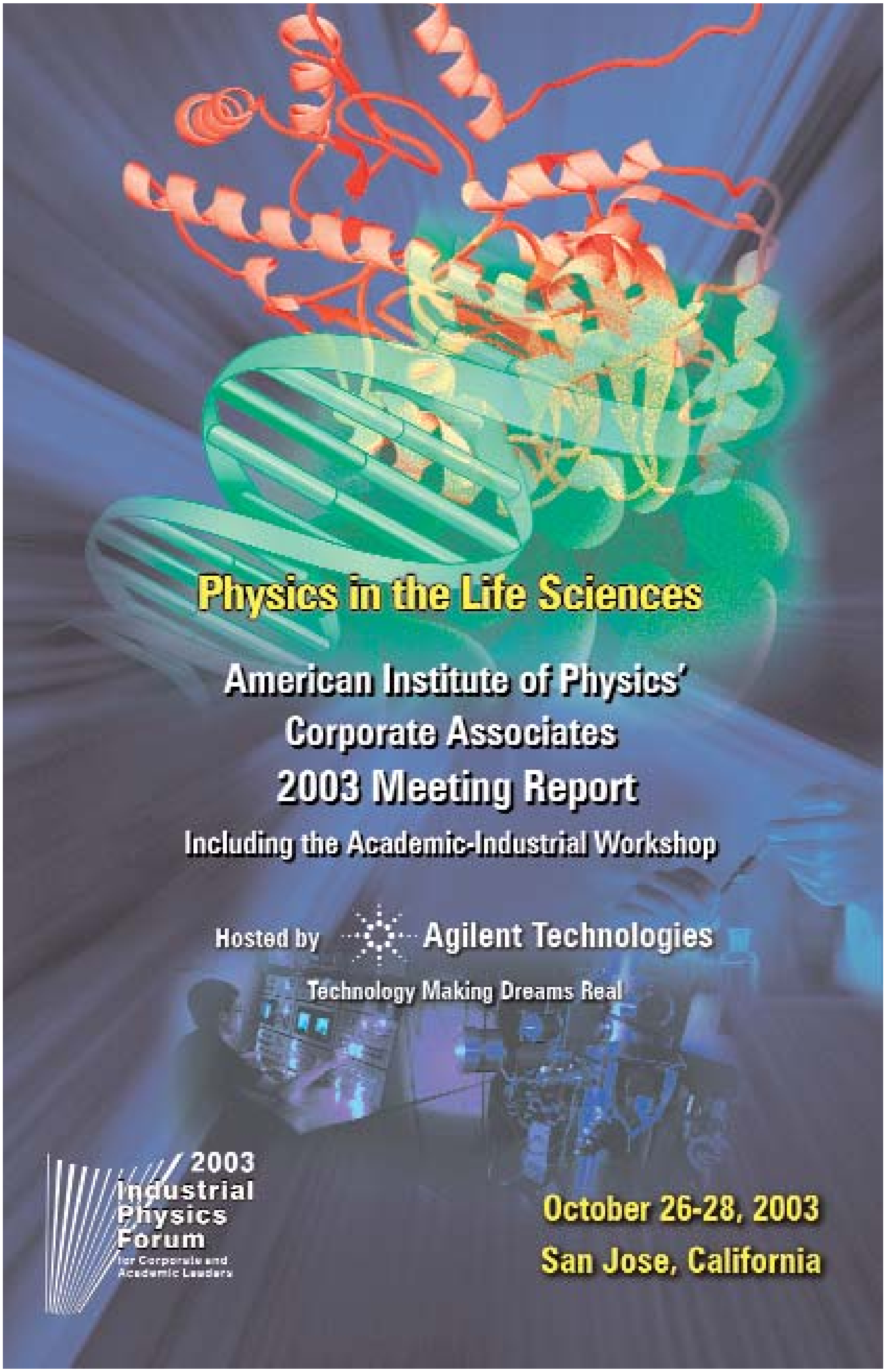
Physics in the Life Sciences
American Institute of Physics'
Corporate Associates
2003 Meeting Report
Including the Academic-Industrial Workshop
Hosted by Agilent Technologies
Technology Making Dreams Real
2003
Industrial
Physics
Forum
for Corporate and
Academic Leaders
October 26-28, 2003
San Jose, California

MISSION STATEMENT OF THE AIP CORPORATE ASSOCIATES

To serve the industrial physics community by improving the effectiveness of people and organizations in advancing corporate goals through the use of physics.

2003
INDUSTRIAL PHYSICS FORUM REPORT

Physics in the Life Sciences
October 26-28, 2003, San Jose, California

Among the scientific achievements of the 20th century, two that have had a profound impact on our lives are the revolutions in our understanding of the foundations of physics, and of the molecular basis of life. One hundred years ago, we did not understand quantum theory or the fundamental forces that bind atoms and molecules. The nature of life was a mystery and, to many, seemed outside the realm of scientific inquiry. Thanks to the contributions of scientists from multiple disciplines, including physics, many of these mysteries have now been explained. As we enter the 21st century, some of the most exciting questions in physics relate to the physical basis of life, prompting a resurgence of activity among professional physicists who are applying their skills, tools and approaches to the life sciences. The continued vital role that physics plays in enhancing breakthroughs in the life sciences provided the thematic underpinning of the 2003 Industrial Physics Forum, hosted by Agilent Technologies and held in San Jose, California, October 26-28.

About Agilent Technologies

Based in Palo Alto, California, Agilent Laboratories is the central research organization of Agilent Technologies. It supports the parent company's businesses in communications, electronics, automated test, and the life sciences, bringing together experts in electronics, photonics and systems with biochemists and molecular biologists to explore the rich opportunities that exist at the intersection of these disciplines. Having benefited greatly from the technological revolutions in the electronics and communications industries over the last few decades, Agilent sees the life sciences as the next great opportunity for both business growth and contributing to a better world.

“Innovation is the lifeblood of our company; without it, we wouldn’t survive,” said CEO Ned Barnholt in his welcoming remarks. “We provide key enabling technologies to help our customers build their products.” In fact, the company’s tag line is “investing in innovation for growth.” The company’s commitment to R&D is evidenced by its level of investment in R&D, about $1.17 billion (19.6% of net revenue) in 2002, $85 million of which went to Agilent Labs.

