWER: In the longer term, nanotechnology will permit the low cost manufacture of inexpensive computer controlled greenhouses. By providing an optimal environment for plant growth, these greenhouses would permit plants to grow at their theoretical maximum rate throughout the year. Such controlled environments would eliminate insects and other pests and provide optimimum levels of CO2, humidity, temperature, and nutrients. Crop yields per acre could be increased by an order of magnitude or more, reducing the need for crop land.

Reducing the total land area devoted to crops would permit the restoration of huge tracts of land to a more natural state.

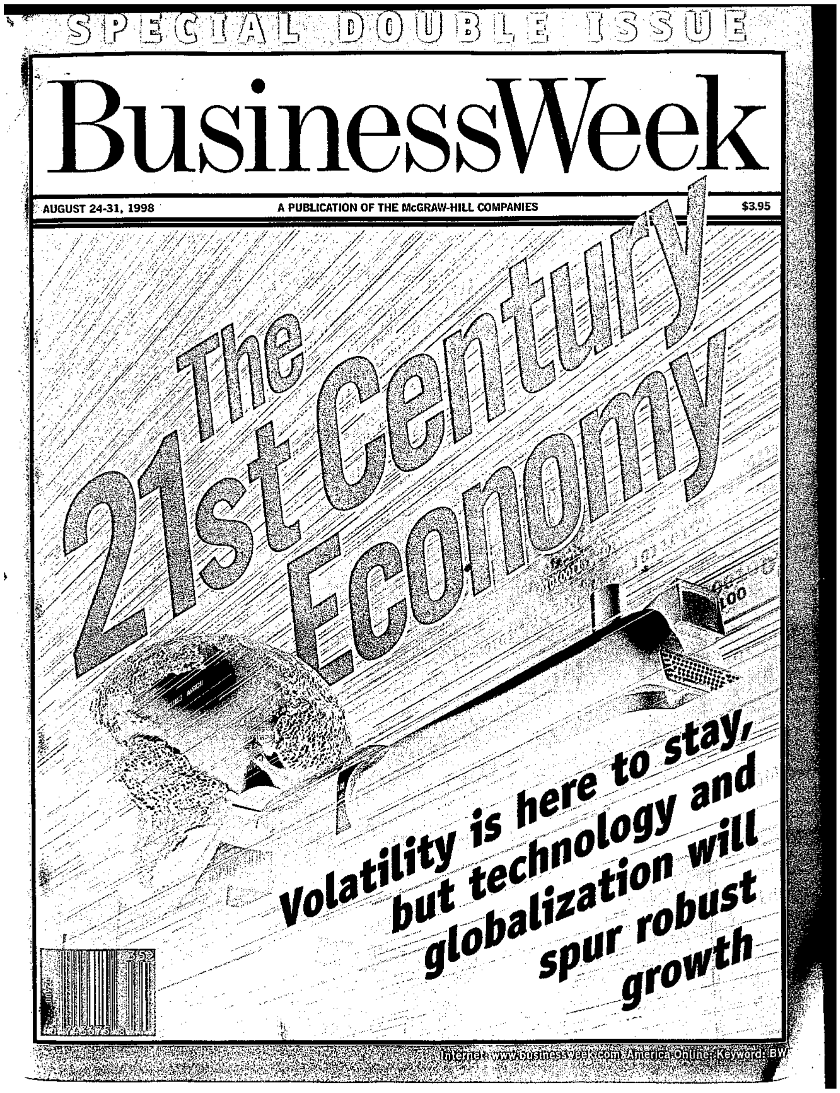
QUESTION 9: You point out that many researchers think self-replication will be the key to unlocking nanotechnology's full potential as a robust manufacturing technology. Could artificial self replicating systems pose unique risks?

ANSWER: Powerful technologies can be used for both good and ill: nanotechnology is unlikely to be an exception. Because it will be able to make large quantities of inexpensive high performance products, it will also be able to make large quantities of inexpensive high performance weapons. Historically, more powerful weapons have meant smaller and smaller groups could inflict greater and greater damage. Nanotechnology will permit the continuation of this trend into the future, and could theoretically permit a handful of people to inflict damage world wide. Because this ability is today theoretical, there is no need to limit or constrain the free and unfettered discussion of these problems. Indeed, early research aimed specifically at analyzing the potential risks and effective methods for avoiding them should be encouraged.

Today, we are uncertain about how long it will take to develop the full capabilities of nanotechnology. When we are discussing potential benefits, the conservative approach is to assume the development time will be long. When we are discussing potential hazards, the conservative approach is to assume the development time will be short. Research aimed specifically at analyzing potential hazards should start today, so that we will be prepared if nanotechnology develops more rapidly than expected. Should the development time be longer than expected, we have lost little. If we fail to pursue such research today, and if nanotechnology is developed more rapidly than expected, we will be forced to deal with hazards that we have not considered and are unprepared to deal with. Given the power of the technology, this scenario has substantial downside potential.

Research on potential military consequences of nanotechnology should be pursued by the defense and intelligence communities. This research should be informed by the system design proposals and the computational modeling of such proposals involved in the development of nanotechnology (discussed earlier). In view of the long procurement times (decades) involved in the development, deployment and use of military systems, this research must necessarily take a multi-decade perspective. Failure to anticipate the capabilities of this new technology will result in an unprepared and possibly ineffective response when it moves from theory to practice.

APPENDIX 3: Material for the Record


SPECIAL DOUBLE ISSUE
BusinessWeek
AUGUST 24-31, 1998
A PUBLICATION OF THE McGRAW-HILL COMPANIES
$3.95
The 21st Century Economy
Volatility is here to stay, but technology and globalization will spur robust growth
Internet: www.businessweek.com America Online: Keyword: BW

Silently and efficiently, the new team member toils away in a chemistry lab at the University of California at Santa Barbara. With perfect precision, she lays down an ultrathin layer of an organic substrate. Onto this, she deposits interlocking calcite crystals, atom by atom. The two layers bond into a delicate crystal lattice. Under a microscope, it calls to mind the flawless thin-film layers on a silicon chip.

But there is no clean room, vacuum chamber, or chip gear in this lab, where professors Galen D. Stucky and Daniel E. Morse brainstorm new materials. For that matter, the "team member" is no ordinary staff researcher. She's a mollusk—an abalone. And like so many of nature's creations, she has acquired, through millions of years of evolution, an exquisite form of molecular machinery to create her shell—machinery that leaves today's best fabrication tools in the dust.

TECHNOLOGY

THE NEXT WAVE

One day, scientists will be able to create materials atom by atom. The upshot: Doing everything nature can do, and more

At Santa Barbara and hundreds of other research centers, scientists and engineers are getting ready for the next great technological revolution—the leap into the world of the very small. Nature has an unrivaled genius for designing and producing tough, versatile materials—from seashells to spider's silk—in self-replicating "factories," and at an atomic scale. Scientists want to clone this ingenuity, to forge new industries of the 21st century. "Atom by atom—that's how nature designs and builds things," muses Cherry Murray, Physical Research Lab director at Lucent Technologies' Bell Labs. "If you could influence design at such a scale, you could make any material you ever wanted."

BYE BYE PC BUGS? That ultimate goal is still mostly a glimmer. But the high-tech landscape is on the brink of change. The development pipelines at many high-tech companies already showcase a whole new breed of miniaturized marvels with capabilities well beyond today's chips. Over the next half-decade, these so-called "microelectromechanical systems" (MEMS)—which combine sensors, motors, and digital smarts on a single sliver of silicon—are likely to supplant more expensive components in computer hardware, automobile engines, factory assembly lines, and dozens of other processes and products. The operating software for these devices, now in the process of being written, is expected to suffer neither the bugs nor the bloat of today's PC programs.

Going somewhat further out—probably 15 to 20 years—high-tech visionaries foresee a transition that's far more radical and disruptive. Its quintessence won't be smaller, cheaper, faster electronics—though we will have all that in abundance. The transition scientists speak of involves nothing less than the hijacking of nature's own creative machinery.

In medicine, this spells the ability to repair or replace the body's failing organs. In manufacturing, it means coercing molecules to assemble into useful devices—the same way that crystals and living creatures assemble themselves. The coming wave of miniaturization and molecular electronics—sometimes called "nanotechnology"—is taking shape at the intersection of chemistry, physics, biology, and electrical engineering. And if it crests as many scientists predict, it will bring a wholesale industrial transformation, more dramatic than the late-20th century flowering of microelectronics.

No one dismisses the enormity of the challenges. Atoms, at room temperature, inhabit a turbulent world ruled by forces we don't fully understand. Today's best theories, scientific instruments, and computer simulations provide only imperfect access to this domain.

Why, then, do so many scientists believe in a Molecular Revolution? Because some of the necessary capabilities are already within reach. As scientists at Bell Labs figure it, the widths of the circuit lines that make up electronic elements on chips will shrink 80%, to just 50 nanometers, by 2010. That's 50 billionths of a meter—the distance of about 300 atoms tethered in a row—and roughly the thickness of the protein layers in the abalone's shell.

In other words, engineers are already plunging deep into nature's hidden preserve. And in life sciences, they've gone even further. Biotechnologists can tailor antibodies that fight cancer. And they can slip new genes into plants or animals, to produce plastics or drugs (page 86). Nano-engineers believe they can build on this base, and write new recipes or scripts

GETTING SMALL IN THE NEXT **HALF-DECADE**, SILICON CHIPS WITH MICROSCOPIC SENSORS, MOTORS, AND OTHER MOVING PARTS ARE LIKELY TO SHOW UP IN COMPUTER HARDWARE, CAR ENGINES, ASSEMBLY LINES, AND **DOZENS** OF OTHER PROCESSES AND PRODUCTS.

MALCOLM TARLOFSKY

that will instruct unruly atoms to form desired materials. The first successes—though not quite at the atomic level—are already visible. Bell Labs boasts of chips that literally pick themselves up off a substrate. And at the University of Rochester, researchers coax polymeric molecules to form hollow cylinders and solid rings. Once perfected, such devices alone stand to bring enormous savings to many industries. Says Venkatesh Narayanamurti, dean of the engineering college at UC-Santa Barbara: "The Internet is nothing compared to what's coming."

QUAKE WARNINGS. The shifting economics are already evident with the arrival of MEMS. Early mass-produced applications include tiny automobile accelerometers, which trigger air bags in a crash, and a host of other industrial sensors. But as sketched out by Sandia National Laboratory's MEMS research chief, Paul J. McWhorter, the next wave will be far more dramatic. Deployed in networks, MEMS will sense one another and configure themselves to perform information-processing tasks. In the not-so-distant future, MEMS will steer our planes, monitor our health, and warn us of earthquakes, faulty aircraft parts, or cracks in bridges.

Since most MEMS chips have less circuitry than memory chips or microprocessors, they can be fabricated inexpensively on older chipmaking lines. That signals the first stage of a whole new paradigm for technology evolution, says Bell Labs' Murray. In the past, breakthrough devices carried a premium when they hit the market, and they were deployed sparingly. But with MEMS, Murray says, from the beginning, "you can manufacture in high volume at low cost. This has the potential to break down the old economic order."

