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ABSTRACT

Magnetic Information Technology (MINT), which involves use of magnetic techniques and materials to store information, is a critical growth industry in the United States. However, experts from both industry and academe forecast the inability of the United States to meet demand in this area. According to these experts, growth of magnetic information capacity will, in the near term, be limited not by the industrial capacity to manufacture equipment but by the availability of new basic and applied research data in all areas of MINT. Furthermore, growth in MINT will be limited by the absence of trained engineers, scientists, and faculty. These and other conclusions emerged from a MINT workshop which focused on what universities must do to address the various research needs in MINT and on how more students can be encouraged to pursue graduate study in areas applicable to mint. Recommendations made to the National Science Foundation include requests that the agency supplement and encourage industrial support of two to four centers of excellence in MINT at universities, establish a MINT research program for single investigators, identify MINT as a national priority, encourage industrial laboratories to become more active in supporting MINT research at universities, and encourage university-industrial interchanges. (JN)

REPORT OF THE WORKSHOP ON MAGNETIC INFORMATION TECHNOLOGY

-MINT-

HOSTED BY

DR. ANGEL G. JORDAN, DEAN, CARNEGIE INSTITUTE OF TECHNOLOGY
CARNEGIE-MELLON UNIVERSITY

DR. M. LEA RUDEE, DEAN, DIVISION OF ENGINEERING
UNIVERSITY OF CALIFORNIA, SAN DIEGO

WASHINGTON, D.C., JUNE 22-24, 1983

REPORT PREPARED BY
ALFRED B. BORTZ
SUSAN B. DUNKLE
CARNEGIE-MELLON UNIVERSITY

BASED ON THE CONTRIBUTIONS OF THE WORKSHOP PARTICIPANTS

*Supported by a grant from the Office of Interdisciplinary Research, Directorate for Engineering, National Science Foundation

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1. EXECUTIVE SUMMARY

Magnetic Information Technology (MINT) is a critical growth industry for the United States. All sectors of the economy, both public and private, need to store and retrieve rapidly increasing volumes of information at rapidly increasing rates. Annual sales of magnetic devices to meet these needs have reached $15 billion and are growing at about 35% per year. This growth in demand is projected to continue for several years. Yet experts from both industry and academe forecast the inability of the United States to meet this demand. *According to these experts, growth of magnetic information capacity will, in the near term, be limited not by the industrial capacity to manufacture equipment but by the availability of new basic and applied research data in all areas of magnetic information technology. Furthermore, growth in magnetic information technology will be limited by the absence of trained engineers, scientists, and faculty.*

Currently, universities are producing approximately 10 Ph.D.s per year with training in MINT, but estimates from industry experts are that 125 Ph.Ds per year are needed in this area. The cost of establishing and maintaining university research programs to meet this need is estimated to be $20 million in capital equipment and $25 million per year in operating expenses.

Those conclusions emerged from a MINT Workshop, June 22-24, 1983 in Washington, D.C., sponsored by the Office of Interdisciplinary Research, Directorate for Engineering, National Science Foundation (NSF), where invited participants from academic, government, and industrial institutions met to define the research needs in MINT and to formulate specific program and funding recommendations for the NSF. The workshop, hosted by Carnegie-Mellon University and the University of California, San Diego, focused on what universities must do to address the various research needs in MINT and on how more students can be encouraged to pursue graduate study in areas applicable to MINT. The consensus of the participants was that as a nation, we must meet the unfulfilled needs of MINT and that to do so, we must develop strong academic research programs in MINT, both in traditional university settings and in University Centers of Excellence or Research Institutes.

A summary of the specific recommendations made to the NSF by the workshop participants follows:

- The NSF should supplement and encourage industrial support of two to four Centers of Excellence in MINT at universities. This support should include funds for equipment, support for faculty and graduate students, and support for visiting faculty. Sponsors should encourage the centers to have complementary activities rather than to compete.

- The NSF should establish a MINT research program for single investigators. To do this, they should stress the multidisciplinary nature of MINT research, encourage new entrants into the field, and direct funds specifically to MINT.
- The NSF should identify MINT as a national priority, and encourage industrial laboratories to become more active in supporting MINT research at universities.
- The NSF should encourage university/industrial interchanges. To do this, they should continue and expand existing methods of encouraging interchanges and initiate industry/university fellowships for exchange of technical staff, especially for small R&D-oriented firms.
- The NSF should expand the pool of referees for MINT proposals.
- The NSF should hold a follow-up meeting in two years to evaluate the progress of MINT research.

The tables at the end of this report provide a more detailed overview of the national needs and opportunities in Magnetic Information Technology.

2. INTRODUCTION: WHY A MINT WORKSHOP?

Magnetic Information Technology (MINT), i.e., the use of magnetic techniques and materials to store information, is a critical growth industry for the United States. It is critical because of the need to store and retrieve increasingly large amounts of information at increasingly rapid rates in such key areas of the economy as the financial, communications, research, and defense sectors. Its growth has been and will continue to be spectacular. Annual sales of magnetic memory devices exceed the sales of semiconductor memory devices and are growing at 35% per year.

In today's data processing systems, both semiconductor and magnetic memories have important roles. Semiconductor memories are typically used for information that must be readily accessible, the so-called random access memory (RAM). Other information, more voluminous in nature, is usually stored in mass storage devices, such as magnetic disks, which are much less expensive per unit of information stored than RAM. A typical large computer system has RAM sufficient to store at least one to two million characters of information. Its mass storage capacity is usually thousands of times greater.

Semiconductor RAM is volatile, i.e., the information stored there disappears when the power is turned off. Magnetic memories, however, are non-volatile and are thus useful for long-term storage of information. One form of magnetic storage, bubble technology, has been a subject of considerable interest over the last several years. The cost of magnetic bubble memories is comparable to RAM, but bubble memories are slower. Magnetic bubble devices are presently used in special purpose applications where nonvolatility or durability are important. If, as many feel, their costs can be lowered relative to RAM, they will also have a market in lower performance applications.

Most observers of the computer field agree that both magnetic and semiconductor memory devices will continue to have large, rapidly expanding markets. Yet, progress in magnetic information technology has been hampered by a lack of long-term basic studies of the recording process and recording devices. Both industry, with its short-term goals, and universities, with their failure to train Ph.D.'s in recording research, have contributed to this problem. This situation is in marked contrast to semiconductor memory technology, where a dozen university research centers, supported by government agencies and industry at levels involving numerous faculty and tens of millions of dollars, exist or are now being built.

