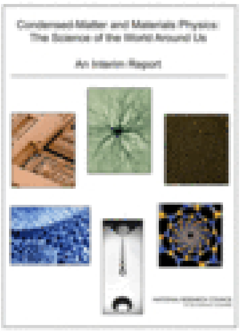

Condensed-Matter and Materials Physics: The Science of the World Around Us: An Interim Report

Committee on CMMP 2010, Solid State Sciences Committee, National Research Council

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CONDENSED-MATTER AND MATERIALS PHYSICS: THE SCIENCE OF THE WORLD AROUND US

AN INTERIM REPORT

Committee on CMMP 2010: An Assessment of and Outlook for
Condensed-Matter and Materials Physics

Solid State Sciences Committee

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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Cover (clockwise from upper left): (1) Colorized scanning electron micrograph of a copper wiring stack on a silicon chip, courtesy of IBM Corporation. IBM's introduction of high-performance copper wiring technology to microelectronics manufacturing in 1997 was based on decades of research in materials physics. (2) Electron flow paths in a two-dimensional electron gas, courtesy of Eric J. Heller, Harvard University. (3) Colorized transmission electron micrograph of self-assembled gold nanochains on copolymer film, courtesy of Ward Lopes and Heinrich Jaeger, University of Chicago. (4) Schematic of theoretically predicted boron nitride nanotube, reprinted with permission from Marvin L. Cohen, *Physics Today*, June 2006, p. 52, copyright 2006, American Institute of Physics. (5) Droplet fission—a drop of water in the process of breaking apart, courtesy of Sidney Nagel and Xiangdong Shi, University of Chicago. (6) Scanning electron micrograph of an echinoderm skeletal element, courtesy of Joanna Aizenberg, Bell Labs. The entire structure is one single crystal of calcite with an intricate, genetically controlled micro/nano-porosity.

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PREFACE

The National Research Council of the National Academies recently established the Committee on CMMP 2010: An Assessment of and Outlook for Condensed-Matter and Materials Physics to study the opportunities and challenges in condensed-matter and materials physics (CMMP) in the next decade. The Solid State Sciences Committee (SSSC) of the Board on Physics and Astronomy developed the charge for this study in consultation with the study's sponsors at the Department of Energy and the National Science Foundation. The CMMP 2010 committee has been asked to review recent accomplishments and new opportunities in the field; identify its potential future impact on other scientific fields; consider how it contributes to meeting national societal needs; identify, discuss, and suggest priorities for construction, purchase, and operation of tools and facilities; examine the structure and level of the current research effort and funding; and make recommendations on how to realize the full potential of CMMP research. The committee's final report is part of the ongoing Physics 2010 survey, the latest decadal assessment of and future outlook for the field of physics conducted under the auspices of the Board on Physics and Astronomy of the National Academies.

This short interim report serves as a summary of the committee's thoughts on grand challenges in condensed-matter and materials physics in the coming decade and provides a brief look at the international landscape. The grand challenges will be discussed in detail in the committee's final report.

In preparing for the decadal survey of CMMP, the SSSC called on the community for input on opportunities and challenges in the field. This input was compiled and presented to the CMMP 2010 committee at its first meeting in February 2006. In addition, the committee received direct input from the community at three town meetings held at professional society meetings—the first at the March meeting of the American Physical Society in Baltimore, Maryland, in March 2006; the second at the spring meeting of the American Chemical Society in Atlanta, Georgia, in March 2006; and the third at the spring meeting of the Materials Research Society in San Francisco, California, in April 2006. The committee also solicited community input through nine focus groups at universities and national laboratories, each with an attendance of between 10 and 15 researchers, and through a public website, and it will continue to welcome input for as long as possible following the release of this interim report.

To address its full charge and expand on the challenges presented in this interim report, the committee is continuing to collect data on funding and international activities and is considering the impact of CMMP on security, health, energy, and the economy. It looks forward to sharing its findings and recommendations with the broader scientific community and its sponsors, with the release of its final report in the spring of 2007.