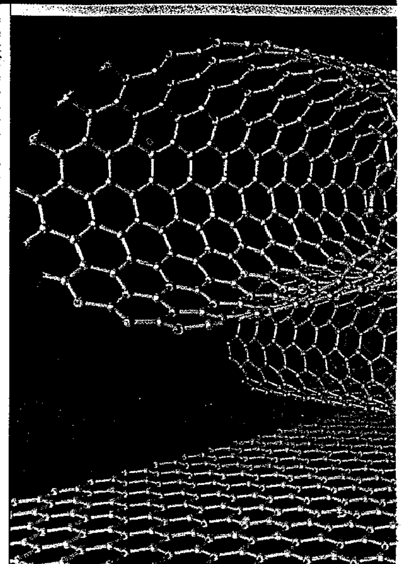
Telecom, she says, will be an important testing ground. At Lucent, Siemens, and Tellabs, engineers want to shrink whole hunks of the next-generation telephone and data networks onto MEMS, possibly beginning in as little as two years. The arena they have targeted is a new mode of high-speed optical transmission called wave division multiplexing, in which a single beam of light is split into multiple colors, or channels, and zipped through fiber. Lucent's Bell Labs already has shown how today's pricey prototypes could be replaced by tiny microscopic mirrors sculpted onto MEMS. Combine that with satellite technology, and long-distance communications costs drop to zero. "This changes how meetings are conducted, how banking is done, how information is transported, everything," Murray says.

Wireless MEMS offer similar promises. At the University of California at Los Angeles, a team of 50 researchers is working on single-chip MEMS radios that could replace the $500 cards used in today's wireless data networks. In about five years, says William J. Kaiser, chairman of UCLA's electrical engineering department, all PCs and palmtop computers will come with radio MEMS. "And they'll be embedded in the ceiling in your office cafeteria, your hotel room, your airplane," he predicts, "all of them seamlessly linked to the Internet."

VOICES | Richard Smalley

TITLE Professor of chemistry and physics, Rice University. 55.
CONTRIBUTIONS After sharing the 1996 Nobel Prize for discovering carbon 60 molecules, or "buckyballs," he's working with elongated forms called carbon nanotubes. These could be the basis for chips with circuits the size of single molecules.
IN HIS WORDS "Nature creates enzymes that are precise down to the last atom. But she doesn't make buckytubes. Maybe we are nature's way of making these."

Around the same time, says California Institute of Technology physics professor Michael L. Roukes, vast numbers of wireless MEMS could be deployed as seismic and metal stress



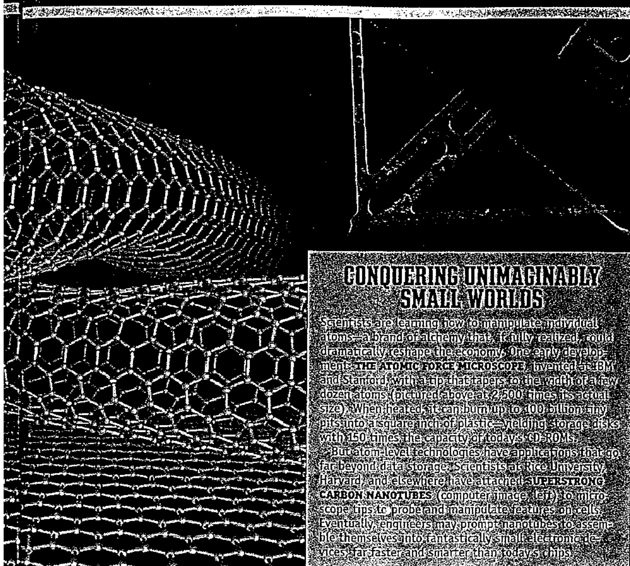
sensors, in patient-monitoring systems in hospitals, and as communications systems on satellites. "This is absolutely not science fiction," Roukes insists. "It's here and now."

In computing, disk storage capacity could be increased a hundred-fold by a MEMS-based instrument called an atomic force microscope (AFM). Such "probe" microscopes, invented at IBM and Stanford University, produce images of atoms by dragging a superfine needle over a surface (above). But these new probes also enable data storage on a near-atomic scale, since they can nudge atoms from one position to another. It's a painstaking process, today. But researchers can speed it up by clustering hundreds of microscope tips on the same silicon device.

Health care is another beckoning frontier for MEMS—and its economics closely mirror those of the computer industry. Lawrence Livermore National Laboratory has developed a MEMS alternative to today's multithousand-dollar DNA sequencers. Its parts can be produced for less than $100. And the same notebook-size box can also include a miniature blood analyzer. Blood analyzer chips could continuously monitor an out patient's blood and radio the doctor at the first sign of a crisis.

Sturdier, more aerodynamic airplanes are another big goal. By studding the back and wings of a plane with thousands of MEMS-size flaps, engineers can alter the lift and drag to

(L TO R) PHOTOGRAPHS BY PAM FRANCIS; IBM RESEARCH



CONQUERING UNIMAGINABLY SMALL WORLDS

Scientists are learning how to manipulate individual atoms—a brand of alchemy that, if fully realized, could dramatically reshape the economy. One early development: **THE ATOMIC FORCE MICROSCOPE**, invented at IBM and Stanford, with a tip that tapers to the width of a few dozen atoms (pictured above at 2,500 times its actual size). When heated, it can burn up to 100 billion tiny pits into a square inch of plastic—yielding storage disks with 150 times the capacity of today's CD-ROMs.

But atom-level technologies have applications that go far beyond data storage. Scientists at Rice University, Harvard, and elsewhere have attached **SUPERSTRONG CARBON NANOTUBES** (computer image, left) to microscope tips to probe and manipulate features on cells. Eventually, engineers may prompt nanotubes to assemble themselves into fantastically small electronic devices far faster and smarter than today's chips.

minutely control the plane. In theory, planes with MEMS wouldn't rely so much on wear-prone rudders, wing flaps, or tail elevators. The concept has been proven in wind tunnels. And the military's Defense Advanced Research Projects Agency (DARPA), which is seeding MEMS research to the tune of $47 million a year, is now test-flying one-seventh-scale planes.

DISTANT DREAMS. DARPA is interested in military applications, such as radio MEMS that can assemble themselves into networks in a battle or crisis situation. "You drop them off the back of a truck, they find each other, and establish communication links," says Albert P. Pisano, director of DARPA's MEMS program. In addition, DARPA is spending millions on so-called microbot planes that would be outfitted with MEMS sensors to detect biochemical weapons or relay images of enemy positions.

But in business environments as well, such devices can spell huge efficiency gains. Office networks wouldn't need to be configured manually—they could assemble themselves right out of the box. Laptop computers and cell phones with built-in radio MEMS and GPS circuits will always know exactly where they are, and how to connect to the nearest Internet backbone. MEMS also can be assembled into more complex robotic organisms. Kristofer S. J. Pister, an electrical engineer at UCLA, and two Vanderbilt University mechanical engineers are among those who are developing insect-like robots, which one day will be able to handle assembly jobs in electronics factories, for example, or hunt for survivors in collapsed buildings.

To be sure, the vision of nanotechnology purists—teaching smart devices to assemble themselves from the ground up, atom by atom—is still a distant dream. As Caltech's Roukes puts it, "The only true nanotechnologist today is Mother Nature." But slowly, humans are learning to mimic her handiwork. For example, by vaporizing carbon in vacuum chambers, Rice University physicist Richard E. Smalley and his colleagues create atomically perfect carbon nanotubes that don't exist in nature.

NO RETURN. The tubes are chemically stable, about 100 times tougher than steel, and scientists have just begun to explore their possible applications in industry. This summer, a Dutch research team turned one of Smalley's nanotubes into the world's first single-molecule transistor functioning at room temperature. Just 4 to 5 atoms in diameter, the circuit shattered a size barrier that ordinary silicon devices can't hope to cross, and it offered the first physical proof that atom-scale electronics are feasible. IBM has also demonstrated carbon nanotube transistors.

How far off is a commercial device? Smalley admits that going from one experimental carbon transistor to one trillion of them on a chip is a staggering challenge. "We have good days and bad days," he says.

That phrase perfectly expresses the zeitgeist of nanotechnology at the turn of the millennium. But few scientists seem inclined to turn back. The results will be a big surprise to economists who believe that industry already has reaped all the easy benefits of the Information Revolution. The revolution has barely begun.

By Neil Gross and Otis Port in New York

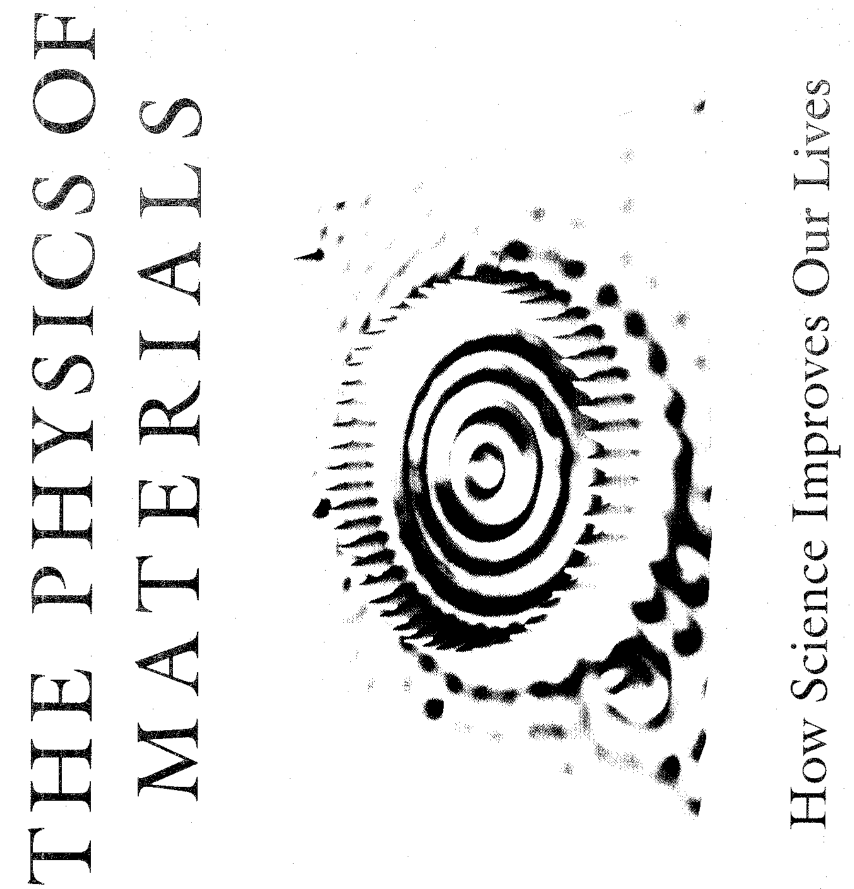
V O I C E S | Cherry Murray

TITLE Director, Physical Research Lab, Lucent Technologies' Bell Labs. 46

CONTRIBUTIONS This year, her lab has unleashed a flood of innovations, from exotic lasers to tiny telecom devices known as optical MEMS. The latter could go commercial in two years.

IN HER WORDS "MEMS could have a huge impact on optical networking. And they'll come in at the low end, not the high end. That's the disruptive part."

(TOP TO BOTTOM) PHOTOGRAPHS BY IBM RESEARCH; MIKE PETERS


THE PHYSICS OF
MATERIALS
How Science Improves Our Lives

The Physics of Materials

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Committee on Condensed-Matter and Materials Physics

Solid State Sciences Committee
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Front Cover: A scanning tunneling microscope image that shows the wave nature of electrons confined in a "quantum corral" of 48 individually positioned atoms. See page 2. (Courtesy of IBM Research.)

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Preface

n the spring of 1996, the National Research Council's Board on Physics and Astronomy established the Committee on Condensed-Matter and Materials Physics to prepare a scholarly assessment of the field as part of a new decadal physics survey. The work of the committee began with a two-day workshop in Washington in June 1996. This workshop brought together some 60 leading practitioners in the field as well as key policymakers from government, industry, and universities. Since then, the committee has met several times to formulate its report, which is to be completed by June 1998.

This short report, *The Physics of Materials: How Science Improves Our Lives,* is an early output of the ongoing study, intended for a broad audience. Based largely on the presentations at the June 1996 workshop, it highlights some of the fundamental science at the forefront of research in the field and demonstrates, through illustrative examples, the field's impact on our everyday lives.

