Science at the NANOSCALE

B. Sands, HP

Hewlett-Packard's R. Stanley Williams took time to answer our questions about nanoscience in the contexts of research, industry, impact on computing, and the future.

SciDAC Review: *What are your roles at Hewlett-Packard (HP)?*
Stanley Williams: I have two jobs in HP. Currently, I am one of four active HP Senior Fellows. In this role, my job is to keep my eyes on the future of technology and to understand how that will affect the business climate for HP. I need to alert the company to both technological opportunities and threats, and provide technical solutions to the challenges that these create. My second job is as the Director of the Information and Quantum Systems Laboratory (IQSL). In this role, I have the responsibility and privilege of guiding a highly talented and motivated team of scientists and engineers in performing research in areas of mathematical and physical sciences that will have a positive impact on HP.

What can the U.S. Department of Energy (DOE) do to support nanoscience?
I think the proper question is: "what can the nanosciences do for DOE?" My view of the DOE science program is that it should focus on the critical energy issues facing the United States and the world. Thus, when important areas such as solar conversion, energy storage and transmission, catalysis, fuel cells, particulate formation, or carbon sequestration, to name a few, require a significant amount of nanoscience expertise, DOE should sponsor research in those areas and help to provide the experimental and computational facilities to support that research. Putting the focus on nanoscience rather than energy outcomes can skew the mission of DOE. That said, by supplying infrastructure and contributing to the knowledge pool, DOE will automatically be supporting the broader goals of moving the nanosciences forward.

What are your views on modeling and simulation? What contribution should they make to nanoscience?
Modeling and simulation constitute one of the three legs of modern science, complementing and completing theory and experiment. Often, modeling and simulation provide an important bridge between theory and experiment by showing whether the two are in agreement or not. However, as computational tools and algorithms become more capable they more frequently provide the key insight for solving a difficult problem. In the nanosciences, modeling and simulation are particularly useful. Nanoscale structures and materials often have counterintuitive properties because of quantum or surface effects that are not only very difficult to access by experiment, but are also beyond a pure paper and pencil analysis. Nanosystems fall into a size range that is nearly ideal for examination by modeling and simulation with advanced but currently available hardware and software tools, and therefore I think there should be a stronger emphasis on computational approaches to nanosciences. A major problem today is that the number of people who have been trained as critical modelers is fairly small, and a lot of published simulations are irrelevant to the systems they were intended to model or just plain wrong because the people doing the studies did not understand the tools or the theory behind them.

In your roles at HP, how do modeling and simulation apply to you?
Modeling and simulation are used primarily in my research role. In IQSL, we perform computations to help us in the design and optimization of various types of circuits and systems, such as integrated nanocircuits containing transistors and memristors, and negative index metamaterials for photonic modulators. Since building a physical system is a time-consuming and expensive process, we often perform a suite of simulation studies that allow us to optimize the performance of a system before we actually build and test it. We then feed the results of measurements on the systems that we do build back into the modeling so that subsequent simulations are more accurate than previous ones.

Research Program

What have been your contributions to nanoscience research?
My research career really began as a graduate student working for Professor David A. Shirley at the University of California (UC)–Berkeley and Lawrence Berkeley National Laboratory performing surface science research that was supported by the DOE. I was primarily working in the area of photoelectron spectroscopy, which provides an experimental window into the chemical and electronic properties of the top few nanometers of a material. I was privileged to be among the pioneers in the use of synchrotron radiation excited photoemission, which greatly extended the capabilities of the technique and enabled entirely new types of experiments to be performed. At AT&T Bell Labs, I continued working in surface science, primarily on studying the atomic structure of solid surfaces using ion scattering. After I joined the faculty of UCLA, I combined a number of electron- and ion-based techniques to continue the study of the chemical and physical properties of the top nanometer of a material. Soon after the invention of the scanning tunneling microscope (STM), one of my students and I built one and intentionally began the study of nanoscale

