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ABSTRACT

The National Science Foundation (NSF) workshop on Optical Science and Engineering was organized to examine approaches NSF could use to identify opportunities in optical science, engineering, and education that meet both the mission of NSF and its broader national goals. The workshop participants identified opportunities where optical science and engineering research conducted by small interdisciplinary teams of investigators would significantly accelerate progress in areas of interest to the nation including the national information infrastructure, biology and medicine, chemistry and physics, materials processing and manufacturing, and education. This report contains: (1) an executive summary; (2) an introduction to the workshop and it's organization; (3) basic findings and recommendations; (4) panel reports (panels include Information and Communication, Biology and Biomedical Engineering, Optical and Photonic Materials and Devices, Fundamental Optical Interactions, Optical Processing and Manufacturing, and Instrumentation and Sensing); and (5) NSF-wide initiative in optical science and engineering. (LZ)

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OPTICAL SCIENCE AND ENGINEERING

New Directions and Opportunities in Research and Education

NSF Workshop • May 23–24, 1994 • Arlington, Virginia

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OPTICAL SCIENCE AND ENGINEERING

NEW DIRECTIONS AND OPPORTUNITIES IN RESEARCH AND EDUCATION

NSF Workshop
May 23–24, 1994
Arlington, Virginia

The opinions expressed in this publication are those of the workshop participants and do not necessarily represent the views of the National Science Foundation.

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Preface

The National Science Foundation (NSF) workshop on *Optical Science and Engineering: New Directions and Opportunities in Research and Education* met May 23–24, 1994. The workshop was attended by more than 40 individuals representing many of the disciplines and application areas included in Optical Science and Engineering (see page i). The participants came from government, universities, and industry and included representatives from those involved in basic research in the physical sciences to individuals interested in the applications of Optics to communications and to advanced manufacturing.

The workshop on *Optical Science and Engineering* was organized to examine approaches NSF could use to identify opportunities in optical science, engineering, and education that meet both the mission of NSF and our broader national goals. Science and Engineering have contributed in the past and will continue to contribute in the future to the health, welfare, education, and defense of the citizens of this nation. Many of these contributions have been integrated so thoroughly into our lives that they are now taken for granted as to their invention, development, or broad application. Radios, computers, lasers, fiber optics, medical imaging, and advanced lithographic manufacturing techniques are only a few examples of ideas and technologies that derived from research and investigation by individuals motivated by the desire to understand the natural world better. The 50 years since the establishment of NSF have seen unprecedented advances in the economic well being of citizens of this country in no small measure due to the understanding and application of basic scientific discoveries.

Our nation is now in the midst of renegotiating the social contract between academic scientists and engineers and the public. This contract over the past 50 years led us to invest 1 percent of our domestic productivity in scientific research, both basic and applied. The cold war is no longer the primary justification for our investment in research, and we are striving to define a new set of principles to guide the nation's investment in research and education that meet our nation's goals. These goals include a healthy and educated citizenry; sustained economic growth; a national information infrastructure; improved environmental quality; world leadership in science, mathematics, and engineering; and national security.

Those who have had the privilege of being supported by public funds in their research have an obligation to enter into the public debate. Scientists and engineers need to identify examples that demonstrate ways research has led to discoveries that have contributed to our nation in the past and to inform the public about future opportunities for new discoveries and inventions that will benefit the nation in the future.

The goals of the workshop were to identify research opportunities in Optical Science and Engineering and to propose ways in which NSF could create a multi-disciplinary approach to research and education that would address the identified opportunities. The NSF is unique in that it has built strength at the core of many disciplines. The strength and quality of its research programs allow NSF to undertake a cross-disciplinary research program in Optical Science and Engineering with confidence that the proposed research projects will be of the highest quality.

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Optical Science and Engineering is an enabling technology—that is, a technology with applications to many scientific disciplines and with the potential to contribute in significant ways to those disciplines.

The workshop participants identified opportunities where Optical Science and Engineering research conducted by small teams of investigators from more than one discipline would significantly accelerate progress in areas of interest to the nation including the national information infrastructure, biology and medicine, chemistry and physics, materials processing and manufacturing, and education. The participants of the workshop agreed that NSF should initiate a Foundation-wide research and education program in Optical Science and Engineering that is multi-disciplinary and is motivated by national goals. In keeping with the success of the past, where ideas initiated by individuals have led to fundamental discoveries and breakthroughs, the program would seek ideas in Optical Science and Engineering from small teams of investigators and evaluate these ideas using merit review panels composed of experts knowledgeable in the disciplines. The proposed programs would include education and traineeships as an integral part of the research and would suggest ways to leverage NSF support by joint projects with other agencies, laboratories, and industry.

The proposed NSF-wide initiative in Optical Science and Engineering, which cuts across NSF directorates, is an experiment: a new approach to funding multi-disciplinary research. If adopted, the program should be revisited in five years to evaluate its success and to fine-tune elements of the program to increase its future continued success. If successful, the initiative in Optical Science and Engineering could be extended in the future to other enabling science and technology areas.

Robert L. Byer
Chair

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Introduction

The workshop on Optical Science and Engineering identified a number of critical challenges in Optical Science and Engineering that could lead to major opportunities for the programs of the National Science Foundation (NSF). The workshop determined that investments in research and education in Optical Science and Engineering across multiple disciplines are timely and that significant opportunities exist for leveraging NSF resources by supporting these investments. Moreover, the workshop determined that Optics is an enabling technology and that a multi-disciplinary initiative in Optical Science and Engineering would help meet NSF strategic areas of advanced materials processing, biotechnology, environment and global change, communications, manufacturing, and science, math, engineering and technical education. An NSF-wide, cross-directorate, multi-disciplinary research and education initiative in Optical Science and Engineering would also meet the identified national needs in biology and health; the nation's information infrastructure; world leadership in science, math, and engineering education; enhanced environmental quality; and national security.

Findings

Optical Science and Engineering is recognized as an enabling technology that will allow leapfrog advances in many fields. There are identified opportunities in Optical Science and Engineering that with timely investment will yield significant advances.

Research to address critical challenges in Optical Science and Engineering crosses disciplinary boundaries and by its nature requires informed input from several investigators. Research supported by NSF ranges from individual investigator projects to Science and Technology Centers and Engineering Research Centers. Multi-disciplinary research initiated by small teams of investigators offers a new approach to addressing problems that are in the national interest where the scale of the problem is beyond the capacity of a single investigator and yet does not require the structure and complexity of the larger-center-based programs.

