DOE Nanoscale Science Research Centers Workshop
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Nanoscience and the National Research Agenda

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Thank you for inviting me to speak this morning. Exciting things are happening in science that promise enormous benefits for society. At the same time, these developments are demanding new ways of thinking about the entire scientific enterprise. This morning I want to speak briefly about these things, and relate them to changes that are occurring in the role of the national laboratories.

In almost any period during the past two centuries it could be said that the time was an exciting one for science. The pace of discovery was increasingly linked to technical development. While America was winning its independence during the eighteenth century, the industrial revolution was changing the economy and the way of life of Britain. The technologies employed in that early period of industrialization owed very little to science. In retrospect, it seems as if the machines of water-powered wood and iron could have been deployed anywhere along the line of history. As our new nation established itself in the following century, science was just beginning to add value to technology. The rise of steam power and associated industries stimulated and benefited from the new science of thermodynamics. By the end of the 1800's science and technology were joined together in a symbiotic relation that grew stronger throughout the 1900's. Electricity and magnetism had been added to the list of natural phenomena that could be harnessed for social needs. Now as we enter a new century, it is the extraordinary acceleration of technology that is transforming science, and once again transforming our way of life as well.

One of the bright threads in the tapestry of science during the past two centuries is the endeavor to relate the gross properties of matter to its elementary constituents. Since roughly the time of John Dalton two centuries ago, scientists (some of them at least) have known that all matter is built up from elemental pieces that we now call atoms. Throughout the nineteenth century, atoms played a role in scientific thought, but as somewhat abstract concepts. Doubts about the reality of atoms lingered into the twentieth century, and died away only with the work of Einstein on Brownian motion, and the emerging phenomena of nuclear physics. The nature of the atoms themselves could not even be grasped without the conceptual tools of quantum mechanics whose development during the first quarter of the past century flung open the gates of understanding into the microscopic world.

By the middle of the twentieth century, we had devised a mathematical model, quantum electrodynamics, that is capable in principle of simulating the behavior of chemical atoms to an astonishing degree of accuracy. For the ordinary matter we encounter in ordinary life, excluding only some radiological phenomena, QED is the exact theory. If only we had sufficient analytical power, we could search the equations that QED instructs us to write down for new phenomena and new materials, without ever looking in the laboratory. At the time, this idea was no more practical than Lagrange's assertion that an intelligence of sufficient magnitude could infer all the past and all the future from a snapshot of the positions and velocities of all the particles in the universe. But the insights gained from the *approximate* methods of quantum theory sufficed to transform chemistry, materials science, and eventually biology as well. The growth of semiconductor electronics and its integration with optics during the second half of the last century were products of the new quantum understanding of matter.

From the 1950's onward, the huge market for devices that used electronics to process information encouraged investment in increasingly powerful manufacturing techniques. The symbiotic relation between science and technology stimulated advances in understanding material properties in parallel with the development of ever more capable tools for manipulating those properties to create functional products. The upward spiral of capability is captured by Moore's Law which in 1965 postulated a characteristic doubling time of component density on microchips of eighteen months. (Moore himself thinks the law will break down in 2017, after about 35 doubling times.)

We are all familiar with the impact of this spiraling capability on our lives, and it has just begun. But the impact on science has been truly revolutionary. There are two aspects of this impact. First, *a radically new context for all technical work*. The chores of recording and analyzing data, the preparation of technical talks and publications, the manipulation of mathematical models, the simulation and visualization of experiments and data, the management of apparatus, the organization and communication among scientists, the publication and dissemination of results, have all been changed beyond recognition from the forms and practices of mid-century.

(This transformation impressed me as I returned from administration to physics after a hiatus of fifteen years: No more hand plotting of numerical results on graph paper, no more punch cards, instant contact with colleagues, and marvelous computing power on my desktop with little or no programming effort. I felt like Rip Van Winkle, and it was delightful. The new technology made it much easier for me to access new fields and to catch up with old ones.)

Moreover, the new information technology enables us to execute experiments that would have been impractical in the past, and to design and build apparatus that would have been impossible before. The huge detectors at Brookhaven or Fermilab would be useless without computing powerful enough to swallow their data stream without choking. The utility of the synchrotron light sources depends on the computing power to infer complex spatial structures from the equally complex diffraction images. The sequencing of the human genome, to be completed this year, would have been impossible without a sequence of technical developments closely linked to the exploding capabilities of the semiconductor industry.