structures formed on surfaces during various chemical processes, such as etching and material deposition. Thus, I transitioned from studying the top few nanometers of a material with a large surface area to two- and three-dimensional fabrication and analysis of materials with sizes of a few nanometers. I continued this type of work when I moved to HP Labs, where with my colleagues we made substantial contributions to understanding the thermodynamic and kinetic processes that control the growth of epitaxial nanocrystals on a solid substrate, such as germanium on silicon. This work then branched out in many different directions, such as the growth of one-dimensional strained epitaxial nanowires of rare earth disilicides on silicon, a form of self-assembly, and the formation of metallic wires and other nanostructures by imprint lithography, a top-down fabrication technique. Soon thereafter, we began to build and test simple nanoscale two-terminal devices and crossbar circuits into which we incorporated both molecular and inorganic materials to achieve an electronic switching function. This research is still ongoing, and it was the basis for our discovery of the memristor. In the meantime, we have also used our nanofabrication capabilities to build a wide variety of photonic devices and chemical sensors, two examples of which are negative index metamaterials that act as fast switches for infrared radiation, and highly sensitive transducers of chemical species such as DNA and protein fragments.

What is the memristor, and how does it compare to other circuit elements? What is its significance for the future of nanoscience?

The memristor, the fourth fundamental passive circuit element, complements and completes the set that also contains the resistor, the capacitor, and the inductor. It was predicted to exist in 1971 by Professor Leon Chua of UC–Berkeley, who had generalized electronic circuit theory to include nonlinear elements. He recognized that even networks of the nonlinear generalizations of the resistor, capacitor, and inductor were unable to perform all of the functions that were allowed mathematically by his equations for passive circuit elements, and he postulated that there should be a fourth physical device. This element is very different from the others, in that it is dynamical, or in other words it has a state that is determined by its history. In the cases of the memristor, the name of which is a contraction of "memory resistor," the resistance of the device changes depending on the direction and amount of charge flow through the device.

In my group at HP Labs, we were the first to build and operate memristors intentionally, beginning in 2006. In fact, many researchers had reported apparently anomalous current–voltage characteristics in a wide variety of systems for a period of over 50 years, but they had not recognized that behavior as memristance. I developed a simple physical model for a binary switch based on the coupled movement of both charged dopants and electrons in a semiconductor, and saw that the defining equations for this switch were identical to Chua's mathematical definition of a memristor. I was then able to write down a defining equation for the memristance of this device in terms of its physical and geometrical properties. The key insight that arose from this was that the strength of the memristance was proportional to the inverse of the square of the active length of the device. In other words, memristance is one million times more important at the nanoscale than at the micron scale. This can be appreciated in part by understanding that even one volt applied across a one nanometer distance yields a field of 10^7 V cm^{-1}, which is large enough to physically distort many materials and cause ions to move in a solid. Thus, as the critical feature sizes of devices in electronic circuits have shrunk to the nanoscale, the inherent memristance in those circuits has become much larger. This means that memristance must be recognized and minimized when necessary, and the fundamental understanding of memristance from Chua's general theory and from my simple model are keys to doing that. Up until this time, the effects of memristance have essentially been dealt with on an *ad hoc* basis with no understanding of their root cause.

In memristors, as opposed to other circuits, you have to move atoms—how can you maintain circuit integrity over time?

Memristance arises in a semiconductor material when the equations of motion for the current carriers (electrons and holes) and for charged dopants are coupled, and the applied field is large enough to cause the dopants to move. In fact, the dopants do not have to move very far in a nanometer-scale junction to change the resistance of a device substantially—a few tenths of a nanometer is sufficient in many cases to change the resistance by orders of magnitude. If the applied electric fields are kept within certain bounds, no dopants are lost from or added to the system (for example, very high fields in an oxide semiconductor can cause electrochemical creation or destruction of oxygen vacancies, which are often charged dopants). Thus, the movement back and forth of the charged vacancies as the device is switched on and off is highly reversible. That said, devices do suffer from fatigue and will eventually wear out. One of the primary challenges for finding applications of memristors is to make sure that their endurance—the number of times they can be cycled before they wear out—is much larger than needed by the application.