Research helps identify new businesses for the parent company, and is conducted in three major areas: communications, life sciences, and electronics. The Labs' interdisciplinary approach and integration of key enabling technologies has led to many novel products like DNA microarrays made using inkjet technology and to promising research including microfludics lab-on-a-chip technology for chemical and biological analysis, and nanopore technology for probing individual biomolecules.

Barnholt sees great things for the future if the rate of innovation continues, believing that biotechnology and nanotechnology, for example, are currently positioned at the same point as the electronics industry was some 20 years: on the verge of creating a technological revolution and transforming daily life as we know it. For him, the key to continued success is pervasive innovation, and the most exciting challenges are to be found at the interdisciplinary interface. "We need to make leaps, not steps," Barnholt said; "We need innovation everywhere, in technology, processes, business models, and partnerships. And we need innovation that is market-driven and reality-based."

Theme Session:
Physics in the Life Sciences

James Hollenhorst, Director of Electronics Research at Agilent Laboratories, opened the theme session by providing an historical perspective of the role of physics in the life sciences, maintaining that those universities that achieve interdisciplinary research and instruction over the next 25 years will be the most dominant in the future. Since the days of Isaac Newton (circa 1686), physics has been viewed as the means of explaining all natural phenomena through "mechanical principles." This reductionist approach has driven physics ever since, and such early reasoning was also applied to biology. For example, Galileo once offered a scaling argument as to why elephant bones are chunkier than human bones, and Newton applied it in the field of optics to explain how images are formed on the back of the eye in 1704.

However, it was not until the 20th century that physics truly began to transform the life sciences, first through Schrödinger's suggestion of a molecular genetic code within living cells, and then through Max Delbruck and his work with his so-called "phage school"—so named because they studied the bacteriophage virus, which is life in its simplest form—in hypothesizing how hereditary information is stored and reproduced. The rise of molecular biology and the discovery of the structure of DNA by Watson and Crick came out of a biophysics laboratory. Three key areas where physics has since played a critical role in the life sciences are: developing tools for advancing the life sciences, such as optical and electron microscopes and optical tweezers; developing tools for improving life through the practice of medicine, such as x-rays, laser surgery, MRI and tomography; and advances in unraveling the mystery of life.

By far the most important contribution physics has made, according to Leo Szilard, is "not any skills acquired in physics, but rather, an attitude: the conviction, which few biologists had at that time, that mysteries can be solved."

Having thus established a broad context for the morning’s sessions, Steve Laderman, Manager of Molecular Diagnostics at Agilent Laboratories, described the company's work on DNA microarrays. DNA microarray-based gene expression profiling studies have revolutionized the way in which scientists address specific biological questions by enabling the examination of thousands of genes at once. The technology also has great potential for revolutionizing the manner in which clinicians diagnose and treat disease by enhancing functional genomics-driven drug discovery efforts, and allowing the development of molecular diagnostic assays that detect patient and disease-specific molecular profiles.

One example is the use of microarray expression profile information to discover and diagnose different types and subtypes of cancers in ways that augment and extend those found by more traditional pathology-based methods. Such information also provides vital fundamental knowledge about how normal cellular processes are altered during tumor development. “Cancer is essentially cell replication run amok,” said Laderman. There are 46 chromosomes in the human somatic cell. The genomic DNA copy is stable in most diseases, such as cardiovascular disease, diabetes and neurological disorders. But human breast cancer, for instance, has been shown to derive from multiple genome-wide chromosome aberrations, including copy number changes and rearrangements.

Proteomics is another promising application area. The technology of protein arrays is rapidly evolving and offers a potentially rapid, specific and sensitive method for quantitative identification of a set of known target proteins. The technique has similarities and common elements with the technology based in DNA arrays, and is an evolutionary extension of Agilent's current position in microarrays.

Further afield in the development process is the application of polymer microfluidics for chemical analysis. According to Kevin Killeen, Manager of Microfluidics and Sensors at Agilent Laboratories, microfluidics is a critical aspect of Agilent's ongoing efforts to develop tools to enable a comprehensive understanding of systems biology, or “systemomics,” by gradually making sustained progress in genomics, then transcriptomics, then proteomics, and finally metaboliomics. Agilent is developing a new generation of microfludic “chips” that can perform specific chemical and biochemical analyses useful for proteomics research and drug discovery.

These chips are based on chemically resistant polymer materials (such as polyamide) that can perform multiple steps of sample preparation, followed by chemical detection using mass spectrometry. Scientists pattern micron-scale fluid channels on polyimide substrates using a novel direct-write laser ablation process to create three-dimensional polymer microfluidic chips called "chip LC/MS" devices. The ultimate goal of this work is to develop low-cost, disposable microfluidic devices that have the capability to separate and analyze extremely small quantities of chemically complex samples to enable ultra-sensitive biochemical analysis. For instance, the emerging field of proteomics is concerned with understanding large numbers of proteins in complex biological samples. Combined with genomic and metabolic profiling, it potentially provides a key piece of the puzzle in formulating a systems view of biology.

Subsequent speakers broadened the session's scope by providing a preview of the next generation of technologies looming on the horizon. Jene Golovchenko, the Gordon McKay Professor of Applied Physics at Harvard University, discussed his ongoing work in science and technology with solid state nanopores. The goal is to develop a solid-state detector for rapidly identifying and characterizing single biomolecules with nanoscale resolution, focusing in particular on the DNA molecule. Cell walls have natural conduits, or pores, to control the flow of ions, nutrients, and waste products into and out of the cell. Some of these pores are so small that only one molecule can pass through at a time. DNA can be made to pass through such a pore and also through synthetic pores produced by silicon micromachining technology. Golovchenko has collaborated with Agilent and others to explore the potential to "read" the chemical composition of DNA or RNA strands as they pass through a synthetic pore, one base at a time.

Although earlier studies have used biopore detectors, solid-state nanopores have the advantage that scientists can choose their diameters. Solid-state nanopores are also more physically robust and could be used at high or low temperatures, and under voltage and pH conditions that would destroy biopore-membrane systems. Golovchenko's solid-state nanopores provide a new way of studying the folding and pairing configurations of single long-chain molecules, the differences between chemically identical molecules in a statistical ensemble, and induced changes in molecule structure. The scientists next plan to add electrical contacts to the nanopores, a feature that should enable techniques such as electronic tunneling and near-field optical studies of molecules as they pass through the nanopore for analyzing DNA molecule configurations.