Why has research in MINT not kept up with the growth of the industry? There are two closely related reasons: its low-technology image and the lack of awareness among the nation's research community of its importance and its research opportunities.

Magnetics, technologically speaking, is an old field; therefore, many view it as a "solved problem." That view is far from correct. There are important applications in robotics, communications, and information processing which are awaiting the availability of devices capable of storing tens of billions of characters of information in a few cubic feet of volume and of accessing blocks of that information in milliseconds, then transferring it at the rate of tens of millions of characters per second.

Such devices, based on magnetic information techniques, are realizable in the near future. But building and commercializing them will require the solution of important research issues ranging from better fundamental understanding of magnetic recording to improvement in materials and mechanical systems.

These research issues represent opportunities, not obstacles. Magnetic information technology is hardly a "solved problem." But it has many avenues for progress along which lie soluble problems. Unfortunately, knowledge of the importance of and opportunities in MINT has reached only a small segment of the academic research community in the United States.

Few chemistry, chemical engineering, mechanical engineering, and materials science professors are aware of the challenging research problems that MINT offers. Even electrical engineering and physics departments, where most of the magnetics research takes place in our universities, are not fully aware of the industrial need for specific research in MINT. Until the importance and challenges of MINT research can be effectively brought to the attention of the academic community, the gap between industrial need and supporting university research will continue to widen (Table 1).

Recently, the establishment of academic centers of excellence in magnetics technology or magnetic recording at Carnegie-Mellon University (CMU), the University of California, San Diego (UCSD), and the University of Minnesota has been a heartening development. But these centers are only in their infancy and they alone are inadequate to address all the research issues in MINT. Thus it is essential that industry and government be encouraged to support researchers at these centers and at other universities where smaller, but still significant, MINT programs are underway. Likewise, it is essential to encourage other university researchers in many disciplines to pursue the interesting and outstanding problems related to MINT.

Recognizing the significance of these issues, the Office of Interdisciplinary Research, Directorate for Engineering, the National Science Foundation (NSF) sponsored a MINT workshop[1] in Washington, D.C. on June 22-24, 1983, hosted by CMU and UCSD. The invited participants[2] included academic, industrial, and government experts on MINT. Their charter was to define the research needs in MINT, to explore what universities might do to address those needs, and to discuss how that research might be organized and sponsored.

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[1] See Agenda, Attachment 1

[2] See Attendees List, Attachment 2

June 23, Cont'd.

2:00 - 5:00 PM	Discussion Groups 1) Faculty & Facility Requirements for Magnetic Recording Research (Rm. 419) 2) Faculty & Facility Requirements for other MINT Research (Rm, 519) 3) Government Compared to Industry Sponsorship of University Research: Goals, Rights, etc. (Rm. 619)
	Potomac Room
6:30 - 7:30 PM	Reception
7:30 - 8:30 PM	Dinner
8:30 - 9:30 PM	"State of Computer Science Research & Development" (Dr. Robert Kahn, Director of Information Processing Techniques Office DARPA)

June 24

	Wisconsin Room
8:00 - 10:30 AM	Reports from Discussion Groups
10:30 - 10:45 AM	Break
10:45 - 12:00 PM	Final Discussion

Attachment I

AGENDA FOR WORKSHOP ON MAGNETIC INFORMATION TECHNOLOGY (MINT)

Carnegie-Mellon University
University of CA, San Diego
Sponsored by NSF

June 22

	Potomac Room
6:00 - 7:00 PM	Reception
7:00 - 8:00 PM	Dinner
8:00 - 8:15 PM	Welcome Address (Dean Angel G. Jordan, Carnegie-Mellon University)
8:15 - 8:30 PM	"Current Status of Industry/University Relations in Magnetic Recording" (Dean M. Lea Rudee, University of CA at San Diego)
8:30 - 9:30 PM	"New Opportunities in Research" (Dr. Jack Sanderson, Assistant Director, Directorate for Engineering National Science Foundation)

June 23

	Wisconsin Room
8:00 - 8:15 AM	Charge to Workshop Attendees (Dean Angel G. Jordan, Carnegie-Mellon University Dean M. Lea Rudee, University of CA at San Diego)
8:15 - 9:45 AM	"Current & Planned Capabilities at Universities for MINT Research" (Dean M. Lea Rudee, University of CA at San Diego Dr. Jack Judy, University of Minnesota Dr. Mark Kryder, Carnegie-Mellon University)
9:45 - 10:00 AM	Break
10:00 - 12:30 PM	Panel Discussion "What MINT Research is Needed in Universities" (J. Geusic, J. Lemke, J. Mallinson P. Melz, J. Morrison, R. Potter, D. Thompson, R. White)
	Dumbarton Room
12:30 - 2:00 PM	Lunch

2.1. WORKSHOP ISSUES

The purpose of the workshop was to provide guidance to the NSF from a multidisciplinary and multisectional group discussing the following questions:

1. What are the MINT research needs in such areas as electronics, materials, surface science, magnetic phenomena and devices, aerodynamic aspects of magnetic systems, signal processing, and tribology as it bears on magnetics?

2. How should MINT research be addressed and conducted in the university environment?

3. What are the vehicles in the university environment needed to facilitate addressing MINT research issues?

4. What interdisciplinary settings (such as centers or institutes) would be appropriate?

5. What are the instrumentation requirements?

6. What are the current capabilities in the university research community?

3. MINT RESEARCH: WHAT WE HAVE, WHAT WE NEED

To provide guidance to the NSF regarding MINT research, the participants in the workshop assessed the current state of the field — its research topics, personnel, and equipment. Their general conclusion was that current MINT research in the United States is not adequate to support the present level of activity in the field, let alone the projected 35% annual growth rate. That conclusion was not surprising. More importantly, the workshop produced detailed information about the present and projected MINT research activities in contrast to the present and projected needs of the industry. To put that information in perspective, we provide the following background.

3.1. BACKGROUND

The history of magnetic recording is one of steady progress toward higher density storage of information and increased data transfer rates. The current state of research indicates that this progress can continue for the next decade and beyond. Fundamental limits for recording densities are still orders of magnitude away.

Each increase in recording density and information transfer rate requires advances in many areas, including coatings, magnetic media, recording heads, signal-processing electronics, disk actuators, and disk controllers. A breakthrough in one area alone does not lead to increases in information density. Rather, that breakthrough acts as a stimulus to research in the others, ultimately leading to improved recording systems.