Research in Optical Science and Engineering holds exceptional promise for innovations that will have impact on long-term national goals. The workshop identified opportunities in biology, chemistry, physics, materials, information infrastructure, and manufacturing that could be addressed by progress in Optical Science and Engineering.
The critical challenges to be addressed in Optical Science and Engineering will be identified in proposals submitted by the investigators. Since these proposals incorporate ideas that cut across the disciplines, the merit of the proposed research should be evaluated by panels whose members are knowledgeable in the appropriate disciplines.

The education of students in this new style of small-group research offers an opportunity to teach teamwork: a skill that is critical to the modern work force. Traineeships would allow for an exchange of visitors, scholars, and students to enhance the quality of the research further.

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To be successful in the support of cross-disciplinary research, NSF should sustain the funding for an adequate period and leverage its limited resources by encouraging cooperation with partners. There are significant advantages to be gained by forming cooperative ventures in this small-team style of research. The need for interaction across disciplines and across agencies, universities, laboratories, and industry is well recognized and should be encouraged.

The proposed agency-wide, multi-disciplinary initiative in Optical Science and Engineering is an experiment within NSF, where proposal support and evaluation is now largely discipline based. Like any experiment, there are lessons to be learned by the evaluation of the program. Criteria for success should be established, and the program should be evaluated according to these criteria.

Recommendations

Based on these findings, the workshop recommends that:

- NSF create an agency-wide, multi-disciplinary research initiative in Optical Science and Engineering,
- The proposed research in Optical Science and Engineering be evaluated by multi-disciplinary review panels,
- The proposed research be evaluated in light of long-term national goals,
- The research in Optical Science and Engineering be conducted by small teams of investigators representing several disciplines,
- The proposed research incorporate education and training as an integral part of the effort,
- The research be supported for three to five years' duration and that NSF funds be leveraged by encouraging cooperation with other agencies, laboratories, universities, and industry,
- This agency-wide, multi-disciplinary initiative be reviewed after five years and be evaluated by an established set of criteria as to its success.

Summary

The proposed agency-wide, multi-disciplinary initiative in Optical Science and Engineering builds on the disciplinary strengths of the directorates of NSF. In analogy with building a house, the individuals skilled in each discipline must bring expertise to the program and work cooperatively under a single plan to achieve a goal. A small team of investigators representing different disciplines is in many cases the best approach to solving a scientific or technical problem. This approach to cross-disciplinary research could be extended in the future to other technologies, which, like Optical Science and Engineering, are enabling.

Introduction

Workshop Goals

The goals of the workshop on *Optical Science and Engineering: New Directions and Opportunities in Research and Education* are to identify major growth areas and opportunities in Optical Science and Engineering (OS&E) within the basic research and education mission of the National Science Foundation (NSF) and to stimulate new interactions across traditional disciplinary boundaries. The goal includes consideration of mechanisms for the implementation of multi-disciplinary research and the support for such research within NSF. Any proposed initiative in OS&E must include scientific and technical education and training. Furthermore, the limited resources of NSF should be leveraged, if possible, by joint ventures with industry, government, and other research organizations. Finally, in light of the changing environment for research support, proposed initiatives in OS&E must meet both NSF strategic areas and the nation's needs and provide benefit to society.

The NSF strategic areas include advanced materials and processing, biotechnology, civil infrastructure, environment, global change, high-performance computing and communications, manufacturing, and science, math, engineering, and technical education. These NSF strategic areas reflect, broadly, the national goals of a healthy, educated citizenry, job creation and economic growth, information infrastructure, world leadership in science, math, and engineering, enhanced environmental quality, and national security.

Optical Science and Engineering within NSF

OS&E encompasses research and education that cut across the directorates of NSF. Optics is an enabling technology that has impact from astronomy, physics, chemistry, biology, and materials science to communications, information processing, storage, and display and to medicine. Optics provides a natural and visible approach to education at all levels. For these reasons, and because research in OS&E is timely and is growing in importance, OS&E was selected as the science and technology on which to focus this workshop.

Multi-disciplinary OS&E projects are currently supported within most of the Directorates of NSF: Biological Sciences (BIO); Computer and Information Science and Engineering (CISE); Education and Human Resources (EHR); Engineering (ENG); and Mathematical and Physical Sciences (MPS).

In the BIO Directorate, OS&E includes the development of high-speed charge-coupled-devices recording microscopes, refinement of two-photon fluorescence excitation microscopes, the development of time-resolved fluorescence microscopy, studies of neurobiology of perception, the development and use of optical "laser tweezers," the development of fiber-optics probes, and physiological optics and devices.

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OS&E is supported within the CISE Directorate in the areas of optics for computation, optics for communication and optical networking, computation for optics, and optics for the human interface. The support for OS&E research in CISE represents about 10 percent of the total research budget.

In the ENG Directorate, OS&E activities affect five research areas including information and communications, optical and photonic materials and devices, fundamental optical interactions, optical processing and manufacturing, and instrumentation and sensing. The total investment in research and development (R&D) on OS&E in this Directorate exceeds 20 million dollars annually, primarily through activities in the Division of Electrical and Communications Systems and the Division of Engineering Education and Centers.

The MPS Directorate includes research in OS&E primarily in the Divisions of Astronomical Sciences, Chemistry, Materials Research, and Physics. Applications of OS&E to astronomy are historically in the area of advanced instrumentation and sensors. Virtually all astronomical instruments are optical or quasi-optical in nature, including radiotelescopes. There are on the horizon opportunities for significant advances in OS&E as applied to astronomical observation including flexible mirror telescopes and correction of ground-based telescopic images using an artificial laser guide star.

The Chemistry Division supports OS&E activities at a level of 6 percent of the division budget. The activities include optical materials research, analytical and surface chemistry, organic dynamics, instrumentation, and experimental physical chemistry.

The Division of Materials Research has eight major areas in which OS&E affects the programs. These include ceramics studies, such as the synthesis of optical materials and glasses and optical coatings, and electronics and photonic materials, including semiconductors, nonlinear optical materials, epitaxy materials synthesis, and laser-beam–solid-matter interaction studies for the processing of photonic materials. Polymers, including nonlinear polymers and photoresists, are also an area of research, as are studies of the theory of optical materials. Solid-State Chemistry, Condensed Matter Physics, and Materials Research Science and Engineering Centers also include OS&E research activities. Finally, instrumentation for the evaluation of materials includes an array of optically based devices. The OS&E-related research activities in the Division of Materials Research amounted to 16.1 million dollars for fiscal year 1993.

