BOARD ON
PHYSICS AND ASTRONOMY

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Condensed-Matter and Materials Physics: The Science of the World Around Us

An Interim Report

CMMP 2010: An Assessment of and Outlook for Condensed-Matter and Materials Physics
Chaired by Millie Dresselhaus (MIT) and Bill Spencer (SEMATECH, retired)

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

CMMP 2010 Committee

Mildred Dresselhaus, Co-chair, Massachusetts Institute of Technology
William Spencer, Co-chair, SEMATECH
Gabriel Aeppli, University College London
Samuel Bader, Argonne National Laboratory
William Bialek, Princeton University
David Bishop, Bell Labs/Lucent Technologies
Anthony Cheetham, University of California at Santa Barbara
James Eisenstein, California Institute of Technology
Hidetoshi Fukuyama, Tokyo University of Science
Laura Garwin, Harvard University
Peter Green, University of Michigan
Frances Hellman, University of California at Berkeley
Randall Hulet, Rice University
Heinrich Jaeger, University of Chicago
Steven Kivelson, Stanford University
Andrea Liu, University of Pennsylvania
Paul McEuen, Cornell University
Karin Rabe, State University of New Jersey, Rutgers
Thomas Theis, IBM T.J. Watson Research Center

Task of the Committee

1. Review recent accomplishments and new opportunities in the field.
2. Identify the potential future impact of CMMP on other scientific fields.
3. Consider how CMMP has contributed and will likely contribute to meeting national societal needs.
4. Identify, discuss, and suggest priorities for construction, purchase, and operation of tools and facilities.
5. Make recommendations on how to realize the full potential of CMMP research.
6. Examine the structure and level of the current research effort in CMMP. Gather information on the performing institutions, different levels of aggregation of researchers, the role of the research community and performing institutions in initiating research, the relationship between research opportunities and the current structure of the research effort.

Sketch of Workplan

- In-person meetings held to gather data, involve the community, generate ideas, hold discussions, and build consensus
  - Town Hall meetings, Focus group sessions, Four CMMP 2010 committee meetings
- Interim Report was released September 14, 2006
- Target release of approved prepublication draft of final report is April, 2007
  - Final editing, design, layout, illustration, and publication by the National Academies Press will occur afterward

CMMP 2010 Community Input

- Eight focus groups held to date at universities and national laboratories
- Town Hall meetings:
  - APS March meeting (March 12, 2006)
  - ACS spring meeting (March 28, 2006)
  - MRS spring meeting (April 18, 2006)
  - AVS meeting (November 15, 2006)
  - MRS fall meeting (November 30, 2006)
- Public E-mail Box: cmmp2010-input@nas.edu
  (all input received posted on committee website)
- Committee website:
  http://www7.nationalacademies.org/bpa/CMMP2010.html

Interim Report: Introduction

- CMMP: the discovery, understanding, and exploitation of new materials and phenomena
- Fundamental and applied research in CMMP are inherently intertwined
- Research in CMMP is supported through federal sources and private investment
- Industrial and national laboratories have “evolved”
- Community consensus (reached through town meetings, focus groups, and committee members) to focus on challenges for the field

Eight Challenges for CMMP

1. How do complex phenomena emerge from simple ingredients?
2. How will we generate power in the future?
3. What is the physics of life?
4. What happens far from equilibrium and why?
5. What new discoveries await us in the nanoworld?
6. How can we extend the frontiers of measurement and prediction?
7. How do we revolutionize the information age?
8. How can we inspire and teach others?

How do complex phenomena emerge from simple ingredients?

Most materials are made of simple, well understood constituents, and yet their aggregate behaviors are stunningly diverse and often deeply mysterious. This is a direct result of the complexity of large systems.