Even though the highlights presented are primarily physics based, the committee would like to emphasize the importance of links with other fields of science and engineering and the inherent interdisciplinary nature and unity of materials research. Important examples of these multidisciplinary links include fullerenes (physics and chemistry), macromolecules (physics and biology), structural alloys (physics and materials engineering), and silicon technology (physics and electrical engineering).

The committee would like to express its gratitude for the interactions it has had with numerous scientists and policymakers. As it continues its deliberations over the next several months, the committee looks forward to receiving further input from the community.

1 ❖ Introduction

Condensed-matter and materials physics has played a key role in many of the scientific and technological revolutions that have changed our lives so dramatically in the last fifty years. The years ahead will see equally dramatic advances, making this an era of great scientific excitement for research in this field. It is also a time of stress on the institutions that support the field. The goal of this report is to give the reader a sense of what condensed-matter and materials physics is about of the excitement that scientists feel, the importance of their work, and the challenges they face.

Within our lifetimes, improvements in our understanding of materials have transformed the computer from an exotic tool, used only by scientists, to an essential component of almost every aspect of our lives. Computers enable us to keep track of extraordinarily complex data, from managing financial transactions to forecasting weather. They control automobile production lines and guide aircraft around the world.

Discovery: 1940s

FIGURE 1.1 The world's first transistor, developed in 1947. It was a point-contact device roughly one centimeter across. (Courtesy of Lucent Technologies Bell Laboratories.)

Application: 1990s

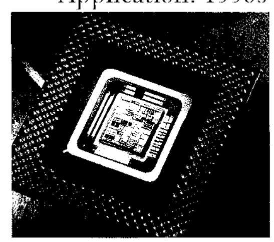


FIGURE 1.2 A Pentium® chip with 3.3 million transistors. Such microprocessors are at the heart of today's personal computers. (Courtesy of Intel Corporation.)

During the same period, telecommunication has evolved from rudimentary telephone conversations to instantaneous simultaneous worldwide transmission of voice, video images, and data. The cellular phone is even unleashing us from telephone wires.

Almost every American can now enjoy, while relaxing in the living room or driving the car or even while jogging, music of a quality that in previous generations was available only to concertgoers.

Just a few generations ago, a trip across the United States was a great adventure. Today, jets whisk us safely across the continent or the oceans in only a few hours.

Making these extraordinary accomplishments possible are a wide variety of polymeric, ceramic, and metallic materials, as well as the transistor, the magnetic disk, the laser, the light-emitting diode, and a host of other solid-state devices. The development of these materials and devices depended on our ability to predict and control the physical properties of matter. That ability is the realm of condensed-matter and materials physics (CMMP), the subject of this report.

Fifty years ago, the major intellectual challenge facing researchers in CMMP was to understand the physical properties of nearly perfect single crystals of elements, simple compounds, and alloys. Today our challenge is to extend that understanding to much more complex forms of matter—high-temperature superconductors, multicomponent magnetic materials, disordered crystals, polymers, glasses and to more complex phenomena like the fracture of solids and the continuous hardening of glass as it cools. Ever in view in today's CMMP is another scientific revolution, the dramatic change under way in the biological sciences. Great opportunities lie ahead as condensed-matter and materials physicists increasingly work together with biological scientists.

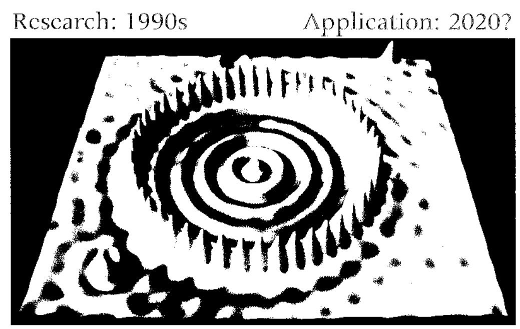


FIGURE 1.3 A scanning tunneling microscope (STM) image that shows the wave nature of electrons confined within a "quantum corral," 14 nanometers in diameter, made up of 48 individually positioned iron atoms on a copper surface. Devices formed by precise positioning of atoms or molecules may one day play an important role in ultrahigh-performance computer chips. (Courtesy of IBM Research.)

Part 2 of this report illustrates the vital impact of CMMP on our daily lives. It consists of a brief story—a few simple events that happen every day accompanied by descriptions that highlight a sampling of the scientific and technological advances in CMMP that make those everyday events possible.

Part 3 explores the nature of the CMMP endeavor itself. CMMP is a diverse, evolving, interdisciplinary field linked strongly to other science and engineering disciplines, which benefit from and contribute to its successes. Indeed, CMMP is distinguished by its extraordinary interdependence with other science and engineering fields. Its practitioners include those who make and refine new materials, those who seek to understand such materials at a fundamental level through experiments and theoretical analysis, and those who apply the materials and understanding to make new devices. This work is done in universities, in industry, and in government laboratories.

Part 3 speaks, as well, of a field in transition. New linkages with disciplines such as polymer chemistry and the biological sciences are growing in importance.

The evolution of CMMP is taking place within an evolving national and international context, as described in Part 4. The great industrial laboratories, so prominent over the last half century, have shifted the scale, scope, and emphasis of their R&D investments in CMMP to adjust to changes in the global marketplace. Industry is looking more and more to universities and government laboratories to perform basic research that will lead to the next generation of technology. Yet these very academic and government institutions are themselves facing considerable stresses that limit their abilities to respond to new demands.

Part 4 also discusses issues arising from the growing dependence of CMMP on shared large and medium-size experimental facilities. Increasingly sophisticated equipment has become necessary for scientific innovation, from electron-beam instruments to giant x-ray synchrotrons. These facilities are essential for continued advances in the invention, understanding, and control of increasingly complex materials. They are required for a broad range of scientific and technological endeavors, not only in CMMP but also in many other fields of science and in industry. But funding large facilities strains the resources of the agencies that have traditionally provided research support to universities and government laboratories, even as those institutions are being asked to play a broader role.

CMMP promises to be a dynamic field of research for many years to come. If the challenges currently facing the field can be met, there are enormous opportunities for scientific and technological advances that will improve our lives. ❖

2 ❖ Technology in Daily Life

Here is a brief story about life today in the United States. It is fiction, but millions of episodes like it occur every day. Each event involves familiar technologies whose present state of development—or very existence—would have seemed extraordinary just a generation ago. The capitalized phrases in the story are links to sidebars on the facing pages that provide more information about some of these technologies.

The owner of a small business is driving her car to the airport. Many structural elements of her car and the airplane that she will be boarding are products of research in **MATERIALS SYNTHESIS.** She is on the way to visit a potential customer. As a seasoned business traveler, she has with her all the tools she needs for her normal daily business. She picks up her cellular telephone and dials her son's pager. The communications revolution represented by the telephone and the pager has been greatly enhanced by advances in **COMPOUND SEMICONDUCTOR ELECTRONICS.**

MATERIALS SYNTHESIS

The materials in modern cars and airplanes that make them safer, lighter, and more fuel-efficient than their predecessors result from advances in materials synthesis and processing. Progress in the synthesis of materials takes many forms: research aimed at discovering new materials, development of methods for inexpensive and reliable production of such materials, incorporation of well-known materials in new geometries and environments, and continuous improvement of the production and processing of traditional materials. Each of these activities has firm roots in materials physics and chemistry.

"Nonequilibrium" materials processing involves raising the energy of the starting materials (for example, by heating) and guiding them into the desired final state. Such an approach has allowed the creation of new surface alloys that improve the wear characteristics of artificial joint replacements and machine tools. The opposite approach, operating very near equilibrium, is also useful. For example, it makes possible the growth of large, ultrapure, defect-free crystals of silicon for use in the semiconductor industry.

The production of traditional materials also continues to evolve. An object as simple as an aluminum can is a good example. The raw material these days consists increasingly of recycled cans. Can walls are being made thinner and thinner, an achievement made possible by close control of the alloy composition and of the processing of the aluminum sheet. Optimization of these processes increasingly requires integration of computer-based modeling over a large range of length scales: from atomic bonds, motion of dislocations, and deformation and rotation of individual crystallites, to macroscopic behavior.

Another example is the development of alloys for jet aircraft. Alloys in early jets suffered from fatigue that ultimately led to disintegration. Modern alloys are not only stronger and lighter but also more resistant to stress.

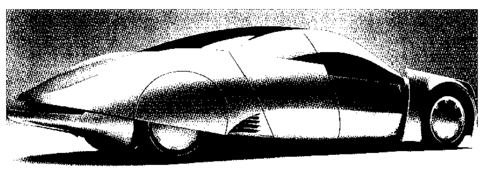


FIGURE 2.1 A futuristic high-performance aluminum car. (Courtesy of Ford Motor Company.)

COMPOUND SEMICONDUCTOR ELECTRONICS

Silicon is the material underlying most electronics, but compound semiconductors composed of more than one element, such as gallium arsenide (GaAs) and silicon germanium (SiGe), have advantages that can lead to devices with intrinsically higher speed and lower noise. The worldwide market for compound semiconductors is estimated to be $750 million in 1996, and it is growing at the rate of 40% per year. Discrete components are now widely used in the low-noise receivers of cellular telephone handsets, in addition to the specialized high-speed microwave applications for which they have long been the materials of choice.

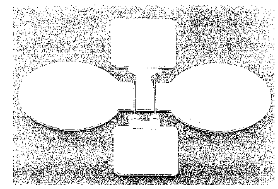


FIGURE 2.2 A high electron-mobility transistor (HEMT) such as those used in cellular telephones. The round bonding pads are 100 microns in diameter, roughly the size of a human hair. The gate of the transistor, just 0.05 microns across, appears as the two narrow lines in the center of this scanning electron micrograph. (Courtesy of Sandia National Laboratories.)

Compound semiconductors such as GaAs, SiGe, and gallium nitride (GaN) are key to the development of the next generation of wireless telephones, which will use higher frequency microwaves in order to transmit more information. GaN transistors, for example, are characterized by high breakdown voltage and great robustness. A potential high-volume application for such transistors is in transmitter power amplifiers for wireless base stations.

Pushing the limits of semiconductor materials technology is essential for increasing the speed of transistors and advancing our ability to modulate lasers for high-speed optical information transmission. Because compound semiconductors are composed of more than one element, they promise a vastly increased range of materials from which to select those with desired electronic properties. This promise can be realized with manufacturing techniques such as molecular beam epitaxy, which allows the repeated, controlled, precise growth of one material on another in single atomic layers, producing compound layered materials not seen in nature. In the future, the use of novel forms of microscopy for fabrication and testing will determine our ability to design and build such structures on the atomic scale—a scale on which the motion of electrons is governed by quantum mechanics.

The woman's son is a college student who, at that moment, is rollerblading across the campus, listening to a compact disk that he has just recorded in his music course. His rollerblades are light and strong and run smoothly because of advances in the physics and chemistry of **POLYMERS**. The compact disk, containing over an hour of high-fidelity music, is a miracle in the development of **OPTICAL STORAGE MATERIALS**. The crucial component of the student's portable CD player is a **SEMICONDUCTOR LASER**.

POLYMERS

Polymers permeate our lives, from the new, lightweight materials that improve the fuel efficiency of cars and airplanes to the high-strength components that make possible in-line skates and other sporting equipment. Polymers are molecules composed of many molecular units ("mers") connected together into macromolecules. A single polymer macromolecule may consist of a million or more atoms. Chemists have learned how to make an almost endless variety of highly complex yet well-defined macromolecules that incorporate a wide variety of monomers. Today, significant improvements in chemical synthesis and a growing collaborative effort between polymer chemists and materials scientists have resulted in the availability of extremely well-defined materials with novel properties. Given the sophistication of current polymer synthesis, it is now possible to systematically test hypotheses about how a polymer's properties are related to its structure and to design macromolecules to form specified microstructures and provide desired physical properties.