The Division of Atomic, Molecular, and Optical (AMO) Physics encompasses the disciplines that historically have supported basic research in OS&E. With the invention of the laser in 1961, OS&E activities spread far beyond the boundaries now defined by AMO research. However, ultrafast optical science, light dynamics and force, laser cooling of atoms, and quantum optics are exciting and evolving areas of fundamental research. Many of these new research areas are less than 10 years old. They form the basis for fundamental understanding of the nature of matter and light and will, in the future, inform us about the limits of the application of light to communications and to materials control. The OS&E research in this division amounts to 11.9 million dollars, which is approximately one-half (the total division support for research.

The OS&E support across all of the directorates of NSF amounts to approximately 43 million dollars per year. The bulk of the research support lies within the Directorates for Engineering and for Mathematical and Physical Sciences. There are, however, significant opportunities for research in OS&E through the Directorates for Biological Sciences and for Computer and Information Science and Engineering.

It is clear that OS&E activities cut across the directorates and divisions and that they are a significant part of the programs with NSF. NSF, however, is organized in a vertical "stovepipe" structure that reflects the departmental organization structure of universities. The need to support the disciplines and to maintain the highest quality of research within each discipline is paramount in the university context. However, modern research often involves more than one discipline and so does not map well onto the existing directorate structure. NSF has responded to the need for coordinating research across the directorates by creating the OS&E Coordinators. The workshop was challenged to consider other approaches to support cross-disciplinary research.

Panel Organization and Challenge to the Panels

The workshop was organized into six working panels structured to include the key areas of OS&E that fall within the research and educational areas of NSF. The six panels are Optical Information and Communications, chaired by Alan Willner; Biology and Biomedical Engineering, chaired by Duncan Steel; Optical and Photonic Materials and Devices, chaired by Gary Bjorklund; Fundamental Optical Interactions, chaired by Dan Grischkowsky; Optical Processing and Manufacturing, chaired by Suzanne Nagel; and Instrumentation and Sensing, chaired by D. Lansing Taylor.

The primary goal for the first panel session was to identify critical challenges in OS&E that would lead to significant breakthroughs in technical and application areas and potentially would have significant impact on the strategic areas of NSF and on national goals. A second goal was to consider means of implementing OS&E cross-disciplinary research within NSF. Thus each panel was to identify research opportunities and then make recommendations for implementation of the research. The recommendations for implementation were to take into account the programmatic elements that would be necessary for a successful project including educational and training elements. Each panel's critical challenges and recommendations are presented in the section on Basic Findings and Recommendations.

To suggest new approaches to the conduct of research is difficult at best and in the current research climate of constrained resources is challenging indeed. Recognizing that the background and experience of the workshop participants was diverse, the workshop chair began by reviewing for the participants the structure of NSF and the national research climate.

The current structure of NSF was reviewed so that initiatives suggested by panels could account for the strengths and the weaknesses of NSF. The climate for R&D in this country was reviewed briefly so that the panel members could begin the discussion with the same understanding. It was recognized that the growth of R&D funding that took place in the early 1980s was now reduced to zero and that the country was concerned about the value it receives from investments in R&D. In the past, R&D was generally

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understood to contribute to the welfare of the nation. In the future, R&D will continue to contribute, but the justification for investment in R&D must be motivated by the long-term national needs.

The panels were asked to consider national needs as part of their recommendations regarding the critical issues in OS&E research. Any new initiative in NSF must take into account NSF strategic areas as well as the national goals. Any new initiative proposed for NSF must be compelling such that it is acceptable to scientists and engineers across the multiple directorates and divisions. It was recognized that the "bottom-up" research proposal process and subsequent merit review has been a very successful approach for determining where to invest research resources. However, multi-disciplinary research in OS&E might demand new approaches to proposing and selecting research areas to be funded. Further, it was recognized that OS&E research is by its nature multi-disciplinary and that opportunities exist for significant breakthroughs in many discipline areas. The challenge to the panels was to find a new style of research that could meet all of the above factors and could leverage NSF investment in OS&E. Cooperative models for research were to be examined in which projects might involve government labs, university labs, and industrial research labs.

The workshop was informed of the National Research Council (NRC) report on AMO Science, which was published the weekend of the workshop. Further, an NRC study on OS&E is planned for the fall of 1994. Two weeks following the workshop, the NRC and Stanford University were sponsoring the third of three regional workshops to examine the Future of the Physical and Mathematical Sciences. Thus the workshop did not take place in a vacuum, but recommendations from the panels and the workshop would be considered in the context of the broader national discussion underway.

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Basic Findings and Recommendations

Introduction

The work of the panels was at the heart of the workshop. The panels in their first meeting were to identify critical challenges in Optical Science and Engineering in their scientific and technical areas that would offer the opportunity for breakthrough advances. The panels were to report back to the plenary session of the workshop their identified research challenges and were to suggest how these challenges supported the National Science Foundation strategic areas and the long-term national goals.

The panels were also to consider the programmatic elements of any proposed initiative in OS&E. The programmatic elements were to reflect the multi-disciplinary nature of OS&E, the directorate and divisional structure of NSF, and the need to include education as an integral part of the research.

The results of the panel deliberations were presented by the panel chairs to a plenary meeting of the workshop. The discussion of the research themes and of the recommendations regarding the proposed program elements was spirited. In many cases, the recommendations of the panels were similar and overlapped in approach and intent. However, the work of the panels in the first session was open-ended so that the presentations and subsequent discussion were far ranging. The consensus of the plenary discussion was that more focus was required for a second panel meeting to move the broad ideas that had been presented to firmer ground.

A second set of panel meetings was held and focused on identifying, in a common format, prioritized critical challenges in OS&E. For this panel session, a mock "call for proposal" form was used to motivate the panel discussion. The goal of this exercise was to test the proposed NSF-wide initiative in OS&E firsthand to see that it could lead to quality proposals that offered the potential for leapfrog advances in technology. The panels, in a short time and under considerable pressure, were remarkably innovative in creating model proposals.

The panel reports contained in this section provide background and support for the recommendations put forward by the workshop. The principal recommendation that NSF create an agency-wide, multi-disciplinary research and education initiative to identify critical challenges in OS&E was unanimously adopted by the workshop. The workshop recognized the unique opportunity for research by small teams and the need for the research to be evaluated in light of national needs by a multidisciplinary panel of experts. Further, the workshop reinforced the value of the long-standing NSF practice of "bottom-up" generated research proposals and ideas and strongly supported the incorporation of education and training as an integral part of the proposed research programs. Recognizing that multi-disciplinary research undertaken by a small team of individuals often requires considerable resources, the workshop participants suggested that NSF funds be leveraged by encouraging joint research programs with other agencies, laboratories, and industry. This recommendation was not to be a requirement but to be an opportunity to enhance the success of the research effort.