Just as a crowd can act in ways uncharacteristic of any individual within it, surprising emergent phenomena are also seen in collections of electrons, molecules, or even familiar objects such as grains of sand. For example, sand can be poured like water from a bucket, but unlike any liquid it also supports our weight when we walk on the beach. In the fractional quantum Hall state, a bizarre liquid state of electrons, an added electron will break up into new particles, each of which carries a precise fraction of the charge of the original electron. In a superconductor, an electrical current can flow indefinitely without decaying. These are impossible feats for individual electrons. The relationship between the properties of the individual and the behavior of the whole is very subtle and difficult to uncover and lies at the heart of CMMP. Our challenge is to understand how collective phenomena emerge, to discover new ones, and to determine which microscopic details are unimportant and which are essential.

Examples:

- superconductivity
- magnetism
- fractional quantum Hall effect

How will we generate power in the future?

Our nation must develop cheap, renewable energy sources to reduce our dependence on fossil fuels while minimizing carbon emissions and other harmful environmental effects. CMMP is strongly positioned to help address these challenges.

Promising technologies for solar energy, hydrogen fuel cells, solid state lighting, rechargeable batteries, and improved nuclear power will play critical roles, but we also need fundamentally new approaches. To meet our needs, many profound scientific challenges must be addressed urgently. CMMP is strongly positioned to help address these challenges, which require better fundamental understanding of energy conversion, storage and transmission, as well as new technologies. Can we convert sunlight to usable energy more efficiently? Can we develop new ways to generate and store hydrogen? Can we create better light-emitting diodes and optical band-gap devices? Can we develop new materials to operate under extreme conditions, such as in reactors and receptacles for waste storage? Discovering and understanding new materials will be key; for example, new superconductors could dramatically reduce energy losses in power transmission, while new thermoelectric materials could enable us to draw valuable power from waste heat. No single strategy will provide a silver bullet, and some approaches may take decades to come to fruition. Investment over a broad front and collaboration with other disciplines and policy makers are needed to meet this immense challenge.

Examples:

- catalysis
- nanostructures
- new materials

What is the physics of life?

The study of living matter poses special challenges for CMMP because the constituent biomolecules are far more complex than the atoms or molecules that form most materials.

We are just beginning to see how our understanding of materials can be extended to living systems and to recognize the organizing principles that govern living matter. Already, our burgeoning understanding is leading to an unprecedented degree of collaboration with biologists, on problems ranging from why proteins misfold and form unwanted structures in diseased tissues, as in Alzheimer's disease, to how the brain works. CMMP will continue to catalyze advances in biology and medicine by providing new methods for quantitative measurement, from rapid genome sequencing techniques to novel medical diagnostics. At the same time, the study of biological systems broadens the horizons of physics. The unparalleled specificity and robust functioning of biomolecular systems, such as those that enable viruses to assemble or cancer cells to spread, generate new theoretical ideas and inspire the creation of novel materials and devices. Finally, a fundamental characteristic of physics, especially CMMP, is its ability to analyze complex systems by identifying their essential and general features. This conceptual approach will be indispensable in sifting through the vast trove of accumulating data to tackle the origins of the ultimate emergent phenomena: life and consciousness.

Examples:

- structure-property relationships
- energetics
- timescales
- physical techniques
- education

What happens far from equilibrium and why?

Isolated systems evolve towards equilibrium, a state in which properties do not change with time. Yet much of the richness of the world around us arises from systems far from equilibrium.

Phenomena such as turbulence, earthquakes, fracture, hurricanes, and life itself occur only far from equilibrium. Subjecting materials to conditions far from equilibrium leads to otherwise unattainable properties. For example, rapid cooling is a key process in manufacturing the strongest and toughest metallic alloys. Processes that occur far from equilibrium also create some of the most intricate structures known, from snowflakes to the highly organized structures of life. While much is understood about systems at or near equilibrium, we are just beginning to uncover the basic principles governing systems far from equilibrium. Breakthroughs in this area of CMMP research would affect virtually every discipline in the physical sciences, life sciences and engineering.

Examples:

– fluctuations and noise
– materials under extreme conditions

What new discoveries await us in the nanoworld?