Engineers and scientists who are involved in studying, designing, and building those recording systems must make choices among advances in old technologies and application of new ones. Particulate iron oxide recording media and bulk ferrite recording heads dominated the first twenty years of magnetic recording. Now there is competition among particulate, metallic thin film, and sputtered oxide recording media. Likewise, MnZn-ferrite heads, thin film inductive heads, and magneto-resistive heads are serious challengers to bulk ferrite heads.

More dramatic changes in recording systems are likely as perpendicular recording, with its promise of greatly increased densities, challenges longitudinal recording, the current standard technique. Perpendicular recording systems would employ new media, new heads, and new signal processing devices in a system which is already one of the most refined mechanical and electronic marvels ever developed.

Other recording technologies, such as optical recording, are also making inroads into the marketplace. These technologies, which used focused laser beams to access bits, can today be made with much more narrower track widths than conventional magnetic recording and information densities on the order of 10^8 bits per square centimeter, roughly ten times higher than conventional magnetic recording. Using magneto-optic media, this optical recording technology could be made erasable, thus providing all the features of present-day magnetic recording at the density of optical recording.

It is the feasibility of devices like these that is driving the demand for higher density, higher speed, magnetic recording devices. Information processing, communications, and defense industries are prepared to build systems incorporating these devices as soon as they are available.

Magnetic bubbles also have an important niche in the magnetic information market. Because they are solid state devices, they are much more resistant to harsh environments (vibration, dirt, radiation) than other magnetic recording systems. Furthermore, they offer the potential of combining large amounts of non-volatile storage with on-chip logic.

On today's market 256 Kbit, 1 Mbit, and 4 Mbit (K=1024, M=1,048,576) memory modules are available with 16 Mbit devices expected by 1985. Their cost is economical in small numbers ($100-$200 for a 1 Mbit card). Because of their durability and non-volatility, they are valuable for military and robotic applications. They are comparable in cost to semiconductor RAM, but slower. If their cost can be reduced relative to RAM, they will also find a market in lower performance applications.

3.2. WHERE ARE WE NOW?

Academic MINT research in the United States is currently a very small activity. Of the six or so universities involved in MINT, most have only a single faculty member in magnetics. In contrast, the Japanese have more than a dozen major university programs in magnetics technology, and these are effectively coupled with substantial industrial research efforts, involving an average of 35 people per industrial laboratory working in recording and a slightly smaller number in bubbles.* Japanese industrial researchers are actively involved in commercializing innovative ideas in magnetics technology which originated in university laboratories.

There are those who look at this comparison and speak of the need to respond to the "Japanese Threat." The workshop participants, for the most part, took a more positive view. They looked at the market in information technology and spoke of the need to respond to that opportunity.

The most notable response to date has been the formation of the three academic centers of excellence, all currently seeking funding from industry. The status and projected growth of each of these, as presented by their leaders at the workshop, follows.

3.2.1. CARNEGIE-MELLON UNIVERSITY

According to Mark H. Kryder, Professor of Electrical Engineering, CMU has a broadly-based magnetics research initiative, including faculty in electrical engineering, mechanical engineering, physics, chemistry, chemical engineering, materials science, computer science and mathematics. This activity has gradually grown over several decades but has only within the past year been centralized in the Magnetics Technology Center.

At present the Center has an established base of eight faculty actively involved in magnetics and eight from other disciplines whose work applies to magnetic recording. Twenty-five graduate students, six visiting scientists, and two technical staff people complete the present activity. Total research expenditure during 1982-83 was about one million dollars. Kryder expects rapid growth to a $3.5 million budget for 1983-84, $2.25 million of which is already committed, and to $4 million annually thereafter. The new research will emphasize magnetic recording although existing activity in magnetic bubbles and other areas will continue at least at current levels.

In 1983, CMU spent $3 million in creating 7000 sq. ft. of new laboratory and office space and 4000 sq. ft. of class 100 clean space for the Center. In addition, extensive laboratory facilities and equipment already exist at CMU and are being used for research in the magnetics area.

The Center plans, in 1983-84, to add two new faculty, including at least one from the magnetic recording area, and will also involve six more CMU faculty currently working in other disciplines. Graduate student enrollment will increase to 37 in 1983-84 and 50 in 1984-85. The number of visiting scientists will increase to 15 by 1984-85, as each Associate Member company will be entitled to have a scientist in residence at the Center.

Research areas at the Center include magnetic recording, magnetic bubbles, hard magnetic materials, magnetic printing, losses in soft magnetic materials, and microwave technology. Associate Members of the Center have, in addition to the right to have a visiting scientist, facilitated access to faculty and graduate students, preprints of research reports, royalty free license to patents, free use of software, the right to attend an annual review, and membership on an advisory committee that meets semi-annually.

3.2.2. UNIVERSITY OF CALIFORNIA, SAN DIEGO

According to M. Lea Rudee, Dean of UCSD's Division of Engineering, the recently established Center for Magnetic Recording Research will encompass a multidisciplinary approach to magnetic recording research, in contrast to an emphasis on magnetics per se, addressing all the key technologies involved in magnetic recording.

UCSD has committed land, $1,000,000, and four new faculty positions to the Center. $8,000,000 has already been committed by industry towards a goal of $11,000,000; $4,000,000 of these funds will be used to construct a building for the Center which will house a large portion of its activities. The University has also provided an additional $1,000,000 to the project for expanded teaching laboratory and general purpose office space.

The faculty at UCSD contains many members whose research specializations are either in magnetics or in other disciplines necessary to technological progress in magnetic recording, thus contributing to the multi-disciplinary approach being taken. These specializations range from the theoretical physics of strongly interacting magnetic particles to polymer processing. The Center is already supporting research of faculty in physics, chemistry, mechanical and electrical engineering.

All companies which contribute $300,000 or more in three years will be represented on the advisory committee for the Center, while those that contribute $1,000,000 or more over three years will be able to designate a staff member in residence. All research results at UCSD will be placed in the public domain through publication in the open literature.

In addition to financial support, two companies have made senior staff available to the Center, one full-time and one part-time, to assist in its establishment.

The Center's main research and educational activities will be in San Diego, where it has brought on board its first visiting professor, but it will also be able to draw on the complete resources of the University of California system as needed. For example, the Center is already supporting the research and course development in the mechanical engineering of disk drives at UC Berkeley.