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Panel Reports

Information and Communications

Alan Willner, chair

Introduction

OS&E is expected to constitute the technical foundation of an information-based United States economy in the 21st century. A major component of our economy will be the new National Information Infrastructure (NII), or Information Superhighway, as it is often called. The role of NSF, through its support of basic and applied research, is to stimulate the creation of the science and technology base required to realize the NII. A major challenge to this national goal is the provisioning of ubiquitous and intelligent user access to the NII through a user ON/OFF ramp. We believe that images and image capture, image display, image storage, and image transfer will be critical to the future of the NII.

A new research initiative in the next generation of image display, storage, and access would meet NSF strategic areas on environment, global change, high-performance computing, biotechnology, civil infrastructure, and manufacturing.

Critical Challenges

The critical challenges in Information and Communication are display, storage, and access of vast quantities of information necessary based on images. In displays, there is a need for a lightweight, robust, low-power, "paper-like" information viewer with all of the high resolution and warm and soft feeling of paper to which we have become accustomed. The multidisciplinary research challenges to achieve this "paper-like" viewer are formidable and include basic physics and surface physics research, computational mathematics, materials research, systems research, and manufacturing research. The display is of strategic importance to all areas of the NII.

Optical data storage is a critical challenge that must be met if images are to be received, handled, displayed, and transmitted on the NII. Large-scale use of images requires terabyte capacity with portability, rapid memory access, and memory correction. A possible approach to this challenge is the use of volume holographic data storage which provides parallel readout. However, nonmechanical readout and recording methods must be devised, and fundamental materials issues must be resolved. Terabyte high-speed memory, if available, would be of strategic importance in supporting large data bases, rapid information processing, and NII switching. Data storage is a huge worldwide market with tremendous national relevance. For progress in meeting this critical challenge, efforts are required in the cross-disciplinary areas of materials science, software algorithms, architecture and networks, optical communications, systems research, fundamental physics, micromechanical systems, manufacturing, and electronics.

Information transfer and switching are critical to realizing the ON/OFF ramp to the National Information Highway. The NII will rely on Optics for transmission, with advanced systems using multiple wavelengths and time domain technologies. The challenge is to increase the system performance and reduce cost by using Optics within the switches instead of converting to electronic switches. Thus high-speed switching is a critical challenge. In addition, faster switching will force reconsideration of the network architecture. A key question is how to best combine the capabilities of Optics and electronics to build networks that can be controlled, managed, and interconnected.

The research directions needed to support high-speed switching and network architecture include ultra-high-speed optical switching, portability of data transfer, broadband wireless communication, routing, control, synchronization, signaling and compression of data, and the understanding of time and wavelength division multiplexing trade-offs in data transfer. Research in these areas is enabling for the NII and requires cross-disciplinary efforts in the physics of nonlinear optical interactions, materials science, software algorithms, architectures of networks, optical communications, and system research.

With the growing use of displays, there is a corresponding need for smart sensors to take the information that is currently available in other forms and to capture an image for digital transfer. This is a critical challenge and one that, if met, would allow the collection, through multiple imaging devices, of information as diverse as a printed page or medical image.

Recommendations

A major goal of the proposed new initiative in OS&E is to leapfrog the present technology base and to lay the groundwork for leading-edge technologies for the 21st century. The proposed new initiative would address fundamental technical issues that cut across a wide range of existing NSF-supported programs. Thus the panel recommends that the research initiative be multi-disciplinary and that NSF provide for an umbrella program for strategic-driven basic research.

It is clear that the proposed research initiative spans the range from basic physics and materials research to advanced system considerations. To be effective in this type of research program, the faculty in universities must learn the needs of industry. The panel recommends that internships in industry be a programmatic element of the proposed initiative. The internships should span all levels to include faculty, graduate students, and undergraduate students. Further, NSF should provide fellowships for industry researchers to come into the university to work side by side with the faculty and students.

A research initiative must overcome the high cost of optoelectronic device fabrication and the limited resources of universities. The panel proposes an Optoelectronics implementation service similar to the Metal Oxide Semiconductor Implementation Services (MOSIS) project for university researchers to obtain access to critical devices.

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Biology and Biomedical Engineering
Duncan Steel, chair

Introduction

The goal of this proposed initiative is to address the basic scientific issues of the interaction of light with biological systems, and to develop optical methodologies for advancing the fundamental understanding of all aspects of life sciences, including plant life sciences. This research will fill a current national need to provide a supply of trained professionals to the expanding job market in the biotechnology industry.

Basic research toward new technologies directed at clinical goals is not supported by NSF or by the National Institutes of Health (NIH). Research proposed to address opportunities for new technologies falls between the priorities for these two organizations. Further, the experience of the scientific community is that, in the present vertically integrated discipline-based structure of NSF, submission and review of interdisciplinary research usually do not lead to funding of a scientific program. Thus there is a critical gap that results from the exclusion of many basic scientific programs that fall within the goals of the Foundation. This gap compromises the leadership role for the United States in developing biomedical technologies.

Critical Challenges

The critical challenge is to exploit the power of Optics to advance biotechnology, biomaterials, and biomedical engineering and to probe the biomolecular structure and function in a minimally invasive manner. Furthermore, the challenge is to integrate basic research across the disciplines of chemistry, physics, biology, and engineering. This research initiative is designed to take advantage of complementary aims of NSF, NIH, and other agencies. The aim of NSF-supported basic research in this initiative is to develop physical understanding of Optical science used in biological systems. The aim of NIH will be to use the knowledge gained toward its application in medical science.

The critical challenge that can be addressed by this initiative is basic research to study the interactions of light with biological molecules, cells, and tissues to understand their structure and function. Examples of key biological problems that could be addressed by this initiative include protein folding, protein–protein interactions, molecular recognition, and protein–DNA interactions.

A second aspect of this critical challenge is to support advanced research to develop new optical and laser-based techniques and methodologies to enable fundamental research in biology. The new techniques that show promise for eventual application to clinical, bioremediation, and agricultural needs should be supported. We recommend that NSF encourage proposals that support the use of OS&E as an enabling technology for biotechnology, health sciences, and other aspects of life sciences.

Examples of applications to biology and biomedical engineering of optical techniques include noninvasive imaging, diagnostic spectroscopy, early detection of disease, blood supply monitoring and purification, brain function, drug delivery, gene sequencing, and hazardous waste cleanup and remediation.

The initiative should also include the support of programs focused on the development of photoactive biomaterials for applications outside of biology. Examples include photoactive biological molecules for engineering applications such as light switches and indicators and light-activated protein synthesis.