Nobel Laureate Steven Chu, Professor of Physics and Applied Physics at Stanford University, presented the latest results from his research on the ribosome. He opened by addressing the question of why physicists should be interested in studying biology. First, the frontiers of physics lie in the very small, the very large, and the very complex, and biology is very complex. Molecular systems in biology also provide clever engineering solutions to things at the nanoscale. "Most of what we know about in chemistry and biology has been determined by bulk studies, but what if we missed something?" he said. "What can we learn by looking at one molecule at a time to gain a better view of things?" In the early 1990s, Chu pioneered the laser manipulation of atoms and particles (such as single molecules of DNA), which led to key fundamental experiments in polymer studies and single molecule motions, and is now being adapted to explore the mysteries of the RNA transcription process.

In the central dogma of biology, DNA goes through a transcription process to produce RNA, which then becomes messenger RNA (mRNA). This in turn is translated into sequences of amino acids to form proteins. A ribosome is a cellular organelle made of protein and RNA. Transfer RNA (tRNA), enters the ribosome, and goes through a process of matching its codon (a sequence of three nucleotides that codes for a specific amino acid) with complementary nucleotides in the mRNA. As the mRNA indexes through the ribosome three nucleotides at a time, a protein is built up, one amino acid at a time. But this only happens if all three tRNA nucleotides make correct bonds. Biologists are still puzzled by how the correct amino acids are selected to form proteins, but Chu believes it is mostly shape discrimination (also known as steric recognition) that enables the correct base pairs to find each other.

The session closed with a fascinating talk by Elias Greenbaum, a Corporate Fellow at Oak Ridge National Laboratory, on how isolating the chlorophyl-containing protein centers from spinach leaves might be useful in restoring sight by replacing a key light-receiving part of the human eye that has lost its ability to function. The research is particularly applicable to those who suffer from age-related macular degeneration (AMD) or retinitis pigmentosa (RP). AMD affects center vision via the macula, the center of the retina. RP is an inherited condition where the rods degenerate, making it difficult to see in dim light and gradually reducing peripheral vision as well.

Although the neural wiring from eye to brain is intact in people with these diseases, their eyes lack photoreceptor activity. Greenbaum is replacing these inactive photoreceptors with a photosynthetic spinach protein reaction center called Photosystem I (PSI). The main function of PSI is to perform photosynthesis by acting like miniature photovoltaic devices, absorbing sunlight and generating small but measurable voltages across spinach cell membranes. It takes five-trillionths of a second for one PSI to turn sunlight into electricity, roughly 100 times faster than with a silicon solar cell. It has been demonstrated experimentally that if retinal tissue is stimulated electrically using pinhead-sized electrodes implanted in the eye, many patients can perceive image patterns that mimic the effects of stimulation by light. So Greenbaum suggested that because PSI proteins can capture photon energy and generate electric voltages of about 1 volt, they could be used to restore photoreceptor activity. This has been successfully tested in both retinoblastoma cells and rabbit retinal progenitor cells, and amounts to “artificial sight.” Most recently, Greenbaum and his collaborators have demonstrated that PSI reaction centers could be incorporated into a liposome, an artificial membrane made of lipids that mimics the composition of a membrane of a living cell.

> ***The life sciences have benefited greatly from advances in physics in the past, and are now poised to return the favor. Physicists are***

drawing on biological models and processes to build better, more efficient, and smaller devices, and to learn more about the inner workings of complex systems.

LABORATORY TOURS

Following the theme session lectures, conference participants were treated to a laboratory tour to see first-hand the various research activities and facilities provided at Agilent Laboratories. The tour included demonstrations of Agilent’s DNA microarray technology described in the theme session, as well as the emerging polymer microfluidics technology for proteomics and nanopore detection. Other labs focused on Agilent's development of high-resolution lightwave spectral measurements; measuring distortion and noise in signals; high-speed optical interconnects; root cause analysis of routing anomalies; solid shape modeling and 3D surface reconstruction with a single camera and multiple light sources; building faster analog-to-digital converters; and building a MEMS micromover with potential application as a tunable optical device. Agilent is also involved in research on photonic crystals, the subject of a talk in the “Frontiers in Physics” session (see below). The day closed with a reception and banquet at the San Jose Museum of Art. After the banquet, the 2003-2004 AIP Prize for Industrial Applications of Physics was presented to Rangaswamy Srinivasan, formerly at IBM and now with UV Tech Associates, for “discoveries, inventions, and promotion of ablative photodecomposition for medical and materials applications.” Perhaps the most renowned applications of his work lie in technological advances in laser surgery. James Bellingham, director of engineering at the Monterey Bay Aquarium Research Institute, gave a presentation on so-called “autonomous underwater vehicles” (AUVs), a field that employs remote-controlled robots to explore the mysteries of the ocean.

POLICY SESSION:
INDUSTRIAL R&D IN A RAPIDLY CHANGING WORLD

Kicking off the morning policy session, E. Floyd Kvamme, a Partner Emeritus of Kleiner Perkins Caufield & Byers, and co-chair of the President's Council of Advisors on Science and Technology Policy (PCAST), addressed the topic of “Can Silicon Valley Rust?” Turning the concept on its head, he contended that yes, it can rust, and that from his perspective, this was a good thing. Rust, he explained, is the result of steel, oxygen and water, and he built the rest of his talk around rust as metaphor. The “steel” of Silicon Valley is the basic infrastructure of the industry, which has transformed daily life around the globe, in virtually every market sector, simply by replacing mechanical parts with silicon-based technology.

Oxygen represents new and innovative ideas. In its heyday, said Kvamme, Silicon Valley encouraged risk-taking and innovation, fostering an entrepreneurial culture that particularly appealed to young people. “The 20-somethings didn’t know it couldn't be done," he joked, and encouraged industry leaders to continue to "watch the 20-somethings" for the next wave of ideas. He also made a plea for maintaining strong university programs to keep producing bright young people for the technological workforce of tomorrow. The water in the rust equation represents liquidity and capital. "Small companies are job creators," he said, and spoke out against recent Congressional decisions that he believes work against job creation by raising the costs of going public, in the wake of the Enron and WorldCom scandals. This is particularly critical in light of increasing competition from overseas. Kvamme recently spoke with a representative from a Taiwanese high-tech company who was eager to hire 10,000 technical workers in that country, at a time when many U.S. companies are instituting hiring freezes or cutting jobs.