Why did you start pursuing the memristor? That is, were you looking for it specifically? What path did you follow to discover it? Why was it able to be found at this point—was it an accumulation of technological prowess, or a fundamental change in the available methods that allowed it?

We set out in 1997 to build a switch that we could toggle on and off electrically, because we thought that such a device would be a very useful circuit element for nanoelectronics. The idea was that we could build a crossbar structure with such a switch at the intersection of every pair of wires and thereby construct an extremely high-density memory. We also had some ideas for building certain types of programmable logic arrays with such switches. We succeeded in building a wide variety of such switches, but we did not understand why they worked. In fact, they were highly variable in their properties and had a low endurance because we did not know how to engineer them. Greg Snider, a senior architect in our lab, found the original 1971 memristor paper by Chua in about 2003, and essentially said that we should be building memristors, as well as another more general device that Chua called a memristive system. In fact, there was a resemblance between the current–voltage characteristics that we were seeing in our switches and those that Chua predicted for the memristor, but there was no obvious physical reason why that should be the case. We continued to study our devices and read Chua's papers for another three years. Finally, we had accumulated a significant amount of (sometimes conflicting) information about our devices—we understood what their internal chemical structure was because of some experiments by Duncan Stewart and others in our lab, and had a lot of uncorrelated data on switching. I just decided I was going to understand it, so I spent the month of August 2006 reading a lot of relevant papers, thinking, and writing down simple equations to model what I thought was going on inside our devices. One day I literally had a eureka moment; I realized that the equations I was writing down looked a lot like Chua's memristor equations. I then played around a little more and was able to come up with a simple physical model and an equivalent circuit that was described by exactly the same equation that Chua used to describe the memristor. After that, I made several predictions based on my model and worked with members of the group to build and characterize new test devices. When the results of our measurements agreed with the predictions I had made, we knew that we had a good model for the memristor. There was no single event, experiment, or technique that magically enabled the discovery—rather, it was a combination of serendipity, a lot of hard work to accumulate a huge amount of data, and the determination to understand it.

What projects you are working on that you think will have a large impact?

CeNSE, an acronym for "Central Nervous System for the Earth," is the new theme for our research lab, the IQSL. The CeNSE theme actually covers all of our projects together. Within this theme, there are some specific things we are doing that I think will have a large impact.

First is Photonic Interconnect, which is our project to replace, as much as possible, the copper wiring in a computer with light paths of various sorts. The idea here is to move data around using photons instead of electrons to dramatically increase the performance of computers by improving the communication bandwidth orders of magnitude while simultaneously decreasing the energy required to move those data around, and using a lot less material in building the computers in the first place—a win–win–win situation for machine cost, performance, and energy consumption.

Second is Dynamical Nanoelectronics, our project to use memristors to build new types of nonvolatile memories and alternate computing systems. We are building nonvolatile memristor systems that have densities much higher than semiconductor memories but are much faster than magnetic disks, and which use less power than either but could replace both. This would provide "instant-on" computing, meaning that people would not have to waste time and electricity every time their computers boot up. Another application is to use memristors for electronic synapses, which would enable us to build an analog computer that would perform tasks more closely resembling those performed by a brain, rather than by a digital computer ("Cortical Computing with Memristive Nanodevices," p58).

Third is Receptors, our project to build highly integrated nanoscale sensors that can detect a wide variety of "state variables," in a single inexpensive package, at unprecedented sensitivities. Since they will be inexpensive, it will be possible to deploy large numbers of them. This large-scale deployment will provide a larger quantity and better quality data than we have ever had available before, dramatically decreasing the problems of false positives that plague isolated sensors and enabling sophisticated data centers to synthesize a detailed real-time understanding of the environment of interest.

What are the goals and benefits of CeNSE?