Recommendations

The panel recommends that the initiative include multidisciplinary opportunities and training that integrate optical science and life sciences. This initiative should be directed by a multi-investigator team with expertise from the fields of chemistry, physics, biology, and optical engineering. The training of students should include core training in biophysical and the physical sciences. The initiative should provide opportunities for cosponsorship of fellowships by industry in the biological and optical fields. The review process for the initiative should include experts from all related disciplines.

This initiative is particularly timely because the problems in biology have become complex and critical; they demand new approaches. Optical science has now developed to a level of sophistication at which its integration into biology can enable research.

Optical and Photonic Materials and Devices
Gary Bjorklund, chair

Introduction

The hallmark of the last half of the 20th century was energy. The hallmark of the coming century will be information technology. The nation that excels in this area will have a distinct economic advantage. The next generation of information systems will influence our society in ways that we can now only begin to imagine. Information not only will improve the educational level of the country, but will have a dynamic impact on the growth of industry and the health of the citizens of our country through the transmission and analysis of medical images. The information revolution has only begun to change our lives. It is mandatory that we guide the revolution with the best scientific and technical skill available.

The underpinning of all photonic and optical applications is advanced materials. The development of these new materials requires the understanding and control of materials at the atomic level, the engineering of the bandgap of semiconductors, and the ordering of three-dimensional structures. We need to understand defects, compositional and epitaxial defined interfaces, and the integration of multicomponent assemblies onto a material substrate.

One aspect of the materials issues that is not well served by NSF is the application of materials in systems. Here the individual investigator programs do not offer the breadth of expertise required to understand all of the system issues that govern the materials uses from devices to subsystems to complex systems. The problems are multi-disciplinary and need to be attacked by three to five cooperating investigators working in teams with graduate and undergraduate students. This is a research program size that "falls between the cracks" with the present NSF structure. In this type of team research, there is an opportunity for NSF to use "smart funding," that is, to pool the resources of the interacting partners to leverage NSF funds in support of the materials research. Systems and subsystems research is in need of this new small-team style of research.

Critical Challenges

The critical challenges that need to be resolved through NSF-sponsored research initiatives include material fabrication and processing, structure and device research, and integration and packaging research for low-cost reliable manufacturing of systems.

The understanding and control of materials at the atomic level and the nucleation and assembly of matter are now essential in modern materials research. For example, to grow generic semiconductor materials on varied surfaces, one must tailor the surface in such as way that the materials to be grown will exhibit the desired characteristics and structure. Epitemplates will be needed for the growth of new materials such as GaN for use in blue diode lasers. These wide-bandgap semiconductor materials will become increasingly important for high-density information storage and for display applications. New materials often grow with an array of defects that limit the quality and the application of the material. There is a critical need to understand the nature of defects and to reduce and control defects. This understanding will shorten the time from discovery of a new material to its development and practical use.

The understanding of interfaces and of thin films grown on interfaces is critical to the development of new materials. For example, strain layer super-lattice semiconductor materials are a recent development but are already a critical aspect of diode laser design and application. Optical coatings are an essential component of many optical systems. Much of the previous work on optical coatings has been more an "art" than a "science." There is a critical need to bring the state of optical coatings onto a sound scientific basis. In optical communications, optical planar waveguide structures, primarily used in telecommunication applications, are an area of materials research that has been neglected. There is a need for increased use of waveguide materials for passive and active devices such as wavelength division multiplexing, beam splitters, switches, and lasers.

The synergistic properties of biphasic materials, such as polymers, present numerous potential opportunities in OS&E. New types of devices are possible, such as bragg gratings, GRIN lenses which depend upon the spatial control of the optical index of refraction, smart materials with controllable physical parameters that can respond to external stimuli, photorefractive materials for information storage, nonlinear optical materials for changing the frequency of the optical field, and bio-optic materials

The development of new and efficient coherent light sources is critical to the future of OS&E. Vertical cavity surface emitting lasers are an example of a new type of semiconductor laser that promises widespread use. New types of laser cavity, microcavities, are another example of materials solving a critical need in source development. In the future, blue light sources will play an important role in the storage and display of information. Tunable coherent laser-like sources are also important for applications. The optical parametric oscillator now being reintroduced as a commercial product meets application requirements from environmental monitoring to chemical detection and analysis. The combination of a low-power, semiconductor laser master oscillator with a power amplifier has led to improved characteristics of diode laser sources with power levels now exceeding 1 watt for small devices the size of a grain of sand. These lasers have extremely narrow linewidths and can be efficiently frequency converted with the use of nonlinear optical materials. There are growing applications for improved laser sources from medical surgery to chemical monitoring and control.

The integration and packaging for low-cost and reliable manufacturing of devices are a critical challenge for the next generation of optical devices. An example of this is the need to invent a low-cost, reliable method to couple a diode laser to a nonlinear waveguide device for the generation of blue light. Packaging to control heat flow is also critical for device performance. Finally, any packaged device must also be manufacturable and low cost to meet the application markets. For advanced devices, the materials that form the device must be integrable into a single subsystem. This involves consideration of fiber-optics coupling, three-dimensional interconnects, and advanced lithographic techniques to allow the manufacturability of new systems.

Recommendations

The materials issues for the next century are important. The panel recommends that investigators be challenged to define the research programs in Photonic Materials and Devices. Further, the panel recommends that NSF should fund an initiative in OS&E that is cross-disciplinary with funding at a level to support three to five cooperating investigators working as a team with graduate as well as undergraduate students. The teams should be encouraged to cooperate with other agencies such as the National Institute for Standards and Technology (NIST) or with the Advanced Research Projects Agency (ARPA) and with other university and government laboratories or with industry in the pursuit of research.

As United States industry moves away from long-range basic research to near-term applied research, it is important for NSF to preserve the capability of the United States industry to look more than three years into the future. To do this, NSF should allow funding to university investigators to be used as matching funds for proposals to NIST and to ARPA. Further, NSF should assist in the resolution of industry–university patent and intellectual property issues that stand in the way of cooperative research activities.

The panel also recommends that Optics be reintroduced into the undergraduate curriculum and be supported by a laboratory course, where possible, to help train the next generation of students in this enabling technology.

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Fundamental Optical Interactions
Dan Grischkowsky, chair

Introduction

Ultimately, progress in OS&E depends on having optical sources. Although dramatic advances in laser power, efficiency, pulse duration, and bandwidth and wavelength tunability have been made in the 30 years since the invention of the laser, there remain major scientific and technical breakthroughs that are restrained by the lack of a suitable optical source. Progress in source development is leveraged to an extraordinary degree across a broad range of applications. Some of the outstanding issues include compact laser amplifier sources compatible with low-dispersion optical fibers, improved nonlinear optical materials, and improved availability to the broad R&D community of low-cost, reliable laser technology.