3.2.3. UNIVERSITY OF MINNESOTA

Dr. Jack Judy, Professor of Electrical Engineering, described his proposal for a Magnetic Recording Center at the University of Minnesota. Judy is optimistic about establishing a center since the university is attuned to the center concept, and it is already supporting centers in microelectronics, surface science, electron microscopy, corrosion, and other fields.

Minnesota has a 30 year history of research in magnetics, producing an average of one Ph.D. graduate per year. It was the first university in the United States to work on perpendicular magnetic recording films. The University offers courses in magnetics, including one in magnetic recording.

Judy pointed out that magnetic recording research at Minnesota will continue even without additional support. However, establishing a Center of Excellence would enable the University to expand its current level of activity. The goals of the Center would be research, graduate education, and technology transfer. Judy's proposal requests $1.5 million in annual funding through 1986. At that level, the Center would conduct research in magnetic media, heads, magnetic recording and reading techniques, and the electronic and mechanical aspects of magnetic information technology. The current core of six faculty would grow to twelve in about a year and to fifteen one year later. Student enrollment would grow from the current 5 to 10 in 1983-84, to 20 in 1984-85, and to 30 by the 1986-87 academic year.

Minnesota is currently equipment-limited, so one million of the first year's $1.5 million would go into capital equipment. That amount would decrease to $500,000 in the second year and $250,000 in the third. The rest of the money will go toward support of students and faculty.

The University would own patent rights to any invention discovered at the Center but would grant non-exclusive rights to sponsors.

3.2.4. OTHER UNIVERSITIES

Fritz Friedlaender, Professor of Electrical Engineering at Purdue University, spoke about magnetics programs at other universities in the United States. At Purdue, Friedlaender's magnetics group has joined forces with the Materials Engineering magnetics group and the Mechanical Engineering School to promote an interdisciplinary institute in magnetic recording. They have had substantive discussions with potential industrial sponsors and are currently in the process of preparing a proposal for the institute.

Purdue's strong engineering research programs and excellent access to equipment have enabled Friedlaender's research in high gradient magnetic separation to overcome its undeserved "low technology" image. But individual investigators in magnetics at other universities are not so fortunate. They must contend with the "solved problem" image noted above as well as with limited visibility. For those professors, attracting graduate students is difficult because magnetics research is not well-known outside of a few schools.

Yet those professors continue to do useful original work, demonstrating the value of the individual investigator in MINT research. Friedlaender emphasized that funding for their research must not get lost in the rush to develop Centers of Excellence and Institutes in MINT.

3.3. WHAT MINT RESEARCH DO WE NEED IN UNIVERSITIES?

One objective of the workshop was to review the current research needs in MINT. In response to this objective, eight industrial panelists presented research interests in MINT. Each panelist discussed the need for university research in a specific area. The major points of those presentations follow.

3.3.1. MAGNETO-OPTIC RECORDING

Dr. Robert White of the Xerox Palo Alto Research Center discussed magneto-optic writing and reading techniques, then highlighted the R&D opportunities in the field.

Magneto-optic writing, which has the advantage of erasability, depends on the temperature dependence of the coercivity of a magnetic material. A focused laser beam heats a small region of the material, lowering its coercivity in the heated region. The magnetization in the heated region aligns itself with the ambient magnetic field while the unheated portions of the material are unaffected. The density of information stored by this technique is limited mainly by wavelength of the laser light; thus, very high information density is possible.

Magneto-optic reading depends on the fact that a magnetic field rotates the plane of polarization of light. A laser beam (of much lower intensity than is needed to write magneto-optically) is focused on the medium bearing the information. The plane of polarization of the reflected light rotates in a sense determined by the direction of the magnetization. A polarizer used as an analyzer can transform the rotation of the plane of polarization into an intensity change. The intensity fluctuations can be easily interpreted as information.

The major issues in magneto-optic information technology are cost of the heads and signal-to-noise ratio. The R&D opportunities are in media and magneto-optic heads. In media, White stated that we need to develop a fundamental understanding of magneto-optic effects and their limits, magnetic anisotropy, and magnetic domains and domain walls. There are also questions of media stability since the amorphous state is not the ground state. Noise, especially the nature of defects in the media, is also an important research topic. In magneto-optic heads White cited two areas for research: (1) the integration of the laser and optics into the system and (2) accessing modes.

3.3.2 MAGNETIC BUBBLES

Dr. Joseph Geusic of Bell Laboratories discussed R&D needs in magnetic bubbles. He stressed that magnetic recording is strategically important to the United States, especially in the face of Japanese competition. For example, Japan leads in audio and video magnetic recording. Although the United States leads in digital magnetic recording, the Japanese are gaining in this area. They are also gaining in moving media, but their gains in fixed media such as bubbles are dramatic since the United States effort there is declining.

Geusic pointed out that fixed media lead to more reliability, which is especially critical in machine control, robotics, and defense and space applications. He indicated that given that magnetic bubble technology is an advanced high performance form of mass storage technology, the digital magnetic recording industry should "embrace fixed media," so that we do not once again make the mistake of pursuing only the short term technologies. He suggested that the United States is losing ground in this area because we lack the basic philosophy to support long-term research.

Stressing the synergism that exists between fixed and moving media magnetic recording research, Geusic identified the following areas for improvement in magnetic bubble technology: device density, performance (temperature range, speed, power), manufacturing cost (process techniques, testing time), and the fundamental understanding of materials and circuits.

In support of these areas, he identified the following research topics to consider: bubble nucleation, strip cutting, coercivity mechanisms and the limits of coercivity, domain wall dynamic limitations, understanding and predicting performance of propagation structures, circuit modelling techniques, effects of the substrate-to-film transition layer, material defect chemistry, understanding of materials growth, new material systems, and strategies for accelerated testing.

In order for the universities to meet those needs, Geusic stated, they must adopt a research role that emphasizes fundamental understanding and knowledge. They must educate *broadly trained* new engineers and scientists, and they must be selective when asked to assist industry to solve short-range problems.

3.3.3. MAGNETIC BUBBLES AND MAGNETO-OPTICAL RECORDING: WORKSHOP RESPONSE

In a later session of the workshop, one group of participants had the responsibility to discuss research in magnetic bubbles and magneto-optical storage in the context of the workshop's charter. Building on the contributions of White and Geusic, they concluded that support for research in these areas should continue. The importance of doing so is summarized in Table 2.