We see that the future of computing and the ability for human beings to interact with and understand the physical world as convergent streams. Our research projects are primarily in the areas of building material systems, usually with nanoscale dimensions or control of dimensions to even smaller length scales, with optical, electrical, and/or mechanical properties that enable us to do something that no one has ever done before. We build plasmonic and negative index metamaterials that enable us to do things with light that were unthinkable just a few years ago. We build nanoelectronic circuits in which memristors and transistors work together to perform old tasks better and new tasks that appeared to be impossible. We build mechanical structures that have moving components for which we can control positions to within the diameter of an atomic nucleus. We build systems that enable us to study individual electrons and photons, and how quantum mechanical information governs the behavior of these systems. These components enable us to measure the environment with unprecedented sensitivity, send data with extremely high bandwidths, and store and retrieve data rapidly and at enormous densities. We realized that when these components are integrated together, they would form the physical infrastructure for a nervous system that could be used to sense a wide range of properties of a system and provide a means to communicate a high level of information to people to both assist in real-time command and control (for example, to maximize the efficiency of a manufacturing plant or to rapidly identify the source of a pathogen in the food or water supply) and for providing long-term intelligence about a system (for example, a forest or watershed). Because all of our components are fundamentally nano-enabled, they are capable of being integrated together in extremely capable systems and manufactured in vast numbers at low cost by semiconductor fabrication techniques. Thus, we think it is literally possible to provide the planet with a nervous system that people could access via their web tools to understand the health of their environment—we hope this will make people better stewards of the Earth. CeNSE is both bold and altruistic, but it also could be a major economic driver for the IT industry in general and HP in particular.

Research in an Industrial Environment

Why is HP funding this type of research? Is this viewed as a continuation of the Bell Labs tradition, or does the research contribute more directly to HP's business mission?

Our research is funded by HP with the belief that it will contribute to the strategic benefit of the company. HP's main businesses are printing and publishing, personal electronics, large-scale computing, and consulting services. In IQSL, we interact with all four of these business segments by providing

Biography in Brief: R. Stanley Williams

R. Stanley Williams is an HP Senior Fellow at Hewlett-Packard Laboratories and Director of the Information and Quantum Systems Laboratory (IQSL), which currently has over 60 scientists and engineers working in areas of fundamental physical sciences and engineering. He received a B.A. degree in Chemical Physics in 1974 from Rice University and his Ph.D. in Physical Chemistry from UC–Berkeley in 1978. He was a Member of Technical Staff at AT&T Bell Labs from 1978 to 1980 and a faculty member (Assistant, Associate, and Full Professor) of the Chemistry Department at UCLA from 1980 to 1995. He joined HP Labs in 1995 to found the Quantum Science Research group, which focused primarily on fundamental research at the nanometer scale. His primary scientific research during the past 30 years has been in the areas of solid-state chemistry and physics, and their applications to technology. This has evolved into the areas of nanostructures and chemically-assembled materials, with an emphasis on the thermodynamics of size and shape. Most recently, he has examined the fundamental limits of information and computing, which has led to his current research in nano-electronics, -ionics, and -photonics. He has received awards for business, scientific, and academic achievement, including the 2007 Glenn T. Seaborg Medal for contributions to Chemistry, the 2004 Joel Birnbaum Prize (the highest internal HP award for research), the 2004 Herman Bloch Medal for Industrial Research, the 2000 Julius Springer Award for Applied Physics, the 2000 Feynman Prize in Nanotechnology, the Dreyfus Teacher–Scholar Award, and the Sloan Foundation Fellowship. He was named to the inaugural *Scientific American* 50 Top Technology leaders in 2002 (and then again in 2005). In 2005, the U.S. patent collection that he has assembled at HP was named the world's top nanotechnology intellectual property portfolio by *Small Times* magazine, and the Chinese Academy of Science voted the crossbar latch as the third most significant scientific breakthrough of the year (behind the Cassini and Deep Impact space missions). He was a co-organizer and co-editor (with Paul Alivisatos and Mike Roco) of the workshop and book *Vision for Nanotechnology in the 21st Century*, respectively, that led to the establishment of the U.S. National Nanotechnology Initiative in 2000. He has been awarded 75 U.S. patents with more than 40 pending, he has published over 300 papers in reviewed scientific journals (with an h-index of 48), and he has written several general articles for technical, business, and general interest publications (including an article in the November 2005 issue of *Scientific American*). One of his patents was named as one of five that will "transform business and technology" by MIT's *Technology Review* in 2000. He has presented hundreds of invited plenary, keynote, and named lectures at international scientific, technical, and business events, including one of the 2007 50th Anniversary Laureate Lectures for the TMS, the 2003 Joseph Franklin Lecture at Rice University, the 2004 Debye Lectures at Cornell University, the 2004 Bloch Lecture at the University of Chicago, and the 2005 Carreker Engineering Lecture at Georgia Tech.