Nanometer-scale materials straddle the border between the molecular and the macroscopic. How do we make real-world nanoscale materials and devices? How do we understand these systems?

They are small enough to exhibit quantum properties reminiscent of molecules, but large enough for their size and shape to be designed and controlled. Furthermore, many of the atoms in a nanoscale object are on the surface, available to catalyze chemical and biological reactions and altering nearly every material property. For example, nanocrystals of semiconductors melt at temperatures hundreds of degrees lower than bulk materials, allowing thin films to be re-crystallized with a hair dryer instead of a furnace. Carbon nanotubes and quantum dots form single-electron transistors that switch from on to off with the addition of a single electron. The potential of nanoscale materials is almost limitless, but we must first overcome two fundamental challenges. The first is physical: how do we control the identity, placement, and function of every important atom in a nanoscale solid, in ways that are practical to apply to real-world materials and devices? The second is conceptual: how do we understand systems that are too large to be handled by brute-force calculation, but too small to be tackled by statistical methods? Meeting these challenges will transform the study of nanoscale materials from a frontier science to a mature discipline, and will have a revolutionary impact on fields from materials to information, and from energy to biology.

Examples:

- new phenomena (catalysis, excitonic effects…)
- quantum properties (quantum unit of energy…)
- close interplay of theory and experiment (carbon nanotubes…)

How can we extend the frontiers of measurement and prediction?

The quest to observe, predict, and control the arrangements and motions of the particles that comprise condensed-matter systems is central to the CMMP enterprise. It will continue to lead to the development of new tools.

The constituent particles span an enormous range of sizes—from electrons and atoms in semiconductor devices, to polymers in plastics, to bubbles in foams—and their motions span a correspondingly immense range of time scales. As a result, the experimental, computational, and theoretical tools required to study them are extremely diverse. Many of these tools are developed by individual research groups; other tools, such as synchrotron x-ray and neutron scattering, are developed at large-scale national laboratory facilities. Technical innovations that extend the limits of measurement and prediction lie at the forefront of CMMP research. For example, scanning probe microscopes were developed to image surfaces at scales too small to be resolved by ordinary optical microscopy, and they immediately transformed surface science, a subfield of CMMP. Moreover, the benefits of new techniques often stretch far beyond condensed matter physics; scanning probe microscopes have now evolved into universal tools at the nanoscale for the physical and life sciences. Experimental condensed-matter tools underlie many non-invasive medical diagnostics, while theoretical and computational tools from our field, such as local electron density approximations and numerical simulation methods, are now used by pharmaceutical companies. The past decade has seen the advent of promising techniques such as coherent and pulsed x-rays, novel optics based on exotic materials, multiscale modeling, and topological approaches to the study of magnetic and superconducting materials. As CMMP researchers seek to answer fundamental questions about materials, they will continue to design tools that will benefit CMMP, other scientific disciplines, and society at large.

Examples:

- new techniques for the nanoscale
- new frontiers of resolution
- Computation and prediction for new materials

How do we revolutionize the information age?

Extrapolation of Moore's Law suggests that, in the next twenty to thirty years, electronic circuit elements will shrink to the size of single atoms. New approaches will have to be developed to continue progress as devices operate deep in the quantum regime.

Even before this fundamental limit is reached, electronic circuits will have to operate in a new regime in which quantum mechanics cannot be ignored. New approaches to communications and information processing will have to be invented, and CMMP will work with other disciplines to enable this transition. Among the many avenues already being explored in CMMP are devices based on spin rather than charge, molecular-scale circuit elements fashioned from carbon nanotubes, and novel computational engines based on biomolecules such as DNA. Perhaps most exotically, quantum information science envisions computation and communication based not on the familiar laws of classical physics but instead on the often counter-intuitive laws of quantum mechanics. The familiar binary "bits" of today may tomorrow be replaced by quantum bits or "qubits" capable of encoding vastly more information. CMMP, the science that launched the information age, will play a pivotal role in determining its future.