Some people still think of polymers as weak and flimsy compared with metals and ceramics, but in fact, truly impressive physical properties have been achieved. Some polymers are 1.5 to 2 times stronger than steel, and because their densities are typically only one-fifth that of steel, this means 10 times greater tensile performance per unit weight! The polymer Kevlar is used in bulletproof vests.

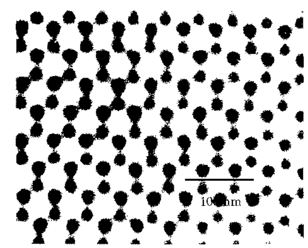


FIGURE 2.3 This false-color micrograph shows the structure of a block copolymer. The orange and yellow regions contain disordered chains of small, chemically distinct units (here denoted A and B many different substances can be used) that are strung together in sequence AAAABBBB. . . . If the B substance (yellow) is chosen to be soft and rubbery while A (orange) is hard and glassy, adjusting the A-to-B ratio permits production of copolymer materials with a wide range of mechanical properties. Such materials are very inexpensive to process, because the array of A and B domains forms naturally. One application is in the soles of high-tech running shoes. The scale bar is 100 nm (10^{-7} m) long. (Courtesy of Cornell University.)

OPTICAL STORAGE MATERIALS

The compact disk in a CD player is the most common example of optical storage, an industry with $8 billion in annual sales. Information is stored on a CD in the form of shallow pits just a few thousand atoms across. These pits are embossed in a polymer surface coated with a thin reflective film, and the digital information, represented by the position and length of the pits, is read optically with a focused laser beam. The same format is also used to store information on a computer—an encyclopedia, for example, or a piece of software—in which case it is called a CD-ROM (compact disk read-only memory).

Many materials challenges had to be surmounted to make this technology possible. The availability of inexpensive semiconductor lasers made it possible to read the disk. Substrate materials had to be invented with the optical, mechanical, and chemical stability to ensure reliability and long life. A manufacturing process had to be developed that could produce high yields of reproducible patterns with small features.

A future challenge is making optical storage erasable so that CDs can be used in the same way that we use memory devices in computers. Two approaches are being studied; both rely on improved materials. One uses light to locally change the direction of a material's magnetization, which can then be read out by detecting its effect on the polarization of another beam of light. The other uses a laser to change the local arrangement of atoms in a material, altering its reflectivity.

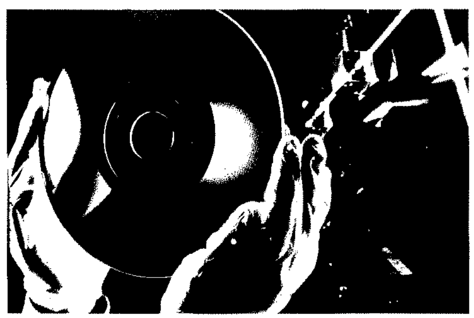


FIGURE 2.4 A magneto-optical disk. Information is stored magnetically and read out optically. (Courtesy of IBM Research.)

SEMICONDUCTOR LASERS

Stimulated emission of light, the physical principle that underlies all lasers, was predicted by Albert Einstein in 1917, but it was not until 1960 that the first working laser was developed, using ruby crystals. (A microwave version known as a maser was built in 1953.) Within five years came a variety of other important developments: laser spectroscopy, the use of lasers for telecommunications, the carbon dioxide laser, and the semiconductor laser.

Semiconductor lasers made the photonics revolution possible. For example, they produce the beams of light used for transmitting information and reading compact disks in a CD player. Lasers made of the semiconductor gallium arsenide (GaAs) can emit light particularly efficiently because of GaAs's electronic structure. In addition, it is possible to combine GaAs and related compounds to tailor the optical properties and vary the color of the emitted light. Under favorable circumstances, nearly perfect single-crystal growth (epitaxy) of layered structures of different semiconductors is possible. This allows fabrication of miniature, continuously operating lasers the size of a grain of salt. Such lasers today find wide application in such diverse areas as telecommunications, laser printing, bar code recording, medicine, and video and audio disks. Nearly 50 million semiconductor lasers are now sold annually.

FIGURE 2.5 Blue Light emission from a gallium nitride semiconductor LED. (Courtesy of the University of California, Santa Barbara.)

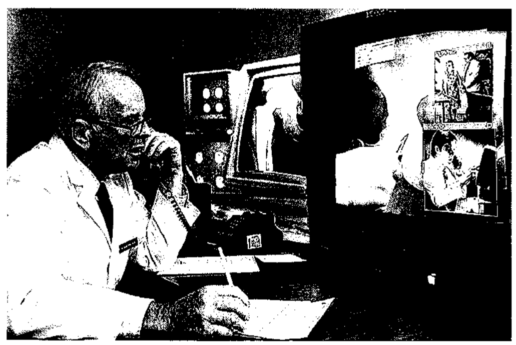
More than 20 billion closely related light-emitting diodes (LEDs) based on the same materials technology are sold each year—enough for 3 to 5 for every person on Earth! With new materials and careful tailoring of the optical properties using advanced crystal growth techniques, lasers can be produced that span the spectrum from medium infrared wavelengths to visible light, including green and blue. Such advances hold new promise for military and space communications, for optical recording and display, and even for longer-lived, more efficient, and more reliable traffic lights.

Feeling the vibration of his pager, the student turns off his CD player and hurries to his dorm room to return his mother's call. The message is about his grandmother, who has been hospitalized following an accident. A CAT scan has indicated that she needs a hip replacement. Artificial bone replacements are possible because of research in **BIOMATERIALS.**

Fortunately, an additional MRI scan has ruled out any spinal injury. Magnetic resonance imaging (MRI) depends on **SUPERCONDUCTING MAGNETS.**

The attending physician believes that the surgery may be more complex than usual, so he has arranged a video consultation with a specialist in another part of the country before operating. Videoconsultation is an example of today's growing use of **OPTICAL FIBERS** for telecommunication.

The surgery has been successful, and the patient is resting comfortably.



BIOMATERIALS

Special-purpose metal alloys and polymer coatings are used to prevent the body from rejecting prosthetic bone replacements. Many other new materials are also used in medical applications where they must stick to bone, mimic color, flex like natural tissues, and keep their form under extremes of heat and cold. The secret in making an artificial material compatible with living substances is in discovering the ways of "soft condensed matter," the plastic materials that act neither as solids nor liquids, whose properties can be modulated by a combination of chemical synthesis and physical treatment.

The next time you have a front tooth filled, notice the range of colors and textures that the dentist is able to create to match that of your particular tooth. Watch how he or she mixes a sticky putty to fill the space, smooths its surface, and applies ultraviolet light to cure the putty into a lump of just the right flexibility and tenacity. What is going on? A mixture of entangled, space-filling polymers flows nicely into the clean cavity. The ultraviolet light drives chemical reactions between the polymer molecules to harden them into place. The whole operation takes only a few minutes, and the full setting takes only hours. A new material has been created right in your mouth.

It is no surprise that these new procedures are coming into use at the same time that we are learning so much about the physics of polymers—how they flow, how they mix, how they stick, how they pack. These have been subjects of intense study, driven by the physicist's desire to explain surprises not seen in traditional solids and liquids and by the chemist's joy in creating materials with novel properties.

FIGURE 2.6 An artificial hip joint made from a special-purpose surgical alloy and processed by ion implantation to reduce corrosion and wear. Approximately 200,000 hip replacements are performed in the United States each year. (Courtesy of Oak Ridge National Laboratory.)

SUPERCONDUCTING MAGNETS

Nuclear magnetic resonance, the basis of magnetic resonance imaging (MRI), was invented to study the local environment of atoms in matter. With the development of high-speed computers and advances in fundamental mathematics, it is now possible to make high-resolution images using this technique. Making such images requires placing the subject in a strong magnetic field, typically provided by a superconducting magnet.

When certain metals are cooled to low enough temperatures, they pass into a superconducting state in which electrical currents flow with no resistance. A current flowing in a closed loop of superconducting wire will flow literally forever. Many useful scientific instruments, including MRI systems, contain coils of superconducting wire to provide strong and nearly perfect magnetic fields without high power consumption and other problems associated with conventional magnets. The worldwide market for metallic superconductors used for such magnets is currently about $500 million.

Superconductivity was discovered by accident in 1911. The scientists who made this unanticipated discovery were measuring how the electrical resistance of metals changed upon cooling to the temperature of liquid helium, which they had just learned to produce. Despite intensive research, nearly 50 years passed before a theoretical understanding of the effect was developed or before any significant practical equipment was built.

The discovery in the mid-1980s of ceramics that display superconductivity at much higher temperatures than any previously known material—temperatures that can be reached using inexpensive liquid nitrogen—has motivated a wide range of research and development activities over the past decade. Though the mechanism by which high-temperature superconductivity occurs is still not fully understood, progress on practical applications has been impressive, with dramatic improvements in the properties needed for use in wires for magnets and power transmission, filters for microwave and cellular base stations, and magnetic field sensors.

FIGURE 2.7 An MRI image of a human lung filled with minute quantities of inhaled laser-polarized helium-3 gas, using a technique invented in 1995. Such scans will allow unprecedented imaging of the gas space and the movement of gases in the lungs, for diagnosis of ventilation disorders. (Courtesy of Princeton University.)

OPTICAL FIBERS

Videoconsultation is possible because of the recently constructed infrastructure of optical fiber for communication—enough to encircle the world seven times. We are in the midst of a revolution in communications brought about by the introduction of optical networks into the marketplace in the early 1980s. With the emergence of the Internet and rapid growth in video and data transmission, demand for network capacity has increased dramatically over the last decade. The information capacity of fiber is far higher than that of copper wire, the technology fiber replaces. The total annual market for communications is now about $100 billion.

This progress has relied on advances in the physics of optical materials. The major advance that enabled the introduction of optical communication was the development in the 1960s of a fundamental understanding of how light is absorbed and scattered in the glass materials used in optical fibers. Subsequent refinements in materials research have led to a steady reduction of optical transmission losses, by a factor of nearly 10,000 since 1965.

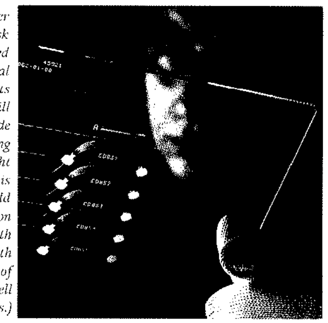


FIGURE 2.8 A researcher holds a lithography mask used to produce integrated photonic circuits for optical communications. Circuits made with this mask will incorporate silicon dioxide waveguides for routing optical signals at eight different wavelengths. This will enable an eightfold increase in transmission capacity compared with present single-wavelength systems. (Courtesy of Lucent Technologies Bell Laboratories.)

The past decade's advances in making fiber components promise to dramatically change the architecture of future optical communications networks and our ability to communicate worldwide. We can now build optical integrated circuits for communications networks, analogous to the electronic integrated circuits used in electronics. Fiber optical amplifiers are just now being installed into optical networks, although the fundamental materials research that enabled this development began 30 years ago.

The woman reaches the airport, parks her car, goes through security to the gate, and boards her flight. Only minutes after takeoff, her airplane is cruising at 500 miles per hour at an altitude of 30,000 feet. It will fly across the continent without refueling.