3.3.4. PARTICULATE MATERIAL RECORDING

Dr. James U. Lemke of Eastman Technology described the advantages of and problems in particulate media recording. This technology (utilizing oxides) is currently dominant in all fields of magnetic recording. Such media are relatively low in cost, resistant to wear and corrosion, and have large potentials for growth in information packing density.

Particulate media are low in background noise and signal-induced noise because there are no Bloch or Neel walls, no exchange coupling between particles, and no sawtooth transitions between domains. The magnetic properties of the particles are easily varied over a wide range. The binder system is desirable since it allows a smooth cast or calendered surface and easily accommodates additives for lubrication and durability. The areal information density, limited only by superparamagnetism, could conceivably reach ten billion bits per square centimeter. Particulate media recording has the highest lineal density ever reported: ten thousand flux changes per millimeter. For perpendicular or isotropic recording, thick coatings may be used that mask the effects of substrate defects.

Lemke suggested research on new particles including barium ferrite, surface-modified oxides, and alloys with multiaxial anisotropy. Research on obtaining perpendicular anisotropy with acicular particles would be an area suitable for university research, having a large technological impact. He noted that no satisfactory theoretical model of media noise exists with theory predicting 20dB more noise than is found experimentally. He also noted that erasure and time-dependent remanence are not understood with particulate systems. Investigation of γFe_2O_3 or Co-doped γFe_2O_3 with spin wave techniques could tell a lot about the surface properties of the particles that are critical to their switching performance in a recording media. He also suggested that more work should be done on particle interactions, calling it the central problem in recording. It dominates the recording process, but the general many-body problem for strong nonlinear interactions with arbitrary anisotropy has never been solved.

3.3.5. THIN FILM MEDIA

Dr. Peter J. Melz of IBM, San Jose, began his presentation with a comparison between universities and industry. The mission of a university is to produce knowledge and train students. University researchers may collaborate, but such collaboration is usually with another researcher in the same field. In industry, on the other hand, the goal is to produce a salable product. Pursuing that goal usually requires an interdisciplinary team effort.

Based on that comparison, Melz concluded that universities should not compete with industry in designing hardware, but rather, they should cooperate with industry by supplying trained students and by providing a knowledge base in areas critical for technological advances. Citing statistics from the 1983 Intermag Conference in Philadelphia, Melz pointed out that *university/industry cooperation of that sort is not common in U.S. magnetics research.* Of 56 papers on magnetic and magneto-optic recording, only two were written by U.S. universities and two more were jointly written by U.S. universities and industry. Two papers were by foreign universities, and three papers were products of collaboration between industry and foreign universities.

With that situation as background, Melz laid out the important areas in thin film recording media in which research is needed. He cited magnetic properties, defect reduction, head-media interfaces, characterization techniques, and fabrication techniques. He suggested university involvement in the following research areas: coercivity mechanisms and the variation of coercivity as a function of film thickness or deposition method; structure of domains in thin film media; magnetic switching mechanisms for thin film media; techniques for studying dynamic magnetic properties; and fabrication techniques producing desired magnetic anisotropy.

3.3.6. HEADS, ACTUATORS, AND SPINDLES

Dr. David Thompson of IBM, Yorktown Heights, discussed reading/recording heads and related topics. Looking at recent trends in the industry, he noted that it is now relatively easy to enter the magnetic recording field. In fact, there have been approximately 90 company startups in the past three years. This ease of entry implies that there is a lot more work that is appropriate to be done at universities.

Thompson identified a large number of areas for head-related research. In the basic research areas, he discussed the need for modelling, including models of fringing, three-dimensional models, and nonlinear models. Domain effects is another fertile area for research, including Barkhausen noise and studies of domain patterns using scanning electron microscopy, the Bitter effect, and microprobes. Improved measurement is also important; techniques to measure bandwidth, flying height, dead layers, and the effective head-disk gap are needed.

Thompson also suggested research into the physics of dead layers and exchange coupling and materials research. Materials with higher magnetizations and permeabilities are of great interest. Magnetoresistive effects, properties of laminated films, wear, and corrosion are also important areas for materials research.

Research into head devices is also needed. Thompson discussed both parametric heads (magnetoresistance, fluxgate, and Hall effect) and compound heads. Research issues related to compound heads include write wide/read narrow heads, tunnel erasing, ring and probe heads, piggyback servos, and side shielding.

Research into heads must also include the head/disk interface. There, a large number of research problems emerge, including analysis and instrumentation to study air bearings, surface analysis, tribology and lubrication (wet or dry), head and media wear, air flow, and start/stop problems. These problems cover a wide range of disciplines, including materials science, chemistry, surface science, metallurgy, and mechanical engineering.

Finally, Thompson listed a number of research areas in track following: position signals (optical, magnetic, capacitive, sampled vs. continuous); improved spindles (ball bearing, air bearing, magnetic bearing); head suspensions; actuators (compound, inchworm).

3.3.7. VERTICAL MAGNETIC RECORDING

Dr. Robert Potter, one of the founders of the LANX Corporation, discussed research issues in perpendicular (or vertical) magnetic recording. LANX was formed in 1981 to manufacture rigid disks for Winchester drives. Using vacuum deposited materials on aluminum substrates, LANX has achieved perpendicular recording using existing Winchester ferrite heads.

One advantage of perpendicular recording is the use of a thicker film (10,000 Angstroms vs. less than 500 Angstroms for the next generation of longitudinal disks).

This thickness leads to ease in manufacturing, greater resistance to corrosion, insensitivity to defects, and greater durability.

A second advantage is the narrower transition length. The lower limit to transition length in longitudinal recording is self-demagnetization if domains become too small. Perpendicular recording transition lengths are limited by the size of the columnar structures in the medium. The narrower transition length permits higher density storage of information, and the information is more amenable to linear filtering on reading.

Potter suggested several research problems in vertical recording. These included head field calculations, development of self-consistent models of the recording process, vector hysteresis models, noise (i.e. non-continuum models), characterization of media by means other than recording experiments (e.g., vibrating sample magnetometer loops), dynamic effects, and mechanical properties.

3.3.8. SYSTEMS

Dr. John Mallinson of Ampex, speaking of recording systems, expressed concern that most ideas in magnetic recording come from abroad. No advanced recording media has originated here. He then listed several areas in which new ideas are needed for both analog and digital recording.