Examples:

- nano development and integration
- biophysics role
- quantum computing

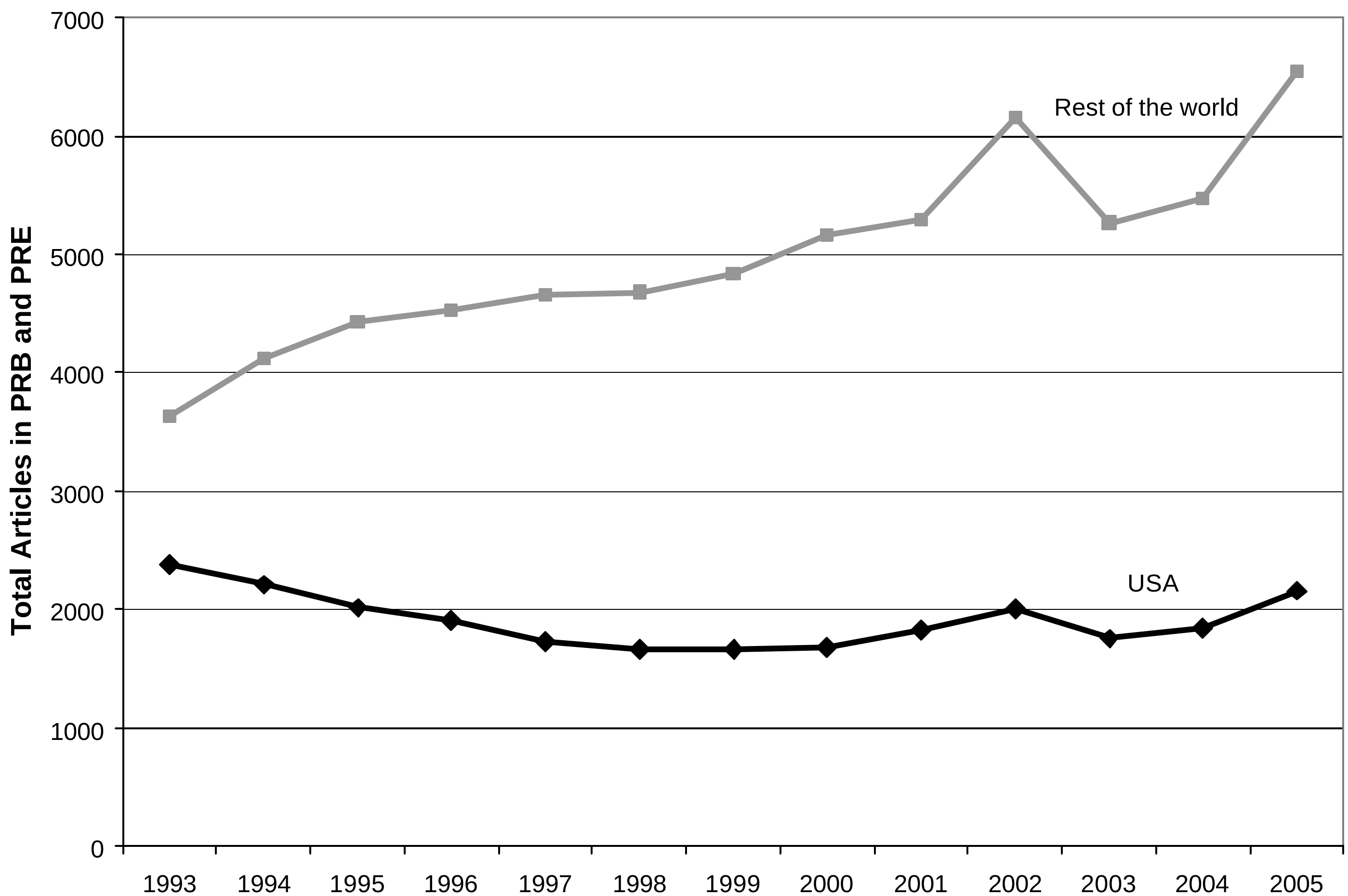
How can we inspire and teach others?