To achieve such power and efficiency, the turbine blades in modern jet engines must operate at very great speeds and high temperatures. To withstand such extreme conditions, they are made of **SUPERALLOYS.**

Once airborne, the businesswoman opens her laptop computer and reviews the presentation that she plans to make on her arrival. The computer's monitor uses one of the new **LIQUID CRYSTAL DISPLAY MATERIALS.** Like almost every other technology in this story, the computer also depends on **MAGNETIC MATERIALS.**

SUPERALLOYS

Superalloys are special combinations of metals that maintain high strength during prolonged exposure to elevated temperatures. This capability is essential for applications such as the turbine blades in a jet engine. Superalloys consist mostly of nickel, with smaller amounts of aluminum, titanium, chromium, and up to ten other elements. The idea behind the design of these alloys is the creation of stable, hard, small precipitates like Ni_3Al or Ni_3Ti in the nickel matrix to obstruct the motion of dislocations, the atomic-scale cause of undesirable deformation.

The performance of alloys in turbine blades is further improved by eliminating crystal boundaries in each blade; those boundaries are the prime sites for the initiation of fracture. Through the development of a detailed understanding of the solidification process, it is now possible to cast an entire turbine blade, with the very intricate shape shown in Figure 2.9, as a single crystal.

Progress in alloy design and processing has led to a continuing increase in the allowable operating temperature of the turbine blades. The most recent improvements have resulted from the application of ceramic thermal barrier coatings to the outside of the blade. Increases in the operating temperature, together with improvements in the blade design (such as air cooling, through the passages seen in Figure 2.9, made possible by sophisticated casting techniques) have greatly increased the efficiency of jet engines and decreased their weight for a given thrust.

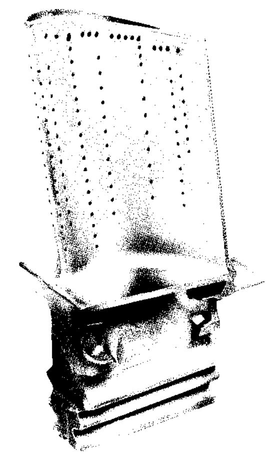


FIGURE 2.9 A turbine blade from a jet engine, cast as a superalloy single crystal. (Courtesy of GE Aircraft Engines.)

LIQUID CRYSTAL DISPLAY MATERIALS

Flat panel displays, such as the liquid crystal display in the laptop computer in our story, will soon be ubiquitous in both the home and the workplace, as the cost of these high-tech products is driven down by the volume market for consumers. Low-power, lighter-weight, thinner displays are already displacing the commonplace cathode-ray tube (CRT) for desktop and especially for portable applications. The portability and compactness of these displays have initiated and driven new applications and markets, such as notebook and palmtop computers, personal digital assistants, large viewing screen video cameras, miniature televisions, and individual televisions for each airline seat. Insatiable demand for lower-cost flat panel displays has created a burgeoning growth of the market from tens of millions of dollars in 1980 to about $11 billion today and to a projected $22 billion by 2001.

FIGURE 2.10 A high-resolution, active matrix liquid crystal flat-panel display. (Courtesy of dpiX, Incorporated.)

Liquid crystals are materials in which the molecules show a preference for alignment with their neighboring molecules even though they can be in a liquid state having no long-range translational order. The molecules in these liquid crystalline phases are easy to orient by the application of an electric field and so can be made to act as a switch for light if they are placed between crossed polarizers and electrodes. Fundamental research on the physics and phase transitions of liquid crystals began in the 1920s, but it was not until the early 1970s that the first liquid crystal displays were developed. Flat-panel liquid crystal displays have only been manufactured in great volume in the last decade. Active-matrix liquid crystal displays used for the highest performance laptops today have high resolution and brightness as well as full color at high speed due to the separate electrical switching elements for each of about 1 million separate picture elements or pixels in the display. Extensive research being carried out today will eventually allow high-performance flexible displays on plastic substrates, with higher resolution and at lower manufacturing cost, which will in turn drive new technology, markets, and applications.

MAGNETIC MATERIALS

From the Ancient Mariner's compass to the automobile starter motor, from refrigerator magnets to the snapshots stored magnetically in the latest digital camera, magnetic materials have grown steadily in their importance and variety of applications. Materials display a host of fascinating magnetic properties, all of scientific interest and many of them useful in technological applications. The accelerating interplay of the science and applications of magnetism is well illustrated by the phenomenon of magnetoresistance, in which a sample exhibits a change in its ability to conduct electricity upon application of a magnetic field.

Beginning in the early 1980s, a decade of work at IBM perfected the use of magnetoresistance in a product with major commercial importance. This application, in the data sensor of the recording head within a hard disk drive, employs a single magnetic film about 200 atoms thick. The film changes resistance as it passes near a small magnetized region of a magnetic disk. Such recording heads are a growing segment of today's $30 billion hard disk drive industry. The time from Lord Kelvin's discovery of magnetoresistance in 1856 to its realization in this commercial product was 135 years.

Another class of magnetic materials, permanent magnets, are essential in a wide variety of electric motors and generators. Research and development leading to stronger magnets has resulted in a steady decrease in the cost, size, and weight of motors in such diverse devices as automobile starters, cordless shavers, hand-held drills, household appliances, toys, and disk drives (again) in laptop computers. The latest of the permanent magnet development spurts, in the late 1980s, illustrates the unpredictable effects of the interplay between politics, economics, research, and development. Samarium cobalt was the magnetic material of choice until the price of the starting materials became prohibitive due to political unrest in Zaire. Intense exploratory research discovered a superior replacement material, neodymium iron boron. The newly introduced magnets are expected to have an annual market of $4 billion within 10 years.

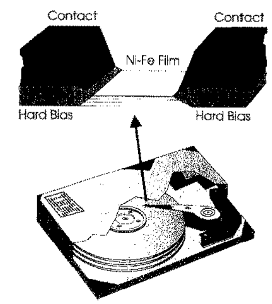


FIGURE 2.11 A hard disk drive assembly with a magnetoresistive sensor for reading the stored data. (Courtesy of IBM Research.)

The computer that analyzed the data from the MRI and CAT scans, and the computers that were involved in essentially every aspect of the airplane trip—making the reservations, assuring security at the airport, determining the flight path, and so on—are based on **SILICON TECHNOLOGY.**

Well into her flight and resting briefly before her important meeting, the woman relaxes in her seat and reflects on just how much of what she has taken for granted in the past several hours would have been unthinkable only a few years ago: modern cars and airplanes, telecommunications, modern medicine, the power and portability of computers. Our lives have been changed by CMMP research—and for the better.

She wonders what equally remarkable changes will take place during her son's lifetime. No one really knows, of course, but perhaps one hint can be found in new advances like **INTEGRATED MICROSYSTEMS.** Other ideas will arise from the scientific challenges discussed in Part 3. ❖

SILICON TECHNOLOGY

Microelectronics based on silicon and its oxides underlies all of today's high-technology industries, from computers to communications to biotechnology. Microelectronics has also become common in our day-to-day lives, in applications ranging from automobiles and banking to control of household appliances.

Although silicon and germanium were used in radar detectors in the early 1940s, very little was known about the physics and materials science of these semiconductors. Scientists at Bell Laboratories soon recognized that a deeper understanding of these materials was necessary for rapid application to communications. Materials research in the mid-1940s ultimately enabled the invention of the transistor in 1947. Extensive, long-term research, along with the unexpected discovery in 1959 that silicon dioxide can passivate (protect) the surface of silicon, led to the invention of metal-oxide-silicon (MOS) transistors. The MOS transistor, combined with the increased understanding of the physics and materials science of semiconductor materials and devices that resulted from almost twenty years of intensive research and development, ultimately led to the invention of the integrated circuit.

Perhaps no other device has had as large an impact on day-to-day life as the silicon-based integrated circuit (IC). Although the IC was based on many years of condensed-matter and materials research at large industrial laboratories, the acceleration of its development and use was driven by government needs. Enabled by stable, long-term research stretching over almost two decades and stimulated by government funding, the discovery of the IC spawned the modern microelectronics industry, which is now a global enterprise. In 1995, IC sales exceeded $150 billion and supported an electronics industry with sales approaching $1 trillion. Without transistors and ICs, none of this would be possible.

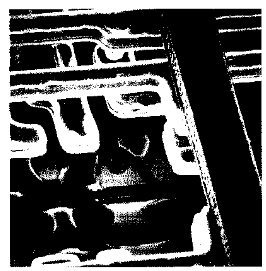


FIGURE 2.12 Intricate layers of aluminum and tungsten wiring on an integrated circuit memory chip are revealed by etching away the interlayer dielectrics and then imaging the chip with a scanning electron microscope. The width of this image is about 10 microns (0.001 cm). A chip can contain as many as 50 million connections like those shown here in an area 1 cm on a side. (Courtesy of Lucent Technologies Bell Laboratories.)

INTEGRATED MICROSYSTEMS

The microelectronics industry has grown explosively over the last forty years. Such phenomenal growth has not been experienced in any other field in history. A key element behind the success of microelectronics has been integration. Integration of electronic functions on ever greater length scales leads to the low cost of production and assembly and high reliability. Miniaturization allowed for integration and simultaneously resulted in increased performance.

In the early 1980s researchers unveiled the first micromachined motor, demonstrating that the tools, facilities, and infrastructure developed to fabricate microelectronic circuits could also be used to build miniature mechanical systems. Though many research problems must be surmounted before microsystems can become as ubiquitous as the integrated circuit, this demonstration raised the hope that complex microsystems that integrate physical and chemical sensing and mechanical response with control and communications electronics can be mass produced at low cost. High-performance microsystems at lower prices would create markets for many products. In transportation, they could be used for position sensing, collision avoidance, navigation, and reliable airbag deployment. Environmental monitoring could be performed in hostile environments with inexpensive, disposable detectors. Microsystems could also be used in areas as diverse as biomedical applications and consumer products. They will probably have a profound effect on our lives and the lives of our children.

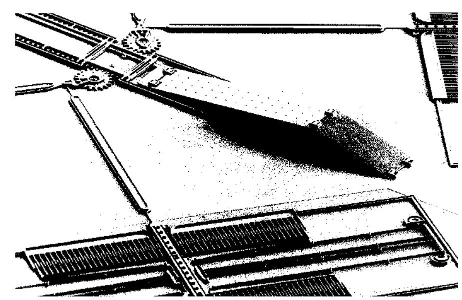


FIGURE 2.13 A prototype micromechanical mirror for use in optical communications systems. Either side of the flat hinged structure in the middle can be used as the mirror. The gears at the upper left are just 50 microns in diameter. (Courtesy of Sandia National Laboratories.)

3 ❖ The Research Endeavor

The brief story told in Part 2 illustrates how much the world has changed in recent years and the enabling role that condensed-matter and materials physics is playing in modern technology. We turn now to a closely related topic, the fundamental scientific challenges of research in this field. Once again, the capitalized words in the main text link to sidebars that provide more information on a few selected topics.

What is "condensed-matter and materials physics"? Fifty years ago, the transistor emerged from this area of physics. High-temperature superconductivity was discovered by condensed-matter physicists, as were the fascinating low-temperature states of superfluid helium. Scientists in this field have long-standing interests in essentially all aspects of magnetism and magnetic materials. They investigate the properties of glasses, polymeric materials, granular materials, and composites in which diverse constituents are combined to produce entirely new substances with novel properties. They are reaching out to researchers in the earth and atmospheric sciences because they share interests in topics such as friction, fracture, and fluid flow. The outreach to biology and the study of biological materials are now beginning in a serious way.

Hardly any other field of science so seamlessly spans the whole range between the most basic research and the most applied. Advances in basic research inspire new ideas for applications, and application-driven technological advances provide tools that enable new fundamental investigations. At the same time, technological problems raise questions that demand new fundamental insights. For example, with new fundamental understanding of **NONEQUILIBRIUM PHENOMENA**, we may soon see a qualitative improvement in our ability to predict and control complex properties of the structural materials used to manufacture everything from airplanes and bridges to electronic devices. Technological advances provide tools such as synchrotrons, neutron sources, electron microscopes, high magnetic field facilities, **COMPUTERS**, and

NONEQUILIBRIUM PHENOMENA

The processes that are used to produce industrial materials—casting alloys for jet engines or fabricating microscopically small features of computer chips—are all exercises in what we call "nonequilibrium physics," the study of systems that are changing their shapes or properties as we exert forces on them, freeze them, or otherwise disturb their states of equilibrium. Predicting and controlling these processes with the precision that will be needed for applications requires fundamental understanding of the nonequilibrium phenomena underlying them and is a challenge for physicists.