According to the next speaker, Thomas Saponas, Chief Technology Officer of Agilent Laboratories, by 2000, the electronics industry accounted for 5% of the U.S. gross domestic product, and 25% of the total material goods market. "It's become so big that growth is more of a problem," he said. However, while the so-called "Moore's Law" (www.webopedia.com/TERM/M/Moores_Law.html) is undeniably slowing and will one day reach its limit, new technology will not be the dominant factor in the future of the electronics industry. He believes a cyclical recovery is now underway. For example, there are alternatives to standard CMOS scaling that could maintain the price/performance ratios in the computer industry, even though some are further afield in terms of practical devices, such as biocomputing, quantum computing, and spintronics. The current slowdown actually began in 1995, and Saponas admits that there is some commoditization occurring in the industry, resulting in thinner profit margins and less capital for R&D. "We've built up a fixation that growth relies on further technological improvements," he said. "But a stall in technology does not necessarily mean a stall in the industry."

He believes that the electronics industry can enjoy many more years of market opportunities at present chip densities because the development of applications is a long way behind those advances, given the dramatically lower power and costs for computing, particularly in the wireless and fiber optic communications sectors. Along with communications, information technology and transportation are the major market sectors for the electronics industry. But there is also agriculture, healthcare and energy, which combined represent a $1.7 trillion untapped future market. For example, in healthcare, many solutions require minimized skilled labor and gaining more accurate diagnosis and treatment through the use of low-cost sensors for self-treatment. The medical industry is notoriously conservative about adopting new technology, but Saponas feels it will represent a major market opportunity over the next 50 years. In the energy sector, a significant upgrade to transmission is long overdue, since the industry is plagued by antiquated equipment.

Solar cells and solid state lighting are other potential energy applications that could be viable within the next decade.

New technology is not the only recipe for growth, even in high-tech industries such as Silicon Valley. While Moore's Law is undeniably slowing, there is still room for substantial growth in the electronics industry by targeting as-yet-untapped potential markets in the agricultural, health care and energy sectors.

For many experimental scientists, scientific progress and research quality are strongly linked to computing throughput, namely, how many floating operations per month or year they can extract from their computing environment. A solution lies in high-throughput computing (HTC), according to Rick Lytel, vice president of the Advanced Systems Development Center of Sun Microsystems. Lytel believes that big innovations are coming in terms of systems design, thanks to numerous converging trends, including exploding processor complexity, memory and IO bottlenecks, and increasing transistor density and capacity. HTC uses available networking and computing environments to perform the same tasks in a comparable time frame, but without the substantial investment in dedicated hardware. In a typical enterprise, workstations can be idle for 75% of each workday. HTC tools manage this unused time in a dynamic cluster configuration to run the same applications as a high-performance computing cluster. There is new software for networking computing that is especially "thread-rich" [a "thread" is the process state plus the execution units]. Transistor density continues to double about every 24 months, and memory has not kept pace with the scale-up rate of processor speeds and densities, so memory bottlenecks are a frequent occurrence. "We need to develop thread-level parallelism as part of the solution, and make more throughputs to overcome the memory bottlenecks," he said.. Thread-level parallelism can result in close to 100% utilization rates, taking full advantage of processor speeds by overcoming memory bottlenecks.

Hans Coufal, Manager of Science and Technology at the IBM Almaden Research Center, opened by describing the earliest forms of punch card machines, to which modern computing was added. IBM's first electronic calculator was introduced in 1953 and took up an entire room, compared to today's handheld technology. Dimensions in lithography continue to drop, enabling chip manufacturers to etch smaller features using shorter wavelengths, but there are fundamental physical limits to the scaling recipe. Oxide thickness is approaching the range of a few atomic layers, thin enough to give rise to quantum tunneling effects, and there are also power density limits and rising cooling requirements. "Integrated circuits have gone on longer than any previous technology, and they are overdue for replacement," Coufal declared. IBM's current strategic thrusts include physical science R&D, developing serves and embedded systems, storage systems, services, and most recently, software. It is also exploring potentially disruptive technologies. The goal, said Coufal, is "better performance without scaling by thinking outside the box." Among the areas being explored are low-K dielectric materials; silicon-on-insulator configurations to address issues of mechanical stability; and strained silicon CMOS solutions. Nanotechnology, organic electronics, spintronics, quantum computing and DNA computing, while further afield, could also provide unconventional extensions to existing computation technology.

AIP Project to Preserve the History of Physics in Industry

Spencer Weart, Director of AIP's Center for History of Physics, and Associate Director Joe Anderson described a new three-year project to create a framework for identifying and preserving the historical record of physicists in industry. They said that although American's economic leadership rests on a century of industrial research and technological innovation, efforts to document and study this rich history are surprisingly narrow in scope. This has severely limited the ability of scholars to explore one of the most vital sectors of the modern economy. The Center is carrying out the first systematic investigation of records-keeping practices and needs in America's high-technology industries.

The project will survey paper and electronic records and conduct interviews with creators of the records at a sample of 15 of the 25 high-tech companies that employ the largest number of physicists working in American industry, supplemented by full autobiographical interviews with at least 15 leading industrial physicists. The target companies are 3M, Boeing, Corning, Eastman Kodak, Exxon Mobil, General Atomics, Hewlett Packard, Honeywell, IBM, Lockheed Martin, Lucent Technologies, Raytheon, Texas Instruments, and Xerox. The project will also identify and catalog laboratory notebooks and other source materials, and will study the few existing public and private archival programs that document industry in the U.S. and Europe. To date, the AIP team has visited eight corporate laboratories and completed interviews with 43 leading managers and scientists as well as 18 information professionals. Ideas and information about endangered records would be welcome; please contact Anderson, janderso@aip.org.