In theoretical areas, he cited the need for three-dimensional head field calculations for saturable (non-linear M-H) materials, for three-dimensional, or even two-dimensional, models of magnetic hysteresis, and for the characterization of channel non-linearities and the inversion problem.

Experimental research is needed in magnetic particle synthesis (small, metallic, etc.), individual particle switching, magnetic structure of thin (vertical/horizontal) metallic recording media, head flying measurement and control, and integrated preamplifiers for low impedance heads.

3.3.9. MINT RESEARCH AND INTERNATIONAL MARKETS

John Morrison of Magnetic Peripherals, Inc. presented an overview of the MINT industry in the United States and contrasted it with the Japanese industry. In Japan, companies share fundamental technology, but they compete in reducing that technology to practice. The Japanese government plays an active role to foster interchange of information among companies and the dozen or more major university efforts in MINT. This approach, he believes, has been effective in generating a high level of productive research in MINT and has led to successful Japanese penetration of the international market for magnetic information storage.

In this country, our biggest problem is industrial access to our technological capacity, since our companies compete at all levels including basic research. In Morrison's view, this is a major reason why our level of effort in MINT research has been so much smaller than Japan's. Therefore, he concluded that we need government involvement with industry and universities in order for this country to compete successfully in MINT.

4. SOME SPECIFICS: RESEARCH PROBLEMS, FACILITIES, AND PERSONNEL

Lynn Preston, Acting Head of the NSF Office of Interdisciplinary Research, charged the participants to develop some specific information and recommendations for NSF. Preston asked the participants to consider the following questions.

1. What research problems in MINT are appropriate for universities to address?
2. What disciplines are involved in MINT research?
3. What instrumentation is required to perform that research?
4. How many students and faculty are needed; how many do we have; and what backgrounds do students need to pursue graduate study in MINT?
5. What knowledge and professional orientation should graduates have?

The following sections summarize the participants' responses to these questions.

4.1. UNIVERSITY RESEARCH OPPORTUNITIES IN MINT

MINT, according to the workshop participants, is multidisciplinary, containing a wealth of interesting problems in many academic fields. To continue to advance magnetic information technology, electrical engineers, mechanical engineers, chemical engineers, computer engineers, materials scientists, chemists, physicists, and applied mathematicians must all contribute to the research. For example, we need electrical engineers and physicists to study magnetic properties of materials, mechanical engineers to investigate the aerodynamics of heads flying tenths of microns above disks, and chemists and chemical engineers to study properties of materials for heads and media. A summary of some of these multidisciplinary problems is presented in Tables 3 and 4.

4.2. INSTRUMENTATION

The participants addressed the question of instrumentation from two perspectives, general and topical. They felt that the general equipment outlined in Table 5 was needed for a well equipped magnetics research facility. The topical list, Table 6, represents equipment needs as defined by research area. The tables include approximate costs, as estimated by the participants. Based on these tables, it takes $1.5 to $2 million to equip a Center of Excellence with one or two areas of unique expertise. This is consistent with Kryder's, Rudee's, and Judy's estimates in their reports about their Centers.

Several university research facilities already have some of this equipment on hand; however, even the best facilities do not have all the equipment they need, and all of them need to upgrade existing equipment to do state-of-the-art research. No facility in the U.S. possesses the more sophisticated equipment, such as electron beam holography or molecular beam epitaxy equipment dedicated to magnetics work. The Japanese invented the electron beam holography technique, and none of the molecular beam epitaxy systems in the U.S. are applied to magnetics problems.

4.3. PERSONNEL ISSUES: SKILLS AND NUMBERS

Without question, the lack of appropriately trained personnel is the greatest threat to the success of MINT-related industries in the United States. Many, including recent B.S. graduates and practicing professionals, are simply unaware of opportunities available in MINT and do not realize that MINT industries require personnel from a variety of fields. Consequently, the number of people actually entering the field has fallen dramatically short of the needs.

At present, the demand for graduates is nearly an order of magnitude greater than the supply. Even with the MINT centers most optimistic estimates, they will be able to meet only 40% of industry's demands by 1986. Table 7 summarizes the participants estimates of the current personnel situation. Clearly, a national initiative is needed to close the gap.

That national initiative will require significant funding. Based on a $2 million cost of equipping a MINT Center with 50 students, $20 million in capital equipment will be required to support the education of the steady-state population of 500 graduate students needed by industry. Likewise, estimating $50,000 per year per student to cover stipends, tuition, equipment, computer time, and faculty supervision costs, the annual operating cost of needed MINT research in this country comes to $25 million.

Beyond the numbers, the participants also considered the issue of appropriate training. Because MINT requires researchers from so many areas, the participants called for increasing graduate student research in MINT within traditional departmental programs. It was stressed, however, that there is a real need for all of these graduates to have a good basic understanding of non-linear magnetics. Professors in such programs should be encouraged to pursue research in the context of MINT.

The participants also noted that as MINT Centers grow, an entirely new breed of graduate will emerge, characterized by multidisciplinary or interdisciplinary skills as well as specialized knowledge. Such graduates will be especially valued by industry.

5. STRATEGY AND RECOMMENDATIONS

Preston of the NSF also charged the participants to consider the appropriate goals of universities relative to the national and industrial needs in MINT research. In particular, she asked them to consider how these needs should be addressed in the university environment. Should they be addressed in departments or centers? Should we establish complementary centers? How should intellectual property rights be handled? Their response was a suggested strategy and set of recommendations, described below and summarized in Table 8.

5.1. CENTERS AND SINGLE INVESTIGATORS

The strategy is to begin with a few (two to four) Centers of Excellence. With present industrial needs, these centers will soon prove their utility. It is, of course, highly desirable for these centers to cooperate and to develop complementary strengths. Such cooperation can be encouraged through the influences of sponsors, including the NSF.

At the same time, the NSF should establish a well publicized and supported program for single investigators. To enhance individual research programs and to redirect some faculty toward MINT research, that program should include the support of visiting faculty at the MINT Centers.

5.2. UNIVERSITY/INDUSTRY RELATIONSHIPS

Likewise interactions between industry and university MINT researchers must be strengthened. In MINT, traditional interchanges, such as faculty sabbaticals in industry and visiting industrial scientists in universities, are currently not as effective as they should be. Part of the problem is that much of the innovation in MINT is taking place at newly started companies, and such companies cannot afford exchange programs. The NSF can contribute here by maintaining and expanding its present programs to encourage industry/university interactions. Of particular value would be a fellowship program to foster interchange of professional staff between universities and small R&D-oriented firms.