For example, snowflakes form by a branching process that is called "dendritic crystal growth." Research in this area has been driven not only by our natural curiosity about snowflakes, but also by the need to understand and control metallurgical microstructures. The interior of a grain of a freshly solidified alloy, when viewed under a microscope, often looks like a collection of overly ambitious snowflakes. Each grain is formed by a dendritic mechanism in which a crystal of the primary composition grows out rapidly in a cascade of branches and side branches, leaving solute-rich melt to solidify more slowly in the interstices. The speed at which the dendrites grow and the regularity and spacing of their side branches determine the observed microstructure, which in turn governs many of the properties of the solidified material such as its mechanical strength and its response to heating and deformation. We cannot yet predict microstructures accurately, but much progress has been made in the last decade. Figure 3.1 shows one of the best new theoretical efforts in this direction.

Much of the most important recent progress in nonequilibrium physics has consisted simply of recognizing that fundamental questions remain unanswered in many familiar situations. The recent growth of interest in fracture and friction, for example, has led us to realize that we need to establish first-principles understanding of the difference between brittleness and ductility, especially in noncrystalline materials. We are learning about the dynamics of granular materials, systems that are like liquids in some respects, like solids in others, and unlike either in many of the most important ways. And we are just beginning to learn which questions to ask in a search for understanding the dynamics of fracture at crack tips, failure at interfaces between different solids, or rupture on earthquake faults.

COMPUTATION IN CMMP

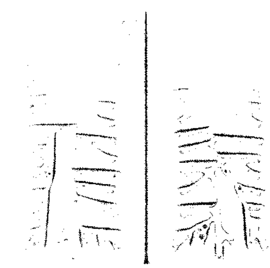
Because of the astonishingly rapid advances in both hardware and software, the small workstations or PCs that sit on almost every scientist's desk these days have the power of machines that we called supercomputers little more than a decade ago. Today's supercomputers can simulate the behavior of hundreds of millions of interacting classical molecules or follow the transitions among comparable numbers of quantum states. This exponential growth in computational power will continue for at least another decade.

Computers play a central role in modern experiments, controlling apparatus, acquiring and storing data, and analyzing data. Theorists also find them essential for solving mathematical problems that once seemed intractable. But the computer is now emerging as much more than just a tool for assisting the work of scientists; it is making a qualitative change in the kinds of research that will be done in the near future. Consider just a few examples.

Starting from little more than the masses and charges of electrons and atomic nuclei, as well as the rules of quantum mechanics, we are approaching the point where we will be able to predict accurately the properties of molecules, of atoms at solid surfaces and interfaces, of defects in solids, and even of larger structures such as the recently discovered fullerenes (see page 21).

In situations that justify neglecting quantum effects, multimillion-molecule simulations are beginning to provide valuable information about complex solid-state phenomena such as fluid flow, fracture, friction, and deformation. The great advantage of such computational investigations is that they can tell us in detail about the behavior of individual molecules. Thus, computer-based studies of this kind have features of both experimental and theoretical research.

FIGURE 3.1 Computer simulation of dendritic growth in the solidification of a nickel-copper alloy. The colors indicate relative concentration of copper, from low (red) to high (blue). The orange and red regions are solid; the green and blue regions are liquid. (Courtesy of the National Institute of Standards and Technology.)



SCANNING PROBE MICROSCOPES. These tools, in turn, provide unprecedented opportunities to investigate materials on the atomic scale, leading to fundamental discoveries that drive both science and technology. The new physics of **THE FRACTIONAL QUANTUM HALL EFFECT**, for example, was made possible by new materials fabrication technology. The study of **MATTER UNDER EXTREME CONDITIONS** has led both to fundamental and practical breakthroughs.

Several of the most profound conceptual developments in science have occurred in CMMP in the last two decades. The so-called "renormalization-group" theory of critical fluctuations in condensed matter has helped us understand phenomena as varied as phase transformations, the interactions between elementary particles, and the fluctuations of the stock market. Chaos, turbulence, and pattern formation are other core concepts in this field that have had wide-ranging implications across the world of science. The historic role of condensed-matter physicists, ever since the emergence of quantum electronics and the transistor, has been to discover new concepts and phenomena and to develop their new knowledge in ways that are meaningful for fundamental advances in many fields and for practical applications.

SCANNING PROBE MICROSCOPY

Although the atomic picture of the world was formed over a century ago, it is only in the last few decades that compelling visualization of atoms has become possible. Since there are only 92 stable elements, the diverse materials known to us derive their complexity for the most part from the patterns of their atoms' arrangement, in molecules and in solids. Direct atomic-scale visualization of these patterns allows us to develop new materials and better understand old ones. It has been used to look at the action of semiconductor devices, the workings of chemical reactions, and the structure of genes.

Many new visualization tools emerged from condensed-matter and materials physics. One such advance was the invention of scanning probe microscopy. In this class of techniques, a sharp needle-like tip is moved around (scanned) near a surface. A map of the surface is then constructed in real time by measuring some response of the surface to the tip—the force of the surface on the tip, for example, or the electric current that flows between the tip and the surface. Using precision actuators called piezoelectrics, a tip can be moved up and down or sideways by less than the size of an atom. Scanning the tip across the surface in this way while measuring the response allows an atomic-level image to be built up, much as a blind person can acquire a mental picture of an object by feeling its shape.

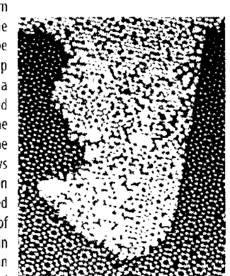


FIGURE 3.2 A scanning tunneling microscope image showing a snapshot of the growth of germanium on a silicon surface. Each bright spot is a single atom. (Courtesy of IBM Research.)

The first suggestion of a super-resolution microscope can be traced back as far as 1928 to the British scientist E.H. Synge, but the first working scanning probe microscope with atomic resolution was not invented until 1981, at IBM's research laboratory in Zurich, Switzerland.

In the decade and a half since then, a wide variety of related visualization techniques have been developed. Scanning probe techniques now exist that allow atomic-scale sensing and mapping of electrical, optical, and magnetic properties, surface forces, and other phenomena.

A particularly important recent innovation has been the possibility of using a scanning tip not just to study a sample but also to manipulate atoms actively. The "quantum corral" shown on the front cover and in Figure 1.3 was made in this way. This microscopic atom-by-atom "engraving" makes even microsurgery look like the metaphorical bull in the china shop.

THE FRACTIONAL QUANTUM HALL EFFECT

The fractional quantum Hall effect is an example of beautiful and fundamental new physics made possible by technological advances in the fabrication of artificially structured materials. It takes place in a two-dimensional electron "gas" produced in a transistor-like device subjected to extreme conditions of high magnetic fields and low temperatures. Under these conditions, electron correlations become dominant. The basic observation is a precise quantization of the Hall conductance with the unusual property of being described by a quantum number that is fractional rather than an integer.

The application of a strong magnetic field at low temperature induces large numbers of vortices ("whirlpools") that attach themselves to the electrons to form composite objects, which condense into a special quantum "fluid." This fluid of composite particles has the bizarre property that the low energy excitations consist of a single vortex that binds a fraction of an electron charge. These objects have recently been observed through direct measurement of their fractional charge and by tunneling experiments in which an electron added to the system is seen to break up into three excitations, each with one-third of the charge. Theoretical work on this problem has led to profound and intellectually exciting new concepts and techniques with applications both in other areas of condensed-matter physics and in quantum field theories studied in elementary particle physics. We are familiar with the idea in high-energy physics that certain elementary particles such as protons are actually composite objects made up of fractionally charged quarks. These quarks can be observed in collisions at very high energies (or equivalently, high temperatures) carried out using particle accelerators. In condensed-matter physics, one does the reverse: the analog of the accelerator is the refrigerator. At sufficiently low temperatures, in a strong magnetic field, electrons added to a quantum Hall system break up into fractionally charged elementary vortex excitations. This, then, is a fundamentally new form of conduction in an artificially created, layered material.

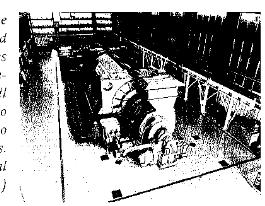
FIGURE 3.3 A pictorial representation of the many-particle state that underlies the fractional quantum Hall effect. The height of the green landscape represents the amplitude of the quantum wave of one electron as it travels among its companions (gold balls). The arrows indicate the vortices induced by the magnetic field. These vortices attach themselves to the electrons to form composite particles. (Courtesy of Lucent Technologies Bell Laboratories.)

MATTER UNDER EXTREME CONDITIONS

An important frontier of materials science is in the behavior of condensed matter under extreme conditions: heat and cold, high pressures, mechanical stresses, large magnetic and electric fields, and intense radiation environments. Experiments at this frontier will continue to have a major impact on engineering, where breakdown of component materials in various hostile environments is a significant concern. Topics of major national interest include jet engine technology and weapons. Progress in the physics of materials under extreme conditions has great significance for other areas of science—notably geophysics, where conditions of high heat and pressure are routine, and astrophysics, because extreme conditions routinely occur elsewhere in the universe. Extreme conditions sometimes also occur unexpectedly on the simple laboratory scale and yield novel phenomena such as sonoluminescence, in which flashes of light are emitted from collapsing air bubbles under the influence of sound waves.

Many of the most important breakthroughs in materials physics, ranging from the discovery of superconductivity at the beginning of the century to the discovery of the quantum Hall effect near its end, have occurred as the result of explorations whose goal was simply to find out what happened to known substances under more extreme conditions than they had been exposed to previously. Discoveries found at this frontier can be translated into practically useful technologies either as subsequent advances make the extreme conditions routinely achievable (as for the superconducting magnets in magnetic resonance imaging devices with medical applications), or by inspiring scientists to create new materials that display the newly discovered phenomena under less extreme circumstances. We suspect that throughout the rest of human history, the agenda of this most human of pursuits in materials research—namely to produce the world's highest magnetic fields and pressures or the lowest temperatures, and to be the first to observe what these conditions imply for materials from hydrogen to gallium arsenide—will remain the same, with equally productive outcomes.

FIGURE 3.4 A generator at the National High Magnetic Field Laboratory. This generator serves as a power supply for a high-performance magnet that will provide unprecedented insights into the behavior of matter subjected to extremely strong magnetic fields. (Courtesy of Los Alamos National Laboratory.)



What does the future hold for condensed-matter and materials physics? There must be many surprises in store for us. Consider the fact that essentially none of the most important discoveries in this area made in the last decade were anticipated in the 1986 National Research Council report *Physics Through the 1990s*. And the pace of scientific change, especially when viewed on an international scale, is now accelerating.

A particularly dramatic surprise was the discovery in 1986 of **HIGH-TEMPERATURE SUPERCONDUCTIVITY**, which disproved a consensus then growing among scientists that superconductivity could exist only at temperatures very near absolute zero. Now, just over a decade later, we are beginning to see commercially marketed devices based on superconductivity at easily accessible liquid-nitrogen temperatures, and we can look forward to decades of new developments. Even more important, condensed-matter and materials physicists have learned that chemically complex materials, like the new superconductors, can have extraordinarily interesting properties. The study of such complexity in solids is emerging as a whole new style of inquiry.