Fundamental studies in optical interactions also inform us about the ultimate limits of what is physically possible. Thus the understanding of the interaction of the electron and the photon or the atom and the photon at the fundamental level informs us of possible future progress across many disciplines of science. Current basic research is exploring the interactions of a single atom with a single photon and is exploring the fundamental quantum limits of measurement and detection accuracy. We have moved from a world governed by statistical interactions of many particles to a world of single particle interactions. The knowledge gained at this fundamental level has implications on our understanding of nature from communications to biology.

Critical Challenges

The panel identified optical sources, optical communications and information processing, materials design and fabrication, metrology, and education as critical areas in which progress is needed to meet broad societal needs. Progress in these areas depends on the support and progress in fundamental studies of optical interactions.

There is a critical need to improve laser sources to meet the needs of a broad range of research and scientific applications. The laser sources need to be tailored in their wavelength, pulse duration, and power for the application at hand. The laser sources need to be compact, less expensive to buy, and less expensive to operate so that they are available to a wider range of users — not just to those with adequate funds and experts dedicated to the operation of advanced laser systems.

There is a crucial need for accurate metrology of temporal and spatial coordinates from the global scale to the nanoscale. The use of lasers stabilized to high precision will allow accurate navigation using "smart" vehicles, may allow progress in earthquake prediction, and air and ship navigation. On the microscopic scale, precision frequency-stabilized lasers will allow accurate control of semiconductor fabrication through advanced lithographic techniques and the accurate alignment of structures to a nanometer scale. This area of research has long been the domain of the National Bureau of Standards. There may be opportunities for NSF and the NIST to encourage joint research in this area that include studies of basic to applied metrology using advanced optical sources.

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Complex materials play an increasingly important role in advanced technology. Natural and biological materials offer examples of complex materials where optical characterization of surfaces, interfaces, thin films, multilayer structures, and structures of mesoscopic size scales, such as quantum dots, clusters, and ferroelectric domains, must be developed. These optical characterization tools can be viewed by one community as tools for analysis and by another community as a tool for nondestructive evaluation or by a third community as a tool for control and modification of the material. Thus the optical tools are by their very nature used across multiple disciplines. There is need for a concomitant educational drive to foster the training of students in new optical methods that bridge disciplines. Further, there is a need for interaction between the academic and the industrial community to inform each about the other's needs. This is an area in which an active educational effort at the student through professional level could have a major impact on R&D breakthroughs.

"Designer" nonlinear optical materials tailored and controlled for specific nonlinear responses are an important critical challenge. The need for high nonlinear response with low loss and high speed remains primary. Improvements in periodic polling of ferroelectric nonlinear materials and other fabrication techniques on the scale of the optical wavelength to the size of the atom are critical. Fabrication at these length scales will provide enabling technologies for x-ray to optical wavelength applications.

Recommendations

Addressing these critical challenges requires an interdisciplinary approach to research that joins optical engineering, materials science, electrical engineering, and the fundamental understanding of nature through basic research. Optoelectronic material and system improvements require close interactions among fabrication, evaluation, and testing at the device level. These interactions often require strong university–industry interactions which in turn should lead to improved graduate education training and should expose students to future career paths that are an alternative to the traditional specialized training of a graduate student for a future in the academy.

Optical Processing and Manufacturing

Suzanne Nagel, chair

Introduction

Optics enables advanced manufacturing of a broad set of products, and advanced optical systems and products require manufacturing breakthroughs to make optical sources, detectors, displays, communication equipment, imaging systems, sensors, and storage devices economically. Both of these aspects of Optics in manufacturing are critical to achieve an industrial infrastructure for manufactured goods and to affect multibillion dollar markets.

Advanced manufacturing takes advantage of a multiplicity of unique attributes of optical technology including massive parallelism; nanometer accuracy and precision; photon delivery controlled in time, intensity, energy, wavelength, speed, and spatial resolution; remote distribution and delivery of optical power through optical fibers or by line of sight; precision ranging; and light-controlled surface interactions.

These attributes give rise to a broad range of capabilities which include materials processing, such as laser machining, nanofabrication, and lithography; process control, such as machine vision, sensors, and metrology; process monitoring, for example, bar code readers, scanners, displays, and optical local-area networks; rapid prototyping, such as laser stereolithography and three-dimensional model fabrication from digital information; advanced packaging, including welding and joining using optical means; and optical writing, such as imaging holography, gratings, pattern generation, and the labeling of products.

Complete realization of the potential for Optics in manufacturing requires firm scientific understanding and engineering control of the interaction of light with matter.

Critical Challenges

Critical challenges include continued advances in fundamental OS&E to overcome some of the current limitations in optical assisted manufacturing. Generally, these advances include new materials, improved sources and associated Optics, system integration of materials and devices to realize a practical approach to a given manufacturing process, and a continued basic understanding of the interaction of photons with materials on all scales from molecular through bulk. Cross-disciplinary and multidisciplinary investment of resources in optical processing and manufacturing will provide new and unique, cost-effective, optical-based manufacturing approaches and processes.

Equally important, the panel identified the need for low-cost manufacturing of a range of new products based on Optics and optoelectronic devices. The combined efforts to address materials issues, component, assembly, and manufacturability requirements include key advances in OS&E. Displays, storage devices, sources and detectors, optoelectronic integrated circuits, imaging devices, sensors, instruments, optical switches, and computers are all examples of information age technologies that represent huge markets. Success in bringing such products to market will be determined by engineered materials, optical and optoelectronic components, new approaches to high-throughput, high-yield materials, growth and fabrication technology, and new paradigms for assembly such as self-assembly, that result in cost-effective end-to-end manufacturability.

Recommendations

NSF can play a critical role in sponsoring longer-term horizon research activities that build the fundamental knowledge to allow breakthrough approaches to advanced manufacturing and that encourage creative new ways to realize products. For example, why does a display have to be "flat"? Why can we not design and produce displays in flexible rolls, similar to making film, and overcome the limitations of glass-based flat panel displays? We need to encourage investigations that will lead to an image display that has the look and feel of the paper we now use more widely than at any time in history.

The panel strongly endorses an NSF-wide initiative approach for OS&E to build the longer-term enabling capability in this important area. The nature of the field encourages cross-disciplinary and functional interaction, and leads to teamwork and integrated solutions. A strong foundation in OS&E not only prepares the next generation of scientists and engineers with enabling technology, but is critical to the health of the national industrial infrastructure. An NSF investment in this area can benefit and be coupled to mission-oriented initiatives of other agencies and benefit from industrial interactions.