Interaction between universities and industry in MINT can also be broadened by the publication of state-of-the-art review papers, the establishment of a MINT newsletter, and the development of MINT sessions at large national meetings. The mechanisms for these activities must grow largely out of the MINT research community itself.

5.3. REFEREES

The NSF's pool of referees for proposals in MINT must be expanded as MINT research is encouraged. Some of the referees could come from the existing pool of evaluators if they are alerted to the importance of MINT through appropriate program announcements. New referees, recruited for their expertise in MINT, will of course, have to be made familiar with the policies and philosophies of the NSF system of peer review. Because of the empirical nature of much of the research, referees from industry as well as academe should be included. The most difficult problem facing the NSF in this area will be to find appropriate mechanisms for review of interdisciplinary proposals.

5.4. FOLLOW-UP WORKSHOP

The workshop participants recommended that a follow-up workshop be held within two years. The purpose of that workshop would be to reassess MINT research and to make mid-course corrections in the new MINT initiatives that come out of this workshop.

5.5. INTELLECTUAL PROPERTY RIGHTS

The participants recommended that in the future, as now, intellectual property rights should be negotiated individually in each case. No blanket policy could possibly be satisfactory to all parties concerned.

6. ACKNOWLEDGEMENTS

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We also thank Dr. Lea M. Rudee, Dean, Division of Engineering, University of California, San Diego and Dr. Angel G. Jordan, formerly Dean, Carnegie Institute of Technology, Carnegie-Mellon University and now Provost of the University, for hosting the workshop. Likewise, we thank our evening speakers. Dr. Jack Sangerson, Assistant Director, Directorate for Engineering of the NSF set the tone for the workshop with his interesting keynote address, "New Opportunities for Research." Dr. Robert Kahn, Director of Information Processing Techniques Office, DARPA, provided the Department of Defense's view of the "State of Computer Science Research and Development."

Finally, Barbara Barris deserves the thanks of all the participants. She ably handled all the arrangements for the workshop and good-naturedly accepted complaints about misspelled names and her choice of Peach Melba for dessert. She and Barbara Longdon were also responsible for preparation and distribution of the draft and final version of this report.

TABLE 1

THE NEED TO ENCOURAGE MINT RESEARCH

- Magnetic Information Technology is a Critical Industry
  - Need to store and retrieve more information at increasingly rapid rate in key economic sectors such as

    Financial
    Communications
    Research
    Defense

- Magnetic Memory is a Growth Industry
  - Bigger than semiconductor memories
  - Growing at 35% Annual Rate
- Current Research is Insufficient
  - Progress hampered by lack of long-term, basic studies of the recording process and recording devices
  - Insufficient Number of Trained Ph.D.s
  - Low-tech, "solved problem" image is an obstacle
  - Research community is largely unaware of the importance of MINT
  - Researchers don't recognize relevance of their disciplines to MINT

TABLE 2

THE IMPORTANCE OF RESEARCH
IN MAGNETIC BUBBLES AND MAGNETO-OPTICS

- Magnetic bubble technology today fills a market niche where nonvolatility and ruggedness are important, e.g., DoD, robotics.
- Continued research will maintain confidence in and open new applications for bubble technology.
- Garnets are particularly convenient for studying fundamental magnetic phenomena. Thus there is synergism between research in bubbles and recording.
- Magneto-optical storage is approaching commercialization.
- Magneto-optic effects have broad device potential.

TABLE 3

UNIVERSITY RESEARCH OPPORTUNITIES IN MAGNETIC RECORDING

ELECTRICAL AND COMPUTER ENGINEERING/PHYSICS/APPLIED MATHEMATICS

- Models and measurements to understand magnetization mechanisms in heads and media
- Information theory: encoding, error correction, signal/noise ratio
- Signal Processing: equalization, decoding
- Control Theory: ultra-precise positioning

MECHANICAL ENGINEERING/APPLIED MECHANICS

- Dynamics and stability of moving structures
- Tribology: head/media interface, including fluid dynamics, air bearings

MATERIALS SCIENCE/CHEMISTRY

- Improved materials for heads, media, lubrication, wear-resistance, corrosion-resistance

TABLE 4

UNIVERSITY RESEARCH OPPORTUNITIES IN MAGNETO-OPTICS AND MAGNETIC BUPBLES

ELECTRICAL AND COMPUTER ENGINEERING/PHYSICS/APPLIED MATHEMATICS

- Exploitation of new ultraviolet source and picosecond techniques to explore high frequency; short-time phenomena
- Domain nucleation and dynamics
- Properties of Bloch lines
- Development of better magnetic transducers (Magnetoresistance, Hall effect)
- Identification of major microscopic factors in magneto-optic phenomena
- Modelling and application of magnetic bubble devices

PHYSICS/CHEMISTRY/MATERIALS SCIENCE

- Assessment of potential of amorphous rare earth-transition metal films for bubbles
- Establishment of better understanding of anisotropy in amorphous films for magneto-optic devices

TABLE 5

GENERAL EQUIPMENT FOR UNIVERSITY MAGNETICS RESEARCH

Equipment	Approximate Cost (K=$1000)
Vibrating Sample Magnetometer (VSM) with programmable field	110K
Dedicated Scanning Electron Microscope (SEM) with energy dispersive x-ray system	150K
Test Beds	
Instrumentation	50K
Mechanical	50K
Plus technician with industrial knowledge	
B-H Meters	50K
Torque Magnetometers	10K
Laser Magnetometers	100K
Ferromagnetic Resonance	150K
General Instrumentation *Also need head fabrication capability* (Evaporators, ion milling, sputter etching, photolithographic equipment)	250K

The Center also needs access to a well equipped analytical laboratory with TEM, SEM, Auger spectroscopy, X-ray diffraction, etc.