HIGH-TEMPERATURE SUPERCONDUCTIVITY

By the mid-1970s it seemed that the limiting temperature for superconducting materials was near 25 K, a temperature still requiring expensive liquid helium cooling. Theoretical calculations based on the mechanism that controlled electron pairs in known superconductors indicated a maximum temperature for superconductivity of less than 40 K. In 1986 a totally unexpected, even shocking, discovery was made. A class of copper oxide ceramic materials was found to become superconducting at temperatures much higher than 25 K. We now have many complex materials that become superconducting at temperatures well above the boiling point of inexpensive liquid nitrogen, 77 K.

The occurrence of superconductivity in a totally unexpected class of materials, and the potential for its practical use above the temperature of liquid nitrogen, have motivated a wide range of research and development efforts over the past decade. Superconductivity has now been observed in specially prepared ceramics at temperatures as high as 135 K.

Despite extensive worldwide efforts, however, an understanding of the mechanism for superconductivity in the new oxide materials is still lacking. For example, physicists cannot reliably predict whether a material could exist that would superconduct at room temperature. These new materials are brittle ceramics, with properties completely different from those of the ordinary metals in which low-temperature superconductivity occurs. Paradoxically, in their pure state, these oxides do not conduct electricity at all—they are magnetic insulators. Even when charge carriers are introduced by chemical doping, they are poor conductors at room temperature.

The superconducting state itself appears to have pairs of electrons orbiting around each other in an unconventional manner. (See Figure 3.5.) The sensitivity of this state to magnetic fields presents technological challenges that must be overcome for certain practical applications; but on the positive side, it has also led to exciting new fundamental scientific ideas.

The discovery of high-temperature superconductivity has focused attention on the enormous variety of complex oxide materials. In addition to superconductivity, many of these materials exhibit other novel magnetic and electrical properties.

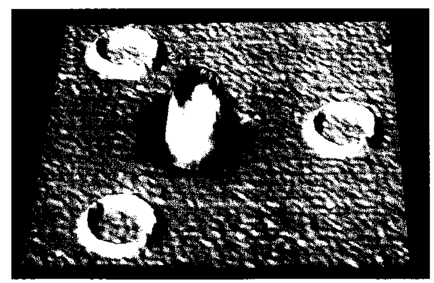


FIGURE 3.5 This magnetic image shows four high-temperature superconducting rings, each 60 microns in diameter, fabricated on a specially prepared multicrystal substrate. The height out of the plane at each point in the image represents the strength of the vertical component of the magnetic field at that point, measured at a constant elevation above the substrate. The volume of each structure thus represents the magnitude of the magnetic flux trapped within that ring. The trapped flux in the center ring is exactly half the normal quantized amount; the other three rings contain no flux. This half-integral flux quantization effect is strong evidence for unconventional electron pairing. (Courtesy of IBM Research.)

A different kind of unanticipated complexity is emerging in **ARTIFICIALLY STRUCTURED MATERIALS**, engineered with features so small that they behave like artificial atoms. These structures are candidates for the next generation of computing elements, but their potential uses in both science and technology go far beyond computing as we know it. As we learn how to assemble increasingly complex structures from more and more complex building blocks, perhaps even from biological molecules, we can anticipate a whole new world of scientific phenomena and practical applications.

Other completely unexpected discoveries of the last decade include **FULLERENES**, and carbon nanotubes spherical and cylindrical arrangements of carbon atoms that have remarkable chemical and structural properties. Even more glimpses of the future have recently been provided by observations of intrinsically quantum mechanical behavior in systems so large that they had been thought to be outside the realm where such effects could occur. Such macroscopic quantum phenomena include Bose-Einstein condensation of collections of large numbers of atoms and the excitonic laser. Suddenly, deep philosophical questions about the meaning of observations in quantum mechanics are becoming relevant to the development of entirely new kinds of electronic devices, perhaps even the development of ultrafast quantum computation.

ARTIFICIALLY STRUCTURED MATERIALS

Artificially structured materials are structures not available in nature. Often the surfaces and interfaces of these materials dominate their properties. Artificially structured materials are critically dependent on enabling technologies for fabrication and characterization, tying progress in science to advances in relevant technologies. Although the field was born in the 1960s, there has been impressive progress in the last decade. New structures are possible because of increased cleanliness, extreme growth conditions, and substrate modification before growth. Our scientific understanding has increased through atomic-level elucidation of surface and interface structure and defects using the new scanning probe microscopies that have completely changed our thinking about how to study surface phenomena.

Artificially layered structures have enabled the realization of many new devices, including high electron-mobility transistors, semiconductor lasers, giant magnetoresistance materials, and x-ray optics. Some of these devices are now ubiquitous in such consumer electronics as cellular telephones and compact disk players. Others promise major advances in computing and communications. These technological advances have in turn enabled the structures and materials required for many of the accomplishments detailed in other sections of this report, such as the fractional quantum Hall effect.

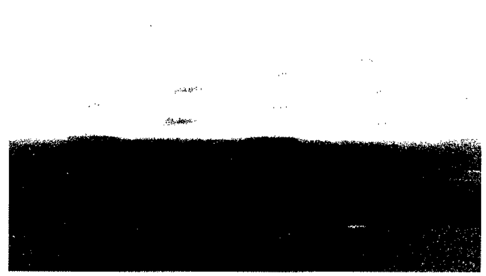


FIGURE 3.6 A self-organized ordered array of InGaAs quantum dots grown in three regular layers on a GaAs substrate. The dots are the bumps on the surface and the light-colored internal structures beneath them. The layers are separated by about 65 nm, and the dots within each layer are about 250 nm apart. (Courtesy of NTT Optoelectronics Laboratories.)

FULLERENES

Solid carbon is well known for its two stable crystalline forms, diamond and graphite. It is also known to exist in a number of other metastable forms, such as coke and glassy carbon. These different forms of carbon are among the most widely used materials because of their remarkable properties, such as the hardness of diamond and the lubricity of graphite. Until recently, no one would have suspected that another large class of carbon structures could be made, with yet more remarkable properties. Yet over the last decade that is exactly what has happened.

In 1985, while working with gaseous carbon like that found in interstellar space, scientists found that under certain conditions (laser ablation of graphite in an atmosphere with a controlled partial pressure of helium) molecular clusters could be made that contained only certain specific "magic numbers" of carbon atoms. The structural motif they proposed for this class of clusters had its inspiration in the geodesic dome designs of the architect Buckminster Fuller. The simplest of these designs is that of C_{60}, which is made of 5- and 6-atom carbon rings fused together into a structure resembling a soccer ball.

Large amounts of fullerene carbon were soon synthesized, allowing a wide variety of experiments to be performed. The proposed structure was dramatically proven correct, and a number of fascinating properties were discovered. One of the most remarkable is that molecular clusters of C_{60} can be doped with electrons by donors such as alkali metals. This makes them into superconductors with critical temperatures surpassed only by the recently discovered copper oxides.

The fullerene forms of carbon are now also known to include capped cylinders, sometimes called buckytubes. These cylinders appear to be one of the promising approaches to the development of nanoscale wires and other electronic components.

For their initiation of fullerene research, Richard Smalley, Harold Kroto, and Robert Curl were awarded the 1996 Nobel Prize for Chemistry.

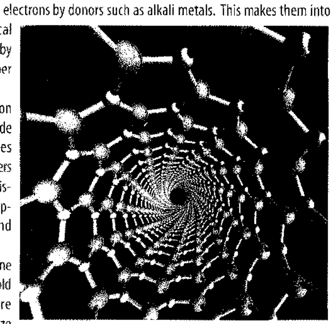


FIGURE 3.7 A computer model of the interior of a carbon nanotube. Such tubes exist in various forms, including this spiral structure. (Courtesy of the University of California, Berkeley.)

Surely one of the most significant developments on the horizon is the movement of condensed-matter and materials physics into the biological and medical sciences. Here, in parallel with advances in materials, communications, and information technologies, is the other scientific revolution that has profoundly changed our world in recent decades. Modern medical techniques such as magnetic resonance imaging and laser surgery were made possible by research in physics, and **THE PHYSICS OF MACROMOLECULES** is a well-established area of research at the intersection of physics, chemistry, and biology. Nevertheless, physics laboratories so far have played only relatively minor roles in mainstream biological research.

THE PHYSICS OF MACROMOLECULES

Progress in molecular biology depends on using a technique called gel electrophoresis to analyze DNA. A sample is placed at one end of a slab of gel, and an electric field is applied. The field pulls DNA molecules of different sizes through the gel at different speeds, separating the components of the sample.

Despite its widespread use, little was known about how DNA molecules actually move through a gel when physicist Pierre-Gilles de Gennes began work on the problem in 1971. Gels are a water-swollen tangle of long chain-like molecules called macromolecules. De Gennes proposed that when other macromolecules such as DNA move through a gel, the tangles force them to slide along their own contours in a snake-like motion called reptation. This theoretical model remained controversial for twenty years, for until recently the motions of individual molecules could not be observed. Optical tweezers can now tug on a single molecule of DNA while its motion is observed through a microscope. The DNA moves along its own contour as predicted.

Recent experiments with simulated gels made from etched silicon have further improved our understanding of the motion of macromolecules. For example, we now know that long molecular chains tend to get caught on post-like obstacles, looping around them like a rope hanging over a pulley. Varying the strength of the applied electric field helps to free the molecules from such obstacles. Theory and experiments in this area are discovering the optimum variation of the applied field for efficient separation of different lengths of DNA.

DNA is not the only important macromolecule; synthetic polymers like polyethylene and nylon are also noteworthy. Predicting the flow properties of molten polymers, whose motion is also dominated by the entanglement of the long molecules with each other, has stimulated new extensions of the reptation model. A better understanding of industrial processes for shaping polymers, such as extrusion and injection molding, should result.

In this way, reptation—a simple idea in condensed-matter and materials physics—has had a major impact on both molecular biology and polymer engineering. Many challenges remain for the future, such as efficiently simulating the motion of macromolecules by computer and following the motion of biological macromolecules on surfaces at high resolution using new scanning probe microscopies. But the reptation idea will continue to provide a starting point for understanding these more difficult problems.

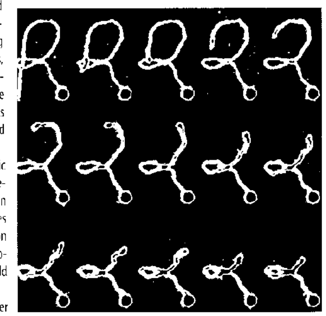


FIGURE 3.8 The motion of a single fluorescently labeled DNA molecule (60 microns in stretched length) in a concentrated solution of unlabeled DNA. In the first image (top left) the molecule has been formed into an R shape by pulling on a small attached sphere (red) with optical tweezers. Subsequent images, taken 8.3 seconds apart, show the molecule moving along its own contour as it unstretches. (Courtesy of Stanford University.)

That situation is about to change. Although we could hardly have imagined such possibilities a decade ago, we now have instruments such as scanning probe microscopes and **OPTICAL TWEEZERS** that allow us actually to see what large molecules are doing inside biological cells and even to measure the forces that they exert on one another. In centers around the world, scientists are just beginning to use these new tools to solve critical problems involving the physics of biological systems. These problems are posing entirely new intellectual challenges; the implications of their solutions are likely to be immense.

As these examples illustrate, condensed-matter and materials physics is a vital field at the very crossroads of the scientific enterprise. It combines the intellectual stimulation of investigations at the frontiers of human knowledge with the satisfaction of providing insights and capabilities that can improve all our lives. ❖

OPTICAL TWEEZERS

Imagine a string that is a ten-millionth of an inch across and a ten-thousandth of an inch long. Suppose you wanted to test its strength, measure its length, or pick it up and move it. How would you hold it? When the string is really a molecule of DNA, you need a pair of molecule-size tweezers.