technologies that improve the products or expand the capabilities of the business. All of the business segments provide a strong pull for the results of our research, and in some cases our research is considered a major strategic initiative for that business. Much of what we do is fairly long-term and involves fundamental scientific and mathematical issues, but all of our research is in areas that will contribute to technologies that are fundamental to HP's products and services—and in some cases, may enable HP to go into new businesses.

How does your group operate? Where does funding come from?

The IQSL is one of 23 laboratories with HP Labs, the central research organization for HP. The job of HP Labs is to be a true research organization, with a portfolio of approximately one-third fundamental research, one-third applied research, and one-third advanced development. Our operating model is for a laboratory to have one or two large projects (10 or more researchers each), a couple of medium projects (about five researchers), and a few exploratory investigations (one or two researchers). The large and medium projects need to be approved by a review board that consists of both researchers and business people from HP. A group of researchers within a lab gets together to write a proposal for a project in order to obtain the resources needed for it; projects can be approved for as long as five years. If a proposal is not approved, then the researchers need to formulate a new proposal and resubmit it to the board. Within a laboratory, 80% of the researchers need to be assigned to approved projects, whereas 20% of the researchers can be working on projects at the discretion of the Laboratory Director. Also, individuals can spend 20% of their time working on their own projects. All of the funding for the permanent staff and for equipment expenses comes from the HP Labs budget, which comes directly from corporate headquarters rather than any business unit, as allocated to approved projects and the discretionary projects sponsored by the Lab Directors. Some labs, such as IQSL, also write proposals to obtain funding from external agencies, such as the Defense Advanced Research Projects Agency (DARPA). Such external funding is used for paying post-doctoral researchers and other temporary workers, covering expenses associated with the externally funded project (which is usually an integral part of one of the internal projects), and supporting the research of academic collaborators who are subcontractors for the externally funded program.

How important is the ability to develop and fabricate the discovered technologies, as opposed to focusing on increasing the intellectual property portfolio and licensing the technologies?

The main job in HP Labs is to provide technologies for the company to use internally to improve existing products or to help create new products or businesses. Thus, in IQSL our focus is on building physical things that will eventually go inside HP products. That said, not every technology winds up going into a business, or a business can change its direction before a technology is completed. In those cases, HP does have an intellectual property licensing office that either licenses or sells unused IP. For example, within IQSL, we developed an imprint lithography machine that enables us to build high-quality nanoscale devices and circuits. HP was not going to go into the nanofabrication equipment business, so we licensed that technology out to a new company. As a serendipitous spin-out from our photonic interconnect project, we also developed a solar cell technology that we are looking to license out.

How does your experience at HP—such as funding level, research freedom, short- versus long-term focus, and so on—compare with the research environment at Bell Labs?