CMMP describes and shapes the world we see. It is critical to educate a new generation with a deeper understanding of the role of CMMP (and science in general) in our society.

Yet few people ponder the quantum mysteries of the magnet on their refrigerator, or realize they are working against entropy when they stretch a rubber band. Many of us benefit from the torrent of new and improved electronic devices, but few are aware that these products are the fruits of a rich and coherent scientific discipline characterized by an inseparable mix of fundamental and applied research. Limited public awareness and understanding of science is an increasing danger to our nation's economic security and is most dramatically reflected in the current crisis in primary and secondary school science education. We must now extend our educational efforts to not only improve general scientific literacy but to also increase the pool of students interested in science and engineering. It is critical that we infuse a new generation of scientists with the knowledge, skills, creativity, versatility and sense of wonder needed to meet the challenges ahead.

- How will we educate the next generation of CMMP researchers?
- How will we attract talented people to the field?
- How do we increase general scientific literacy?

Publication Trends



U.S. leadership in CMMP articles published in leading journals, *Physical Review B* (PRB) and *Physical Review E* (PRE), is eroding.

Warning Signs

- With the changing focus of industrial research laboratories and increasing investments abroad, US leadership in CMMP is uncertain
- Flat funding of CMMP over the last decade
- US is not participating well in the world growth of the field
- Recent advances and discoveries in CMMP occurring elsewhere

Some difficulties encountered with the interim report

- The core intellectual issues of our field are hard to explain in single punchy sentences.
- A report written by a committee tends towards the bland.
- It is difficult to go beyond anecdotal evidence concerning the many serious (even critical) issues that many of us feel face our field.

The fundamental issues in CMMP tend to be hard to explain in a single "punchy" sentence

Excerpts from Elihu Abrahams CMMP2010 Community Input

- "This report is seriously deficient and misdirected. Instead of focusing on the true frontiers of our science, it devotes itself to the same sort of peripheral issues that have constantly plagued such reports in the past."
  - Response: This is an *interim* report from the committee and is focused on communicating to policy makers. The interim report also allows feedback from the community on the science topics.
- "If CMMP2010 is not going to mention, let alone strongly emphasize, fundamental issues in our science, who will?"
  - Response: We agree.
- "Where are the spectacular natural phenomena whose explanations are at the frontiers of research? … Where is one of the greatest challenges of all – that of the strong correlation many-body problem? Where is high-temperature superconductivity? Where is quantum criticality? Where is magnetism? Where is the metal-insulator transition? Where are new methods for electronic structure? Where is low-dimensional physics? Where are non-Fermi liquid metals? Where are heavy electrons? …"
  - Response: These topics belong in the final report. We cannot do them justice in a short document like the interim report. Our challenge is to include these topics in the final report, which is not yet written.

We have little more than anecdotal evidence on many important issues

- E.g. strong feeling that the individual investigator is in trouble, and increasingly inadequately funded (especially in experiment).
- We would like more input from the community concerning priorities for future facilities.

Proposed workshop on facilities for CMMP research

- Proposal to convene a government and scientific stakeholders workshop to evaluate future facility needs for the CMMP community
- "Facilities" range from the large government laboratories supported by NSF and DOE, to mid-scale facilities at Universities.
- Purpose is to generate ideas and consensus for recommendations concerning the facilities priorities of the CMMP community.

Final Report

- Will be released in spring 2007
- Will address questions such as:
  - How should CMMP research by single investigators be supported to keep it focused on addressing the challenges we have just discussed?
  - How can we promote and reward high-risk, high-creativity research?
  - How can we tackle larger-scale, longer-term problems that require the coordinated work of large teams?
  - What are the future instrumentation and facility needs for CMMP?
  - How can we develop, attract and retain the best scientific talent to ensure the continued health of the field, learning both from our own experience and from that of other countries?
  - Could we be spending the research funding we have more effectively? If resources are limited, what are the most critical research problems that should be given highest priority?