Instrumentation and Sensing

D. Lansing Taylor, chair

Introduction

Optical instrumentation and sensing involves the detection, measurement, manipulation and analysis of a variety of physical, chemical, and biological properties. Traditionally most single-investigator research efforts in this area have been focused on the development of individual enabling component technologies and the first level of integration into measurement instruments. Through the development of new concepts in optical instrumentation and sensing, in particular in response to multi-disciplinary applications and with an interdisciplinary approach, it may be possible to integrate and develop high-performance instrumentation systems more fully.

The support and development of advanced optical instrumentation and sensing methods are important for a variety of reasons. R&D in advanced instrumentation requires an interdisciplinary education on the part of undergraduate and graduate students and demands the ability to work in teams to solve problems. Teamwork is an attribute that is critical to success in industry. Research on optical instrumentation promotes extended interactions with an interdisciplinary team and with extra-university researchers, and it facilitates communication between the university and the industrial researchers. Research in instrumentation provides new economic opportunities both in improved optical instrumentation and in the application of the instrumentation, and it provides a bridge between the R&D environment and the application of the technology to meet national needs in health, environment, energy, national security, and space.

Critical Challenges

The Instrumentation and Sensing panel recognized that new optical sources and technologies can lead to the development of new instrument capabilities for characterization, monitoring, manipulation, testing, and processing of samples.

With these capabilities in mind, the panel identified the following critical challenges in new instrumentation and sensing that will improve scientific and technological capability and ultimately lead to commercializable products.

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New microscopes including confocal, scanning probe, time-resolved, two-photon, field synthesis, and x-ray microscopes, need to be developed. Such new microscopes will have applications in biology and bioengineering, advanced materials, environmental studies, biochemistry, and microfabrication and nanofabrication and testing. Advanced telescope systems for astronomical observation and tracking and for environmental monitoring on a global scale are a critical need. Medical imaging systems, including noninvasive optical imaging spectroscopes, x-ray, and other spectroscopes for internal and external diagnostics, with the goal of developing new, better, safer, and lower-cost systems are an identified critical challenge. Massively distributed sensor networks for the real-time monitoring of large civil infrastructure systems such as highways, bridges, pipelines, buildings, electrical generation, and distribution systems is a research need along with self-calibrated instruments that would be used to explore the interface between optical hardware and computer software for advanced robust systems for remote applications.

To accomplish advances in the above-identified instrumentation and sensing systems requires progress in enabling optical component technologies. These enabling component technologies include light sources, detectors, transducers, Optics and electro-optics, and display systems. The light sources also include lasers from the far infrared, infrared, visible, ultraviolet, and extended vacuum ultraviolet regions of the spectrum. These advanced laser sources would have to be controlled in their spectral, power, energy, and pulse width parameters. The applications of these advanced light sources include chemistry, trace analysis, remote sensing, lidar, surgery, micromachining, optical data storage, process control, and displays.

The advances in detectors include the need for two-dimension arrays of greater size and sensitivity, increased spectral range, and increased readout rate. Arrays with on-chip processing would have applications to spectral analysis, data acquisition, biomedical imaging, and astronomy.

Transducers, including those with optical fiber and integrated signal processing, are an essential element in any optical instrumentation and sensing system. There is a need for transducers for biological, chemical, mechanical, thermal, and physical measurements. The enabling component technologies also extend to optical and electro-optical components, especially nonlinear optical materials and devices for shifting laser wavelengths to new regions, spectroscopic elements, modulators, and advanced optical manufacturing capabilities in optical coatings and aspheric Optics.

Finally, display system advances, especially advances in high-resolution two- and three-dimensional displays, are critical to instrumentation and sensors applications.

Advances in optical components allow advanced optical instrumentation systems to be developed. Instrumentation that has been identified that has particular promise for near-term applications includes a microscope that is integrated from the light source to the detector and display with applications to biomedicine, chemistry, and nanofabrication. Remote-sensing instrumentation for environmental sensing has applications to both local and global scale environmental measurements and monitoring. Process control instrumentation for advanced manufacturing and optical metrology for manufacturing control are also identified instrumentation needs.

Recommendations

The proposed initiative in OS&E should involve NSF-wide support. Individual research proposals would likely involve some level of support from more than one NSF directorate. It is suggested that all NSF directorates be involved in the initiative and that proposal review panels incorporate multi-disciplinary input for proposal evaluation. In addition to crossing NSF directorate boundaries, the proposed research projects are encouraged, but not required, to include other organizations such as industry, government laboratories, small businesses, multiple universities, and state and local governments. This interaction with other agencies and entities is especially encouraged when it brings to the project multi-disciplinary expertise, specialized equipment, or test facilities. Where the proposed initiative is similar to that of existing or planned major initiatives of other government agencies or industrial consortia, the relationship and unique contribution of the proposed initiative should be explained.

The proposed initiative should include an educational component. From an educational standpoint, the instrumentation-oriented research requires a systems perspective which is typically a missing link between academia and industry. Students working in this area will see firsthand how scientific and engineering links must be formed, not only from a design perspective but also from the perspective of practical teamwork and personal interactions. Instrumentation research also has the attractive feature of allowing the involvement of undergraduate students in the assembly, measurement, and testing stages.

The panel suggests several possible mechanisms for enhanced research and education in instrumentation and sensing initiatives. Training internships could be a part of the research initiative allowing students to work on site at a company or national laboratory. Conversely, representatives from industry or national labs would be encouraged to work at the host institution. Investigators should be encouraged to incorporate possible involvement at the local primary and secondary schools and to disseminate the research results to the general public.

NSF-Wide Initiative in Optical Science and Engineering

Introduction

The panel reports on critical challenges in OS&E and recommendations for the implementation of an NSF-wide initiative were discussed in a plenary session of the workshop. Several themes were apparent from the discussion and were reinforced in the conversation.

It is clear from the panel reports that there are several significant opportunities in OS&E that could lead to leapfrog advances in science and technology across multiple disciplines. OS&E is clearly multi-disciplinary in nature, and research may be best performed by small teams of investigators.

Small teams of investigators can attack problems that are more complex than those usually studied by a single investigator. The team approach also involves students in collaboration with other team members

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and with other laboratories, universities, and industry groups when appropriate. This joint venture approach to the research initiative would allow NSF support to be leveraged.

The workshop participants noted that NSF's directorate and division structure is vertically integrated and that there are very few programs that are funded across directorate lines. The workshop also noted that the merit review process for this multi-disciplinary initiative in OS&E would have to be reviewed by a panel composed of experts from appropriate disciplines. This in turn argued that the initiative should be NSF-wide to be successful.