The "optical tweezer" was invented around 1980. It turns out that a tiny bead attached to a strand of DNA can be attracted to the spot of a laser's light. Pick one end of the strand, shine the light, and you can hold the molecule in place. Fix the other end, move the light, and you can stretch the molecule.

In 1995, scientists were able to pull straight the normally crumpled DNA molecule and measure the amount of work it took. The force required was only about a millionth the weight of a drop of water. The researchers showed that DNA first stretches by being straightened; but once it is straight, the "string" itself can stretch. By looking at just one molecule, they were able to test a theory of how DNA acts as a mechanical object.

The entire genetic code for a human being (the human genome) has 4 billion "base pairs" of molecular data. The full set is stored in duplicate in almost every one of the body's roughly 10^{13} cells. Altogether, this amounts to about 20,000,000,000 miles of DNA per human body, enough to stretch around the earth a million times. At the normal rate of cell reproduction, each of us is making new DNA at a rate faster than 10,000 miles per hour.

Only a small part of this DNA is actually used in any single cell. The rest contains the code for making other types of cells in the rest of the body. This means that each cell must find just the right little bit of the DNA crowded into the small space of the cell nucleus. It becomes a big problem to hold all that DNA, pick out the right bit, and open it up to read its message. The physics of DNA stiffness, twisting, and sticking becomes a major factor in understanding how this genetic material works.

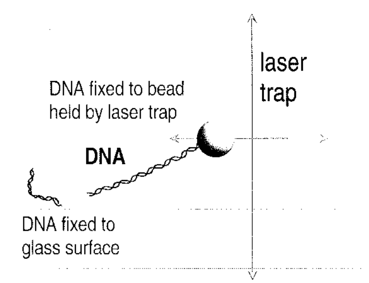


FIGURE 3.9 Using "optical tweezers" to stretch a strand of DNA. One end of the strand is attached to a stationary glass surface. A tiny bead attached to the other end is then trapped using laser light. Adjusting the laser trap moves the bead and stretches the DNA molecule. (Courtesy of Princeton University.)

4 An Era of Change

We live in a world shaken by change. The Cold War has ended. A global economy is emerging. The information technology revolution continues apace. Social and economic systems are struggling to adapt to new ways of doing business. Economic strength is replacing military strength as the barometer of greatness. High technology, once confined to the developed nations, is propagating through the world literally at the speed of light. This era of rapid and pervasive change has profound implications for our future.

Science is also undergoing unprecedented change. The great industrial laboratories the engines that have driven technology for the past half century—have adjusted to the realities of the new global marketplace and changed both the scale and scope of their long-term R&D investments in the physical sciences. Under pressure to balance the federal budget, the U.S. government is reducing its discretionary expenditures, the category that includes federal support for science. At the same time, many other countries are increasing their investments in long-term R&D. The debate about the appropriate roles in R&D of industry, government laboratories, and the universities is set against this backdrop of constrained resources and increased global economic competition.

In the next century, the United States will need to respond to world tensions arising from economic competition, regional military conflict, competition for energy and other strategic resources, and global environmental issues. These new international challenges differ from those of the Cold War past, and addressing them cost effectively will require continued scientific advances. National issues related to security, the environment, and energy resources will also need to be confronted. Condensed-matter and materials physics will play a pivotal role in ensuring the nation's prosperity in this new world.

This report demonstrates that condensed-matter and materials physics lies at the heart of modern technology. Advances in communications, computing, medicine, transportation, energy, and defense have all been enabled by new materials and materials-related phenomena. Research in condensed-matter and materials physics, pushing forward the frontiers of both science and technology, provides much of the fundamental underpinning for these advances. Its success has been one of the great sagas of the 20th century.

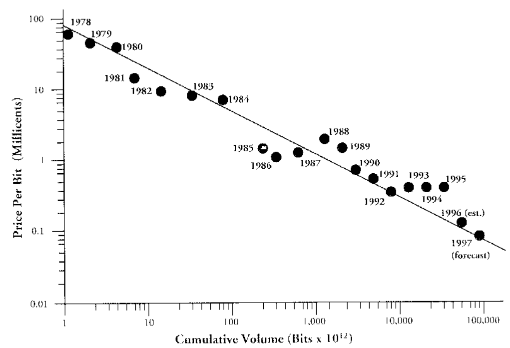


FIGURE 4.1 The price per bit of dynamic random access memories (DRAMs) has been falling steadily by 25–30% per year as the volume produced steadily rises. The capabilities of other electronic components are advancing at similar rates. If aircraft had developed at the same rate, a flight from New York to San Francisco would now take 10 minutes and cost $20. (Courtesy of SEMI/SEMATECH.)

As we enter the new millennium, the field of condensed-matter and materials physics is evolving in several important directions. It is becoming increasingly interdisciplinary, with progress often being made at the interfaces with other disciplines, such as biology, chemistry, engineering, materials science, and atomic and molecular physics. Partnerships across disciplines and among universities, government laboratories, and industry have become essential to assemble the resources and diverse skills necessary to continue advancing our knowledge. The emergence of national facilities, from atomic-resolution microscopes to powerful synchrotron and neutron sources, has transformed both the practice and the substance of the field. These developments foreshadow a condensed-matter and materials physics community more closely connected with industry and with the rest of science, and armed with experimental and computational capabilities that were not even imagined just a few decades ago.

The 21st century will bring significant challenges to condensed-matter and materials physics. Foremost among these challenges is ensuring the future vitality of the field and its continued ability to enhance our quality of life. The shift of the major industrial laboratories away from long-term, funda-

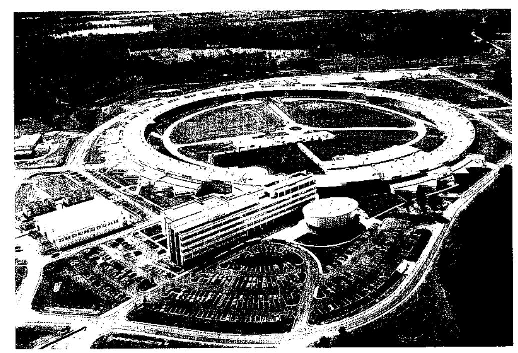


FIGURE 4.2 The Advanced Photon Source at Argonne National Laboratory, commissioned in 1996, is the nation's most powerful synchrotron x-ray facility. It will provide unprecedented research opportunities to thousands of users in the materials, biological, and engineering sciences. (Courtesy of Argonne National Laboratory.)

mental research in the physical sciences leaves a significant gap in the nation's scientific infrastructure and its ability to transform the fruits of research into applications. The economic impact of this shift may not become apparent for decades, because of the time required for fundamental scientific advances to be incorporated into new products. If U.S. industry no longer can support basic research at the levels it once did, then the realities of global economic competition place the burden for support of such research squarely on government. Our nation must move quickly to determine the scale and form of this governmental responsibility.

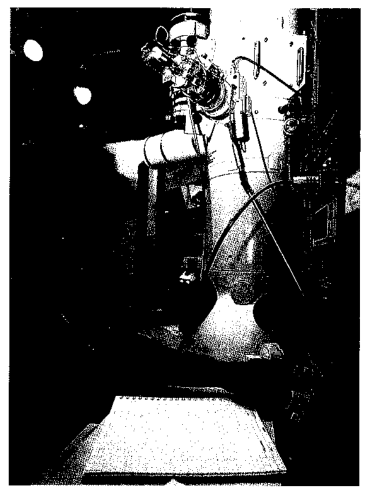


FIGURE 4.3 Microanalytical facilities such as this transmission electron microscope are essential to continued progress in condensed-matter and materials physics. These facilities often include a wide variety of instrumentation available to both internal and external users. (Courtesy of the University of Illinois at Urbana-Champaign.)

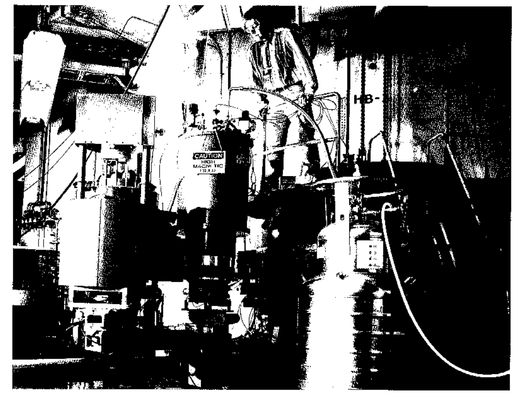


FIGURE 4.4 The High Flux Isotope Reactor provides the nation's most intense steady-state neutron beams for materials research and isotope production. The neutron scattering spectrometer shown here is being configured for an experiment that uses the neutron's unique sensitivity to magnetism. (Courtesy of Oak Ridge National Laboratory.)

Innovation is the key to developing breakthrough technologies. It must continue to flourish despite the resource constraints that are sending shock waves through the R&D system. Constrained resources mean that hard choices must be made, but the system must adapt in a way that preserves the nation's ability to innovate and enables us to meet the challenges of the future.

Progress in condensed-matter and materials physics, as in many other scientific fields, will require continued investment in major facilities for experiments in such areas as neutron scattering and synchrotron radiation. These facilities provide capabilities far beyond those available in individual laboratories. Though they have been developed and supported primarily by the condensed-matter and materials physics community, they also serve thousands of scientists and engineers in other endeavors, such as structural biology and environmental science. The construction and operational costs of large facilities, however, force us to consider carefully their budgets relative to those for other R&D initiatives and to look more closely at the role and impact of the internationalization of science.

Finally, increased cooperation will be required among universities, government laboratories, and industry to leverage existing resources and to ensure the effective integration of science and technology. These interactions will be facilitated by modern communication and information technologies.

We face an era of vast opportunity for condensed-matter and materials physics and the technology it enables. Just as the transistor, the optical fiber, and the solid-state laser have strengthened our economy and changed our lives, new developments in quantum engineering, nonequilibrium phenomena, and biomaterials (to name just a few highlights) hold out the promise of revolutionary breakthroughs in the next century. To fulfill this promise, the condensed-matter and materials physics community will need to build on the unique strengths of universities, government laboratories, and industry, finding new ways to meet the challenges of our changing world.

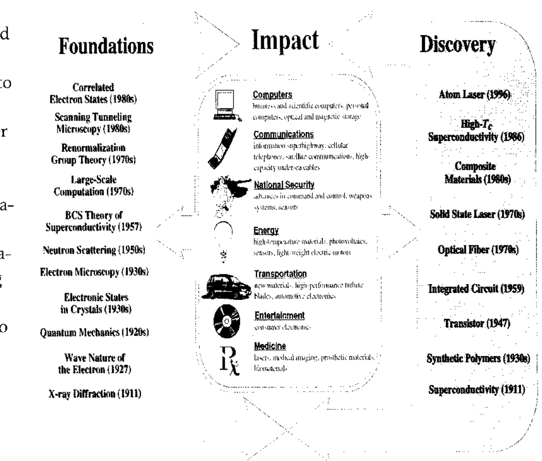


FIGURE 4.5 The incorporation of major scientific advances into new products can take decades and often follows unpredictable paths. Supported by the foundations of condensed-matter and materials physics, the discoveries shown in this figure have enabled breakthrough technologies in virtually every sector of the national economy. The two-way interplay between discovery and foundations is a powerful driving force in this field. The most recent fundamental advances leading to new foundations and discoveries have yet to realize their potential.

The 1996 Nobel prizes for physics and chemistry were both awarded for research in areas discussed in this report. The physics prize (left) was given to David Lee, Douglas Osheroff, and Robert Richardson for their discovery of superfluidity in helium-3. The chemistry prize (right) was given to Harold Kroto, Robert Curl, and Richard Smalley for their discovery of fullerenes, a new form of carbon. (Courtesy of Pressens Bild.)

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