Frontiers in Physics Session

Jody Deming, Professor of Biological Oceanography and Astrobiology at the University of Washington in Seattle, opened the frontiers in physics session with a talk about so-called "extremophiles": microbial life forms that live in extreme circumstances and environments by keeping their morphology and reproductive cycles very simple. Deming and her colleagues use so-called FISH probes (Fluorescent In Situ Hybridization) to study these primitive life forms all the way down to the micrometer scale. Of particular interest are the microbes that inhabit extremely cold environments, such as Arctic sea ice. Sea ice serves as a habitat for an ice-specific food web that includes bacteria, viruses, unicellular algae and invertebrates small enough to traverse the brine network. Studying how they survive in extreme conditions has become a very active research field in astrobiology, which is concerned with the effects of extraterrestrial environments on living organisms. Wintertime sea ice is considered analogous to the possible extraterrestrial habitats on solar bodies such as Mars, Europa, Ganymede, and Titan. Hence this research has important implications for the possibility of extraterrestrial life forms.

Microphotonics is another exciting research area at the physics frontier, according to John Joannopoulos, the Francis Write Davis Professor of Physics at the Massachusetts Institute of Technology. Photonic crystals are materials consisting of a periodic variation (in 1, 2 or 3 dimensions) in the dielectric constant. While such materials are typically not found in Nature (butterfly wings are one exception), scientists can artificially create the variation by etching holes into a uniform dielectric material. For example, one can create a nearly perfect mirror for certain optical wavelengths by etching holes into silicon or indium phosphide. Devices such as waveguides, couplers/splitters, resonators and prisms can be manufactured simply by changing the size of a few holes in the periodic photonic crystal fabric. By carefully utilizing their inherent wavelength dispersive properties, photonic crystal devices can be used in conjunction with more conventional refractive index guiding devices to build compact photonic integrated circuits for use in optical interconnects or optical sensors. Another possible application centers on the newly discovered "left-handed" materials, which have a negative refractive index. This makes it possible for scientists to use photonic crystals to get a negative refractive index at the optical regime, leading to the creation of a "super lens." He and his colleagues are currently using photonic crystals to build other devices, such as a novel channel-drop microfilter for telecommunications; a prototype device is currently being tested by scientists at Clarendon Photonics, a start-up company in Newton, Massachusetts. "Something great must come of this," said Joannopoulos, comparing the discovery of photonic crystals to the invention of the laser, which initially had few applications and is now ubiquitous in our everyday lives.

Three-dimensional quantum biomicroscopy has the potential to transform molecular biology into a truly observational science, according to John Sidles, a professor in the School of Medicine at the University of Washington in Seattle, who described progress in developing this new field of instrumentation. The roots of the challenge can be traced all the way back to Linus Pauling, who was the first to lament the inherent limitations of the electron microscope. "Traditional microscopy has a vast scope and very frustrating limits, particularly for biologists," said Sidles, since current resolutions skip over the scale regime of most interest to them. However, "Higher resolution is associated with shorter wavelengths, but biomolecules are much too fragile" to survive exposure to those wavelengths.

Improving the basic technology is very much an interdisciplinary field, and physics has contributed many enabling breakthroughs, including scanning probe microscopy and quantum mechanics. Engineering has contributed the notion of scaling ["Smaller is better"], while biology is supplying the problems to be studied in the form of genomics, proteomics, and ultimately, systems biology. Sidles and his colleagues are drawing on another physics workhorse, nuclear magnetic resonance, to develop what he terms “radar for molecules.” Known as magnetic resonance force microscopy (MRFM), the technique combines force microscopy with Moore’s law of scaling and magnetic resonance imaging, which is a three-dimensional, non-destructive technique that allows in situ imaging of biological matter. Practical bioimaging is just one of the targets Sidles and his colleagues hope to hit. For instance, IBM’s Dan Rugar and Stuart Wolf are developing a scanner which is approaching single-spin MRFM in terms of resolution. And Sidle’s UW team has just joined the LIGO collaboration in hopes of making key advances in end-to-end analysis by drawing on the project’s collective expertise in gravitational waves, interferometry and quantum microscopy.

Don Eigler, an IBM Fellow at the IBM Almaden Research Center closed the session by describing his work is the use of molecule cascades for future computation, the practical realization of which he admitted was very far in the future. In this innovative approach, individual molecules move across an atomic surface like toppling dominos. The circuits are made by creating a precise pattern of carbon monoxide molecules on a copper surface. Moving a single molecule initiates a cascade of molecule motions. The scientists then designed and created tiny structures that demonstrated the fundamental digital-logic OR and AND functions, data storage and retrieval, and the “wiring” necessary to connect them into functioning computing circuitry. What enables computation is that each cascade carries a single bit of information; a cascaded or non-cascaded molecular array can represent a logical “1” or “0”, respectively. The most complicated circuit he and his team have built to date is a 12 x 17 nanometer three-input sorter logic circuit. Unfortunately, it is 10<12) times slower than if the same circuit were using CMOS, although the area is 260,000 times smaller and it uses approximately 100,000 times less energy per cycle.

> ***The Frontiers in Physics session aptly demonstrated how interdisciplinary research to the interfaces of biology, physics, and other scientific fields could one day lead to revolutionary advances in both fundamental science and practical applications.***

The 2004 Industrial Physics Forum will be hosted by IBM T.J. Watson Research Center in Yorktown Heights, NY, October 24-26, 2004, focusing on the theme, Physics & Information Technology.

2003
ACADEMIC-INDUSTRIAL WORKSHOP
"Cultivating New Scientists through Undergraduate Research"
A Pre-Conference Workshop of the Industrial Physics Forum

October 26, 2003, San Jose, California

Approximately 45 participants representing research careers in academia, industry and federal facilities gathered on October 26th, 2003, in San Jose, California, for the 2003 Academic-Industrial Workshop, held in conjunction with the annual Industrial Physics Forum of the American Institute of Physics (AIP). Jack Hehn, Director of Education at AIP and workshop host, welcomed meeting participants and put the meeting in context. The workshop was intended to stimulate dialog between industrial and academic leaders on subjects of mutual importance to them, and to the physics community as a whole. There were two main thrusts to the day's discussions on cultivating new scientists through undergraduate research: what constitutes a "thriving" academic physics department, and the value of the undergraduate research experience to students, with an overall emphasis on the evolving undergraduate program of study that transforms a student into a scientist and a member of the professional scientific community.

The day was organized into two sessions, each followed by a roundtable discussion concerning the issues raised by the speakers and smaller breakout group discussions. Since one of the principal goals of the workshop is professional networking, the subsequent small group discussions are designed to encourage interaction among the participants as they each offer their personal expertise and experience with regard to several aspects of the research enterprise, and to glean new insights from this exchange of perspectives.