The workshop participants then discussed the importance of evaluating the research with respect to NSF strategic goals and the long-term national needs. The participants agreed that the evaluation should contain an element that judged the research initiative in light of national needs. Further, the participants agreed that the panel reports had identified research initiatives in OS&E that were timely and compelling in their potential to spur leapfrog advances in science and technology.

Recommendations

Based on the panel reports and the plenary discussion, the workshop recommends that NSF create an agency-wide, multi-disciplinary, research initiative in Optical Science and Engineering.

It was noted that the panel reports identified some common characteristics of the research initiatives in OS&E. One of the characteristics was the opportunity for the research initiative to be conducted by small teams of investigators and coinvestigators from multiple disciplines. The multi-disciplinary nature of the research led to the recommendation that **the research in OS&E be evaluated by multi-disciplinary review panels.**

Further, it was noted that the panel reports all had identified areas of OS&E research that were of importance to the nation, to NSF, and to the investigators. OS&E is an enabling technology for the nation that has the potential for significant impact to many disciplines. This discussion led to the recommendation that **the research be evaluated in the light of long-term national goals.**

The interdisciplinary nature of the OS&E research was noted by more than one panel. The workshop also noted that this scale of research would fill the gap between the individual investigator research and the center level of research, both of which are now supported by NSF. The workshop recommends that **the research in OS&E be conducted by small teams of investigators representing several disciplines.**

The panel reports also addressed the education and training aspects of the proposed initiative in OS&E. It was noted that research in small teams involves students in a learning environment and in a style of problem solving that is closer to the norm in industry and is valuable to industry. It was also noted that students should spend time in industrial laboratories and, equally important, that industrial scientists should be supported to spend time in the university research environment. The workshop recommends that **the projects incorporate education and training as an integral part of the effort.**

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Example Proposals

The plenary discussions were positive and reinforced the concept that OS&E offered significant opportunities to enable advances in many disciplines. However, there was some discomfort expressed that the panel reports were broad in scope and did not attempt to prioritize critical challenges. Perhaps the panels could be more focused in their recommendations if their deliberations were to address a set of issues in a common format.

The above concerns were addressed by suggesting that the panels prepare a mock proposal describing the critical challenge in the highest-priority research opportunity within each panel's technical area. This approach had the advantage of focusing the panel deliberations on priority setting and testing the programmatic elements of the proposed NSF-wide initiative. The task of creating a proposal in OS&E would help to bring forward those questions that remained unresolved.

A "call for proposals" to address critical challenges in OS&E was prepared and presented to the panels. Each panel responded by preparing a proposal describing the highest-priority critical challenge in the technical area. The process proved to be valuable and informative. The proposals were presented to the workshop by the panel chairs. Here an element of competition was evident as the panel chairs described their highest-priority critical challenge to the workshop in competition with the other five panel proposals. The process confirmed that there are significant opportunities for identifying critical challenges in OS&E even on short notice, and the process identified issues that needed clarification regarding the programmatic elements of the proposals.

It was recognized that the multi-disciplinary research programs were more complex than the typical single-investigator programs and that to be successful NSF needs to support the research program for a longer period and needs to leverage its funds.

The final two recommendations of the workshop were: **First, the research should be supported for three to five years' duration, and NSF funds should be leveraged by encouraging cooperation with other agencies, laboratories, universities, and industry. Second, this agency-wide, multi-disciplinary initiative should be reviewed after five years and be evaluated by an established set of criteria as to its success.**

The panel mock proposals also opened discussion as to what should be required and what should be recommended aspects of the OS&E research initiatives. The workshop agreed that the incorporation of the educational programmatic elements into the initiatives should be highly recommended but not required. The workshop agreed that cooperative research with other agencies, government laboratories, universities, and industry should also be recommended but not required. The addition of hard requirements for research initiatives as complex as these was seen as an unnecessary burden on the investigators who were to identify critical challenges and propose approaches to solving them through small-team-led research efforts.

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Summary

The proposed NSF-wide initiative in OS&E builds on the core strengths of disciplines housed in the Foundation's directorates and divisions. However, the proposed initiative in OS&E creates a new type of multi-disciplinary research that bridges across the directorates and disciplines. The projects would be proposed and conducted by teams of investigators and coinvestigators from more than one discipline. The proposed research initiative builds on NSF traditions of an investigator-initiated bottom-up proposal process. However, proposals are evaluated by panels of experts knowledgeable in the relevant disciplines. Educational and traineeship elements are to be an integral part of the research initiative. Based on the deliberations of the panels, whose members represented six aspects of OS&E, it is expected that this NSF-wide initiative, if adopted, would have significant impact on NSF strategic goals. Research in OS&E offers the opportunity for leapfrog technical advances that would enable progress in long-range national goals ranging from the nation's information infrastructure, advanced manufacturing, and remote sensing for environmental and global studies, to the use of new optical tools in biology, biotechnology, and medicine.

The workshop noted that the nation had been driven by technology innovations in the past 100 years and is now moving to an information-driven era. More than one panel identified a critical challenge in OS&E that addressed the NII. From advanced materials to new optical sources, panels noted the importance of OS&E to the information highway of the future. New OS&E breakthroughs must occur if the ON/OFF ramp for the information highway is to be designed. Further, there was a clearly identified need for information storage and retrieval if all citizens are to have access to the highway. The need for a "paper-like" display was noted in order to overcome the current flat panel display technology limitations of a hard glass display that takes considerable power to operate and lacks the high-fidelity image quality of a paper display. The manufacturing panel noted that new techniques for inexpensive manufacturing of such a display must also be invented if the "paper-like" display is to become reality.

New optical and photonic materials were another common theme of the panel reports and were reinforced in the plenary discussion. New materials ranged from nonlinear optical materials for laser wavelength conversion to semiconductor materials for the blue laser of the future to biological "soft" materials that are only now being investigated. It was noted that, although Optics is important for the evaluation and understanding of biological materials and systems, Optics has not been integrated into biology. There is clearly a need to alter our educational structure to allow the training of students in both the physical and biological aspects of nature. There was an appreciation that the newer optical tools of microscopy and laser manipulation of biological matter through the invention of "laser tweezers" were to have an important impact on biology in the future.

Research in OS&E offers an opportunity to define the interface for the information era where the storage, switching, and display of information at the ON/OFF ramp of the information superhighway will be achieved through advanced optical technologies. The ability to make these technologies, such as a "paper-like" electronic display, inexpensive is critical to opening access to the information highway to all citizens of the nation. In turn, the ability to access the information, to store and retrieve it at will, and to display it in a convenient manner will have an impact on the education and productivity of all citizens.

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