The second profound change is the *ability to image, simulate, and manipulate matter on the atomic scale*. For the first time since the modern theory of atoms emerged 200 years ago, the notion that everything is made of atoms has a real operational significance. The implications of this capability are staggering. One implication is that the boundaries among physics, chemistry, and biology are erased at small scales. The uniqueness of biology as a field apart from chemistry is no longer a valid concept. In particular, the structures of life are seen to be expressions of information that may be encoded either in DNA or in a computer data base. If a virus can be regarded as a living thing, the chemical synthesis of life has already been accomplished. The machinery of naturally occurring organisms can be used to synthesize new materials, and the processes developed to produce complex semiconductor devices can be used to synthesize organic molecules. Materials can be manufactured with embedded microstructures to produce properties unlike those provided spontaneously by nature: lasers at wavelengths unknown to nature; new kinds of superconductors; optical media with unusual properties.

Everyone at this workshop knows examples of this new power, and I will not say more. There are problems, however, that get in the way of exploiting these capabilities.

One problem is the cost of equipment. The most powerful tools for imaging, analyzing and manipulating atomic level structures are expensive. Not every laboratory can afford to build an x-ray synchrotron, or an intense neutron source, or a high field magnetic resonance device, or a supercomputer. Nor does every laboratory need to have its own. It makes sense to share these costly facilities.

Already during the past three decades shared facilities at the Department of Energy laboratories have played an important role in the technology developments that have sustained Moore's law. Starting with the neutron sources at Oak Ridge, Brookhaven, and Argonne, and followed by the synchrotron light sources at Argonne, Berkeley, Brookhaven and Stanford, DOE has fostered the development not only of increasingly powerful tools, but of new paradigms for the conduct of science itself.

Immediately following the collapse of the Soviet Union in the closing decade of the last century, science planners and policy makers raised many questions about the role of the national laboratories. In the popular view, these laboratories were linked to cold war objectives, and many expected them to diminish in numbers and significance in the new century. The popular view, however, was ignorant of the rapidly multiplying links between the capabilities of the national labs and the technology that was already then changing the way we live. Thanks to the insistence, and the persistence, by DOE science leadership that the laboratories sort out their priorities and the rationales for their own existence, the decade of the 1990's witnessed a rapid evolution of the laboratories, particularly the multi-program laboratories, toward a new paradigm.

One of the drivers toward this new laboratory paradigm was the concentration in the labs of accelerator expertise, and the importance of that technology for atomic-level imaging. Accelerators can be used as the primary energy source for every variety of visualizing radiation: photons, electrons, protons, and neutrons.

A second driver was the model of large user collaborations on the great detectors for particle physics. The particle physicists developed new modes of communication, including the World Wide Web and the Los Alamos preprint server, to keep themselves in touch and up to date while dispersed throughout the globe.

Not as well recognized is a third driver whose influence is still implicit. That is the demise of industrial laboratories as sources of basic knowledge. The closing years of the cold war were also years of deregulation which profoundly diminished the ability of technologically intensive industry to finance its own basic research. While industrial R&D budgets have actually increased, primarily in the pharmaceutical industry, the horizon of discovery in industrial labs has shrunk to issues of immediate concern. The funding of long lead time, high risk research is now primarily the responsibility of the federal government. This administration understands its role in sustaining the basic end of the research spectrum, and acknowledges nanotechnology as an important priority in the President's Fiscal Year 2004 budget proposal.

Today's workshop centers on a new set of capabilities in the DOE laboratories that are a logical next step in a pattern of evolution that began nearly thirty years ago. The new laboratory paradigm includes expensive, shared facilities, essential for the conduct of basic and applied studies of matter at the atomic scale, serving regional communities of researchers from universities, industry, and other government facilities. The DOE labs are strategically located throughout the country, and operated in response to the demands of user communities.

The new nanotechnology centers at each laboratory enhance and complement the existing large scale user facilities. They focus on the preparation of well defined nanoscale material structures whose characterization and analysis requires access to the large scale facilities. The centers are not free-standing capabilities, but are closely linked to the unique capabilities that have evolved in each of the host laboratories. Much credit is due to DOE leadership, and especially Basic Energy Sciences Director Patricia Dehmer and her colleagues, for careful planning that has guided this evolution and matched the program for each of the nanocenters to the capabilities of the host laboratories. I look forward with some impatience to the completion of these centers, and to the outstanding science that I know each of them will produce.

Thank you.