EXPLORING THE ROLE OF PHYSICS DEPARTMENTS

The first session focused on the role of physics departments in the development of undergraduate students. Robert Hilborn of Amherst College opened with a brief summary of the findings of the Strategic Programs for Innovations in Undergraduate physics (SPIN-UP) project, organized by the National Task Force on Undergraduate Physics (NTFUP), co-chaired by Hilborn, Ruth Howes (Ball State University) and Kenneth Krane (Oregon State University). The study team visited 21 "thriving" undergraduate physics departments—i.e., departments that increased or maintained their number of undergraduate physics majors in the midst of substantial declines nationwide, beginning in 1985. Careful attention was given to mixing both the type of physics departments and their geographic distribution. Ultimately, the purpose of the site visits was to discover the common elements to their success.

Why is undergraduate education so important? Hilborn contends that it serves as a critical bridge between high school and any number of future career directions, from graduate school or K-12 education, to any number of careers in the science and technology sector, as well as academia and government laboratories. "A physics program is not just coursework," he said. It also incorporates recruitment, advising and mentoring students; engaging students in research; providing appropriate and excellent curriculum; building a sense of community; and informing and preparing students for diverse careers. The department itself is a critical unit for fostering change at the undergraduate level. "All reform is ultimately local, and one size does not fit all," said Hilborn. "And the process of 'revitalization' is never finished."

The SPIN-UP team defined the criteria for a "thriving" undergraduate physics department as one that has strong and sustained departmental leadership, along with a well-designed sense of mission and strong recruitment and retention of physics majors. The latter includes having challenging and supportive programs and solid courses; providing career information, especially through contacts with alumni as examples of successful role models; strong introductory courses; mentoring; multiple tracks and options for tailoring individual degrees to each student's specific needs; and offering research experiences for undergraduates early and often to help them become part of the active physics community. There should also be an emphasis on the entire program of the department, including interdisciplinary interactions with other departments, and social events have proven to be just as important an element of a thriving department. "It's basically evolution in action," said Hilborn of the need for widespread undergraduate reform. "Some species die out, others adapt. Physics needs to adapt."

The next activity for NTFUP is exploring diversity issues, aimed particularly at discovering the most effective means of increasing the number of women and underrepresented minorities in physics. They will also work with physics departments to build upon the SPIN-UP analysis, working with funding agencies to develop programs to enhance undergraduate efforts in science, math, engineering and technology. Finally, while two-year colleges were not included in the final SPIN-UP report, Hilborn said that this will be the subject of an NSF-funded spin-off study, because two-year colleges have a very different structure than their four-year counterparts. Ten site visits will be conducted, with a report due at the end of 2004.

Roman Czujko, Director of AIP's Statistical Research Center, provided an overview of the findings of a recent survey of undergraduate physics programs in the U.S., included in the SPIN-UP report. The online survey polled department chairs about their physics courses and curricula, including credit hours, alternative tracks, and undergraduate research opportunities, as well as their recruitment efforts for physics majors, the interactions between faculty and students, and the involvement of alumni. Although the news from the survey is encouraging—after nearly two decades of decline, the number of physics majors has begun to increase slightly in the last few years—there are 95 physics departments with two or less majors. About 86 departments boast 25 or more majors, while 25 awarded no physics bachelor's degrees at all in the last three years combined.

In addition to an overall rise in enrollment, the physics curriculum has grown more varied as schools have moved away from a one-size-fits-all approach. For instance, there has been an increase in conceptual physics classes, which are less math-intensive than standard calculus-based courses. The percentage of students who take conceptual physics classes has increased to 21% from 18% in 1997, while only 13% of students take an accelerated or honors first-year physics course, and 11% sign up for advanced placement or second-year courses. Above all, said Czujko, "Physics is small; the number of new fields is growing rapidly and physics in general is becoming more interdisciplinary." In fact, the options available are growing faster than the student body, and thus physics departments need to be much more proactive in their recruitment efforts, particularly through fostering connections between students and faculty.

Ken Krane of Oregon State University built on Hilborn's and Czujko's remarks by providing more details from the SPIN-UP report. Among the findings is an "impressive uniformity" in the physics curriculum nationwide, although whether this is an advantage or disadvantage is still subject to debate. However, in addition to the standard degree program requirements, colleges and universities are increasingly providing alternative physics degree tracks and a greater diversity of physics curricula to include such options as earning a complementary teaching degree, combining degrees, or specializing with a degree in a prominent subfield, such as geophysics. According to Krane, departmental efforts do not seem to correlate recruitment efforts directly with the number of physics degrees awarded, which proved to be a fairly random distribution. Nor do departments invest much money in active recruitment efforts.

Nonetheless, some recruitment approaches have proven to be more effective than others. Pulling physics majors out of introductory courses is the most successful recruitment activity. Thriving departments seem to offer a variety of informal interactions between professors and students, which Krane said were the most important for "shaping students' attitudes towards the department. The greatest strength is individualized attention from faculty to students, and that is not always a formalized process." Healthy departments also tend to emphasize undergraduate research opportunities and experience. There, the objective should be to get students interested and excited about a project, even if the research they conduct is not immediately publishable. "Students need to feel ownership with a project, so sometimes smaller can be better," said Krane. The greatest needs and challenges currently facing physics departments cited by respondents were the need to continue increasing the number of students majoring in physics, adding additional faculty members, and acquiring improved laboratory equipment and space. Increasing minority representation was not cited as a high priority, which Krane found "surprising and discouraging."

His points were aptly illustrated by two case studies. Paul Leath spoke of his experiences chairing the physics department at Rutgers University, one of the "thriving" departments included in the SPIN-UP report. The university as a whole boasts about 26,000 undergraduate students, and his department (comprised of 65 faculty members) graduates roughly 40 physics majors per year, and has ranked sixth in the nation for the last three years in production of physics PhDs. He attributes the department's success to the availability of multiple physics major options, and a strong honors-level introductory physics sequence (required for engineering majors, among others) from which the department draws most of its majors. Undergraduate participation in research is strongly encouraged, and there is a centralized advising structure and a number of endowed physics scholarships, internships and prizes. There is also a very active chapter of the Society of Physics Students that organizes social activities such as field trips, guest speakers, and an annual student/faculty awards banquet, all of which help foster a strong sense of community within the department.