TABLE 6

TOPICAL EQUIPMENT FOR UNIVERSITY MAGNETICS RESEARCH

TOPIC Equipment	Approximate Cost (K=$1000)
PARTICULATE MEDIA	
Fluidized Bed Reactor	125K
Electron Beam Curing	150K
Miscellaneous	125K
Subtopic: Metal Particles	
Chromatographs	No estimate
* Safety Problem: Nickel Carbonyl *	
CONTINUOUS FILMS	
Sputtering (incl. gas analyzer)	250K
Ion beam deposition	250K
Evaporators	150K
TRIBOLOGY	
Surface Analysis	Materials Research Lab
Test Systems	10K
MODELLING	
Dedicated Computer (e.g., VAX)	150K
ELECTRON BEAM HOLOGRAPHY	250K
* Plus Dedicated Faculty Member *	
MOLECULAR BEAM EPITAXY	350K
Dedicated to Magnetics	
POLYMERS	
Rheometers	No estimate

TABLE 7

PERSONNEL SUPPLY AND DEMAND IN MINT

Supply		
Graduate Students Produced Annually by Magnetics Programs		
Ph.D.'s	10	
M.S.'s	5	
Total	15	
Total MINT Center Projections by 1986 (Assuming support is forthcoming for 4 centers and a number of smaller efforts)		
Students	200	
Faculty	50	
Graduates per year	40	Ph.D.
	40	M.S.
Demand		
Present Annual Need for New Ph.D. Graduates		
Industry	100	
New and Replacement Faculty	25	
Total	125	
Long-term Steady-state Need in MINT Research		
Students	500	
Faculty	125	
Graduates per year	100	Ph.D.
	100	M.S.

TABLE 8

A NATIONAL STRATEGY FOR MINT RESEARCH

Start with 2-4 Centers of Excellence

- Research there will demonstrate utility of the concept
- Sponsors should encourage complementary activities rather than competition

Establish Well-publicized and Supported NSF Program in MINT for Single Investigators

- Identify MINT research as high national priority
- Stress multidisciplinary nature of MINT
- Encourage new entrants (faculty and students)
- Direct funds specifically to MINT

Establish Support for Visiting Faculty at MINT Centers

Encourage University/Industrial Interchanges

- Continue and expand all existing methods
- Initiate industry/university fellowships, for exchange of technical staff, especially for small R&D-oriented firms

Expand Pool of Referees for MINT Proposals

Follow-up Meeting in Approximately Two Years

ATTENDEES

MINT Workshop
Washington, DC; June 22-24, 1983

Dr. James Aller
Quantum Electronics, Waves and Beams
Division of Electrical, Computer & Systems Engineering
National Science Foundation
Washington, DC 20550

Prof. David Bogy
Mechanical Engineering Department
University of CA at Berkeley
Berkeley, CA 94720

Dr. Alfred Bortz
Assistant Director
Magnetics Technology Center
Carnegie-Mellon University
Pittsburgh, PA 15213

Dr. Norman Caplan
Deputy Director, Electrical
Computer & Systems Engineering
National Science Foundation
Washington, D.C. 20550

Mr. Stewart Cummins
AFWAL/AADE
Wright Patterson Air Foce Base
Ohio 45433

Prof. Ed Della Torre
Electrical Engineering &
Computer Science
George Washington University
Washington, D.C. 20052

Ms. Susan Dunkle
Office of the Dean
Carnegie Institute of Technology
Carnegie-Mellon University
Pittsburgh, PA 15213

Dr. Thelma Estrin
Division Director, Electrical
Computer & Systems Engineering
National Science Foundation
Washington, D.C. 20550

Prof. F-itz Friedlaender
School of Electrical Engineering
Purdue University
West Lafayette, IN 47907

Dr. Joe Geusic
Bell Laboratories
600 Mountain Avenue
Murrayhill, NJ 07974

Dr. Paul Hayes
NASA Langley Research Center
Hampton, VA 23655

Dr. Al Hoagland
IBM Corporation
5600 Cottle Road
San Jose, CA 95193

Dr. Richard Hollman
Intel Magnetics
3000 Oakmead Village Drive
Santa Clara, CA 95051

Dr. John C. Hurt
U.S. Army Research Office
Research Triangle Park, NC 22709

Dr. Angel G. Jordan
Dean, Carnegie Institute of Technology
Carnegie-Mellon University
Pittsburgh, PA 15213

Prof. Jack Judy
Electrical Engineering Department
University of Minnesota
Minneapolis, MN 55455

Prof. Mark H. Kryder
Electrical Engineering Department
Carnegie-Mellon University
Pittsburgh, PA 15213

Dr. James U. Lemke
Spin Physics, Eastman Kodak Co.
P.O. Box 2663
Delmar, CA 92014

Dr. John Mallinson
Ampex Corporation
401 Broadway
Redwood City, CA 94063

Mr. William Meiklejohn
General Electric
Corporate Research & Development
Schenectady, NY 12301

Dr. Peter Melz
IBM Corporation
5600 Cottle Road
San Jose, CA 95112

Prof. Jim Monson
Engineering Department
Harvey Mudd College
Claremont, CA 91711

Mr. John Morrison
Magnetic Peripherals
7801 Computer Avenue
Minneapolis, MN 55435

Dr. Robert Potter
LANX Corporation
1750 Junction Avenue
San Jose, CA 95112

Mr. John Povolny
3M Corporation
Memory Technologies Group
St. Paul, MN 55144

Ms. Lynn Preston
Acting Head, Office of
Interdisciplinary Research
National Science Foundation
Washington, D.C. 20550

Dr. Jan Rajchman
268 Edgerstoune Road
Princeton, NJ 08540

Mr. Andrew Rose
Memorex Corporation
Santa Clara, CA 95052

Dr. Robert Rottmayer
Digital Equipment Corporation
146 Main Street
Maynard, Massachusetts 01754

Dr. M. Lea Rudee
Dean, Div. of Engineering
University of CA at San Diego
La Jolla, CA 92093

Dr. Jack Sanderson
Assistant Director of the
Directorate for Engineering
National Science Foundation
Washington, D.C. 20550

Dr. Elias (Al) Schutzman
Electrical and Optical Communication
Division of Electric, Computer and Systems Engineering
National Science Foundation
Washington, DC 20550

Prof. John Sivertsen
Materials Science &
Chemical Engineering
University of Minnesota
Minneapolis, MN 55455

Prof. Ron Soohoo
Electrical Engineering &
Computer Science
University of CA at Davis
Davis, CA 95616

Prof. Harry Suhl
Physics Department
University of CA at San Diego
La Jolla, CA 92093

Dr. David Thompson
IBM T. J. Watson Research Center
PO. Box 218
Yorktown Heights, NY 10598

Dr. Robert White
Xerox Corporation
PARC
Palo Alto, CA 94304