The scale and the structure of the Bell Labs that I knew in the late 1970s was completely different from HP Labs. The old Bell Labs structure actually had two different divisions, which they called Research and Development (R&D), and then there was a separate Engineering division which actually took prototypes out of Bell Labs for productization. There were fairly significant walls separating each of these entities, movement of people among them was unidirectional, and there was a lot of redundancy and competition among the divisions. In today's environment, we would call the type of work done in the old Bell Labs Research division "fundamental research," that which was done in the Development division "applied research," and that in the Engineering division "advanced development." One of the great things about the old Bell Labs was that there were a huge number of extremely talented scientists; any time one had a question about an area of research, one of if not the world's expert was just down the hall to speak with. Many of them were happy to discuss science and work together when possible. That said, collaborations among scientists within Research and especially between Research and Development were often explicitly discouraged by Bell Labs management. The model of the day was the lone hero researcher, who might at most have a technical assistant and a post-doc, but had a lot of freedom to choose a research topic and then compete against the rest of the world, including others at Bell Labs. This made it difficult to work on large multidisciplinary projects and also made the hand-up of ideas from research to development very uncertain—we frequently talked about "throwing something over the wall and hoping there was someone there to catch it." Despite any problems it had, Bell Labs for many decades set the world-wide standards for research excellence in terms of creativity, quality, and quantity of contributions, and I view the demise of this great institution as a national tragedy. I have hoped that Americans would recognize this and that a government institution like one of the DOE labs would step up to fill the void.

In today's corporate environment, the amount of funding available for research and development as a fraction of sales is much lower than in the past, so every dollar invested needs to be stretched much farther. The R&D organizations are therefore smaller and more focused than before. Within HP Labs, we have fundamental and applied research and advanced development all going on within each laboratory, and often individual researchers are involved in all three activities simultaneously. This way, there is less risk of a fumble as a project progresses from the idea stage to a product, but it is more difficult to specialize and become a dominant figure for a particular type of activity. There is a much higher premium placed on efficiency, teamwork, and multidisciplinary research to tackle large and complex problems. However, for the most part, new research topics are chosen and pursued by individual researchers who then socialize their ideas among their colleagues to build larger teams from the bottom up. Within IQSL, we have a broad range of disciplines: many different types of chemists and physicists, materials scientists, electrical and mechanical engineers, mathematicians, computer scientists, and architects. This diversity is both a strength and a weakness—we can bring many different talents to bear on solving a problem, but we sometimes get into a Tower of Babel situation in which people from different disciplines have trouble communicating with each other. However, we have developed our own local creole of technical terms (which completely mystifies outsiders and newcomers), and for the most part the eureka moments in our group come when two researchers with completely different technical backgrounds realize that by working together they can solve a problem that neither alone could tackle successfully. One final difference between research today and thirty years ago is the ethnic and nationality mix—in the old days, Bell Labs was dominated by American-born researchers, with a significant number of Indians, Canadians, and Brits who moved up the management ladder because of their superior communications skills (I always attributed this to their common educational system). Today, IQSL has a majority of Asian-born researchers, especially Chinese, with a significant number of Europeans and relatively few Americans.

Impact of Nanoscience on Computing

How does nanoscience, and particularly simulation and modeling, contribute to improved computing?

We anticipate that nanoscience will contribute heavily to the eventual realization of an exaflop (10^{18} floating point operations per second) computer. To be affordable in terms of material and power costs, an exascale computer will require a significant amount of photonic interconnect and memristor-based memory and storage. It will be approximately 10–15 years before such a computer exists. For a zettaflop (10^{21} flops) computer, it will be absolutely essential to re-invent the processor around a new architecture, which could very well be a hybrid system of photonically interconnected transistors and memristors, with light carrying almost all of the bits over distances longer than one micron in the system. Simulation and modeling will be essential for designing the nano-optoelectronic circuits of the future, and computational tools will contain both a much higher level and a broader range of physics (quantum and electromagnetic equations) and non-linear dynamics than have been used in the past.

What roadblocks do you see for the semiconductor industry? How does the memristor help? What about other technologies?

The major roadblocks to the semiconductor industry are the huge power requirements of future-scaled computer systems, coupled with the fact that these systems will be choking in terms of the ability to move and store data. Photonic interconnect promises to improve the data bandwidth issue by as much as two orders of magnitude, while at the same time cutting power consumption in the interconnect dramatically. Eventually, much of the volatile semiconductor memory (DRAM and SRAM) and magnetic disk storage should be able to be replaced by memristors, a nonvolatile technology that will be less expensive, higher density, lower power, and higher net bandwidth.