Among the multiple major options offered by the Rutgers physics department is a "professional" track, intended to provide excellent preparation for graduate studies and a subsequent career as a PhD physicist. However, this branch has the lowest growth rate. There is also a new astrophysics major aimed at preparing students for interdisciplinary careers in astronomy and astrophysics; an applied option to prepare them for industrial careers; and a five-year dual degree program with the engineering department. But the department has seen the most growth in its general degree option, which prepares students for high school teaching, medical studies, law, journalism, or business. Students can thus tailor their degree to their individual needs; one reason the program is now the largest in the department.

Elizabeth McCormack then described the physics department she chairs at Bryn Mawr College, a very different kind of department from Rutgers, but the conclusions of the SPIN-UP report nonetheless still apply. Bryn Mawr's undergraduate physics program features a highly research-active faculty who encourage student participation in their activities. All incoming freshmen are given a tour of all the laboratories, and students are encouraged to pursue summer research positions. There is a strong emphasis on building a sense of community and inclusiveness, and on promoting diversity, fostering not just future PhD physicists but also liberal arts physics majors. There are field trips and conferences, and invited talks by alumni.

McCormack identified six key elements of Bryn Mawr's success: the use of effective physics pedagogy (i.e., focusing on how students learn physics); ample laboratory time and early research opportunities for undergraduates; developing a rigorous yet flexible curriculum for physics majors; employing "interventionist" student advising (including both formal and informal mentoring); fostering an inclusive physics community; and offering inclusive introductory physics courses which recruit rather than filter out prospective students. "The introductory course should be a pump, not a filter," she said. "Real growth comes from identifying students interested in physics and science who don't necessarily realize it's a viable career." Such courses should therefore be taught by the best teachers in the department, on a rotating basis to ensure the program is robust and not dependent on any one individual.

The question of attracting women to physics was among the issues discussed during the panel discussion that closed the session. Bryn Mawr has ranked as high as third in the nation among all schools in the number of female students who go on to earn PhDs in physics, so McCormack was able to offer some useful insights. For example, female students tend to thrive more in cooperative academic and industry settings such as Bryn Mawr, rather than in highly competitive environments. She emphasized that what works for attracting women should work for all students, regardless of race or gender. "It all comes down to whether physics as a career can meet student needs and create a desirable lifestyle for them," she said. While much has been done to alleviate the so-called "cold climate" of mostly male physics departments since the early 1970s, "We haven't really grappled with the lifestyle issue yet." Nor does retaining women and minorities rank among the top ten most pressing needs for colleges and universities, despite the fact that they represent an enormous untapped resource.

After splitting into breakout groups, workshop participants discussed the need for changing the emphasis of PhD programs from the traditional basic research career track, suggesting that department chairs need to foster and maintain contacts with local industry to tailor their programs to industry needs. Industry also provides a good source of research-oriented internships. As for reforming the curriculum itself, most agreed that major overhauls were not necessarily required. One could simply incorporate applied physics problems (such as those faced by the fiber optics industry) as tie-ins to the classical physics material. Finally, diversity and integration is essential. It was, after all, a physics bachelor who invented the ink-jet printer.

A successful undergraduate physics department excels at more than just coursework, and can be a critical component in fostering lasting change. Mentoring, undergraduate research opportunities, career development, and community building are all important elements of a thriving department.

BROADENING EDUCATION:
THE ROLE OF INDUSTRY AND GOVERNMENT

The second session focused on the role of industry and government in broadening the educational experience. Sandra Harpole, Associate Vice President of Research at Mississippi State University (MSU), and Director of the University's Center for Science, Mathematics and Technology, opened the session by describing her experiences directing a number of NSF projects for teacher preparation and teacher enhancement. As a former physics teacher, Harpole knows first-hand the difficulties teachers face, and brings that perspective to the programs in which she participates. She currently heads an NSF-funded effort to provide teachers with real-world experiences in industry, in cooperation with Peavey Electronics Corp.

This in turn has led to a Research Experience in Industry (REI) grant from The National Science Foundation (NSF) to expand the program to include partnerships with Northrop-Grumman, the Tennessee Valley Authority, and the Red Hill Minds. Teams of grades 7-12 teachers in science, math and technology participate in three-day internships in local industry, which also includes 60 hours of mentoring and a four-week summer workshop, three of which are spent in the partner industry. Participants learn workforce skills and values and are subsequently able to apply those experiences in their classrooms. Harpole also leads another NSF-funded project that pairs middle school teachers and students with research scientists who are working to improve water quality in the Mississippi Delta. Benefits to industry partners include having long-term impact on education, while students have the opportunity to learn about career opportunities and to develop competencies and valued skills in the workplace.

Charles Wade, Manager of Scientific Services at IBM Almaden Research Center, described his company's involvement in a series of ten-week summer internships sponsored by NSF Grants for Academic/Industrial Partnerships. Students work directly with research scientists in academic or industrial settings on projects spanning basic science to applied technology. There are weekly special seminar series on research frontier topics and other activities aimed at career enhancement, as well as post-internship mentoring, which Wade believes is critical to achieving long-term benefit and success. There are also eight-week internship positions available for high school teachers. IBM Almaden boasts 400 employees actively engaged in science and technology research. Wade said that the company’s commitment to basic science is one reason for the internship program’s success, since students and teachers can work in a wide variety of subfields. Intern research projects have included developing nanostructures for sensor applications; single photon detection for eventual use in quantum computing; determining grain size in magnetic materials; developing holographic content addressable storage; optical measurement of spin relaxation in solids; and synthesis of dendritic structures.

"The benefits of such programs are legion," said Wade. Participating students gain valuable industrial research experience, which can help them in their career development planning by enhancing their professionalism and presenting various potential career path opportunities they might not otherwise have considered. Benefits to teachers include career enhancement, networking opportunities, hands-on research experience, and the interaction with industrial scientists conducting applied research helps them answer the perennial question, "Why are we studying this?" IBM also benefits, according to Wade, since research breakthroughs are only possible through combined resources and collaboration, and the internships promote vitality through a flow of energy, enthusiasm and new ideas.

> ***Internships increase industrial ties to academia and give the company access to academic talent, as well as a pool of potential future hires. In fact, to date IBM has hired 20 former interns as full-time employees.***

Punctuating the importance of undergraduate research experiences were two presentations by former summer interns of the Society of Physics Students (SPS). Justin Stimatze, a senior at California State University in Chico, CA, who is earning a triple major in physics, math and computer science, spent the summer of 2003 at the National Institute of Standards and Technology in Gaithersburg, MD. At NIST, he worked on numerical modeling of metal-oxide semiconductors, a project that formed the basis of his senior thesis. In the process, he learned about basic semiconductor physics, particularly the capacitance-voltage characteristics useful for measuring types of chip defects, with the objective of further refining manufacturing processes and increasing chip yield by eliminating defects. Thanks to his strong background in math and computer science, he recoded the entire existing computer model into standard ANSI C++, improving the program's execution speed, structure, and information flow. The simulation driver is now complete and is being actively used by researchers, and he also redesigned the graphical interface for easier use. "It was an incredible opportunity to gain practical hands-on experience in a modern field of applied physics, and to work with motivated and enthusiastic scientists to make a useful contribution to their ongoing research," he said, in addition to experiencing the culture and history of the Washington, DC, area.

Lauren Glas spent the summer of 2002 as an intern in the SPS national office at the American Center for Physics in College Park, MD, choosing a more unusual emphasis on physics outreach. Now a physics teacher at Simmons High School in the Mississippi Delta, Glas worked on a project called the SPS Outreach Catalyst Kit (SOCK), which is filled with useful materials for teaching basic physics concepts to children of all ages. She worked on a SOCK titled "Dimensions in Physics," containing foam shapes that can be used for scaling exercises—illustrated with clips from the popular film "Men In Black," among other tools—as well as rainbow glasses to demonstrate how light bends. The various SOCKs are currently under assessment. To date, SOCKs have been used by over a hundred undergraduates to deliver educational workshops to over a thousand K-12 students. "I can't wait to incorporate what

I've learned into my own lessons this year," said Glas of the lasting impact of her internship experience. "I expect my students to learn to problem solve and to realize that physics is everywhere, even if they don't major in it. Everyone can do physics."

Undergraduate research experiences are vital components of the educational process, providing the opportunity to interact with scientists in both industry and government laboratories, and to gain broad first-hand knowledge about available career tracks.

BREAKOUT GROUPS: CONSENSUS AND SUMMARY

At the end of each session, participants split into small breakout groups. While responses varied from group to group, there was general consensus on numerous issues. A shortage of mentors was a major concern; many faculty are burdened with widespread university budget cuts and overloaded courses, and simply do not have time to actively assist students in chasing down internship opportunities or other undergraduate research prospects. Gary White, who heads the SPS internship program, said this model has proven to be very successful. It provides a centralized internship "clearinghouse" and acts as an intermediary between industry and academia, matching students with researchers based on skills and interests. The SPS/AIP program also handles day-to-day practical details such as paperwork and living arrangements for the interns.

It was also concluded that physics departments must begin to recognize the many paths taken by undergraduate physics majors, and to encourage the involvement of more women and minorities, the latter of which, as several speakers pointed out, is not among the top priorities for most university administrators. This brought out the role of the institutional ethos in fostering change. Participants also felt that departmental and university-wide missions should be more effectively aligned.

Finally, participants discussed the question of what attracts people to physics in the first place. There is a strong tradition of "tinkering" among physicists, often emerging while they are still young children, naturally inquisitive, with a tendency to take things apart. How can we re-establish this concept of play, which seems to be lacking in the current generation of students? One approach is the use of toys to demonstrate basic physics concepts, such as The Tinkerer's Workshop [www.tinerereswork-shop.org], formed by Agilent and several other partners to enable students to play with hands-on experiments before learning theory. This has been shown to be an effective pedagogical approach.

The fifth annual Academic-Industrial Workshop will be held in Rye, NY, on October 24, 2004. The discussion involves the impact of student performance accreditation standards on engineering education.

NOTES

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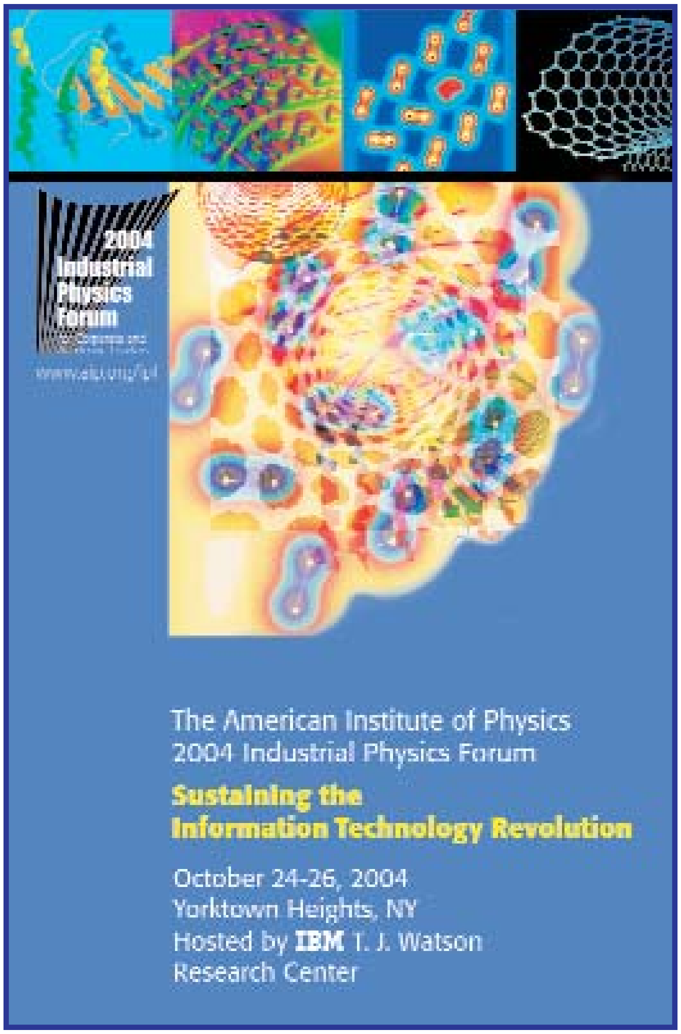

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