Do you believe nanoscience can contribute to new and disruptive technologies that will permit exaflop supercomputing? What potential technologies might these be?
This year, we have the first petaflop computer. An exaflop computer will require computing capacity to improve by another factor of 1,000 without a substantial increase in total system size or power for operation. Traditional transistor scaling will continue to contribute to this improvement, but over the next decade it will likely only yield a net improvement in computational throughput of a factor of 10. Thus, we need to find another factor of 100 to get to an exaflop. Optical technologies, such as photonic interconnect, will be necessary. Although the future of computing still belongs to the electron, the future of communication over any distance longer than a micron belongs to the photon, and over the next decade photonic interconnect should provide an additional net factor of 10 improvement in total computational throughput. Finally, nonvolatile memory and storage, such as could be provided by memristors, should also play a role and could supply the final factor of 10 in system improvement by speeding up the movement of data to and from the processors. These changes to an enterprise class computer system will require a new architecture to utilize the photonic interconnect and new memory and storage. To go beyond an exaflop, entirely new types of computing, including analog processors that use memristors as synapses, will likely be necessary.

When will these types of technologies be coming online to overcome challenges to Moore's Law? What fabrication challenges remain for that to happen?
Photonic interconnect is happening now, but it will be 10 years before it is actually moving data around on the processor chip. However, the types of optical waveguide and modulation technologies that are being developed are silicon based and compatible with fairly standard semiconductor fabs, so actual manufacturing is not much of an issue. Memristor-based memory and storage could appear in the market in three to five years, depending on how the competition with flash and phase-change memories works out. Phase change has been in development for a long time and there are a lot of companies working on it, but from my viewpoint, memristors are a much better technology for the long term. Memristors are also completely compatible with standard semiconductor fabs, so again there are no significant barriers for manufacturing.

Future

Where do you see nanoscience in 10 years? In 20 years?
In 10 years "nanoscience" will be so mainstream that it will have faded away as a separate entity—the issue of creating the understanding, tools, and expertise to design and characterize nanoscale systems will be finished, and researchers will be concerned primarily about specific application domains. I don't think anyone will identify themselves as a "nanoscientist."

Are you optimistic about quantum computation and information processing?
I am very optimistic that quantum information will find some important applications—in IQSL we are working to commercialize a personal hand-held quantum key distribution system that could be inside any hand-held device and can be used for identity verification and secure communication of sensitive personal information. However, I am pessimistic that a large-scale quantum computer will exist, mainly because at present I don't see a commercial use for one.

In the cases of dispersed nano-networks, do you foresee any challenges to privacy, whether through abuse of the data or else design of the system? Do any other aspects of nanoscientific research concern you from a civil liberties perspective?
I am concerned that any technology can be used against people, as well as for people. This is true of all human technologies—rocks can be used to crack nuts or skulls. We need educated consumers and legislators who demand that standards of privacy and security are set and upheld, and that technologies are built with such concerns as a part of their basic architecture. We need to learn the bitter lessons from the consumer software industry about what happens when security is not a prime consideration when building technology for the information age. I think that the most important use for quantum information will be for keeping people's information private.

How should the education of future nanoscientists take place? Is the market big enough for specialized graduate programs, or will they still be drawn from subject disciplines? Which type would you hire?
In the future, I don't think there will be "nanoscientists"—the pursuit of nanoscience is a transient phenomenon that was necessary to both build a critical mass to convince governments to fund new research initiatives, and to develop the general tools and understanding to enable a wide range of scientists and engineers to exploit specific opportunities within their disciplines. I have always opposed graduate programs and degrees in nanoscience, since my experience has been that those programs turn out people who are too broad and shallow to make significant contributions to any project. I have never hired someone with a degree in nanoscience, and I doubt I ever will (and I have hired about 100 people during the past 13 years). Biologists of all types, material scientists, molecule makers, physicists, and engineers of many varieties will utilize nanoscience—but I think the most valuable contributions come from people who are very deep in a particular core discipline and then have the ability to communicate with their peers in other disciplines. I think of myself as an Information and Quantum Scientist who happens to do a lot of work at the nanoscale. ●

Further Information
http://www.hpl.hp.com/research/qsr/index.html