Mildred Dresselhaus	William Spencer
Co-chair	*Co-chair*

ACKNOWLEDGMENT OF REVIEWERS

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Elihu Abrahams, Rutgers University
Frank Bates, University of Minnesota
Gordon Baym, University of Illinois at Urbana-Champaign
Arthur I. Bienenstock, Stanford University
J.C. Séamus Davis, Cornell University
Barbara Jones, IBM Almaden Research Center
Marc A. Kastner, Massachusetts Institute of Technology
Hyla S. Napadensky, Napadensky Energetics, Inc.
Julia M. Phillips, Sandia National Laboratories
Peter G. Wolynes, University of California at San Diego

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Venkatesh Narayanamurti, Harvard University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

CONDENSED-MATTER AND MATERIALS PHYSICS: THE SCIENCE OF THE WORLD AROUND US

AN INTERIM REPORT

Condensed-matter and materials physics (CMMP) is the science of the material world around us. From the dawn of civilization, curiosity about the natural world has led to questions about the character of everyday substances such as water, snow, ice, and rocks, and how these respond to light, heat, and mechanical forces. This thirst for fundamental understanding is inextricably tied to the desire to manipulate nature to create new materials that satisfy human needs—from the Stone Age, to the Iron Age, to today's Silicon Age and beyond.

The discovery, understanding, and exploitation of new materials and phenomena are the heart of CMMP. Invention and innovation in this field have had a pervasive impact on our daily lives. Examples are everywhere: semiconductor lasers are in our DVD players; advanced magnetic materials store data on our computers' hard drives; liquid-crystal displays show us our photographs and our telephone numbers. But these technological marvels tell only half the story: studies of new materials and phenomena have also led to significant advances in our basic understanding of the physical world. For example, the development of ultra-pure layered semiconductors made possible not only the production of high-speed transistors for cell phones, but also the discovery of completely unexpected new states of matter. Efforts to understand magnets, ferroelectrics, superconductors, polymers, and liquid crystals, exploited in innumerable applications, spurred the development of the elegant, unified conceptual framework of broken symmetry that not only explains how the characteristic behaviors of these materials are related, but also underlies much of modern physics. These examples illustrate the inherent intertwining of the pure and applied aspects of condensed-matter and materials physics; they are opposite sides of the same coin that define and enrich the field.

Materials and their behaviors are also key elements in other branches of science; as a result, CMMP is the broadest field of physics. Advances in CMMP have an impact that is immensely amplified by the intrinsic interconnectedness of CMMP with other fields of physics, chemistry, biology, geology, and astronomy, as well as nearly all fields of engineering.

The 20th century was a period of remarkable fundamental and technological progress in CMMP. Starting in the 1930s, U.S. researchers in academia and in industrial and government laboratories spearheaded the growth of the field. Long before World War II, industrial laboratories had initiated significant private investment in fundamental and applied CMMP research, which was strongly bolstered by war-time research in newly established, focused national laboratories. Continued federal and private investments led to remarkable advances in understanding and to the invention, years and often decades later, of many new devices, including the transistor, the integrated circuit, the laser, improved batteries, magnetic resonance imaging, liquid-crystal displays, and, more recently, high-efficiency solid-state lighting. This inventiveness and the resulting market leadership of the United States have contributed significantly to our nation's economic strength. In particular, the industrial development of many of these technologies has led to the current U.S. leadership in global computing and communications. Although the relationship is difficult to measure quantitatively, there is a consensus among economists that advances in technology have been the main driver of economic growth over the past 60 years.[1]

In this report, the committee looks ahead to ask: What are the prospects for CMMP in the early part of the 21st century?

As the demands of a growing world population increase, there has never been a greater need for sustainable technological alternatives to the depletion of Earth's non-renewable resources. As the magnitude and urgency of this and other societal problems become increasingly evident, clear challenges and opportunities emerge for CMMP research worldwide. These demand a substantial and focused effort that will stimulate lively competition and the development of new ideas. At home, the United States remains a leader in CMMP, but its premier position is in jeopardy. With the gradual maturing of information technology, industrial research investments, once aimed at semiconductor materials and devices, have shifted toward software and services. With many U.S. industrial laboratories focused on such shorter-term goals, there is concern that the next great revolution in technology will be triggered by research developments off-shore. Certainly the decline in industrial materials research has limited the ability of U.S. industry to respond quickly to new developments. For example, failure to maintain strength in materials synthesis and crystal growth has led the United States to depend on other countries, especially Japan, for high-quality samples for investigation. Meanwhile, other parts of the world are investing heavily in research and development. Without adequate federal and private investment in basic research, U.S. leadership in CMMP is unlikely to survive.

The committee has identified eight important challenges facing CMMP researchers in the coming decades, including several that have major relevance to other fields. Meeting these challenges will lead to significant advances in both fundamental science and materials-based technology. The challenges are to address the following questions:

1. 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

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[1] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, prepublication, The National Academies Press, Washington, D.C., 2006, pp. 2-7.

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. The challenge is to understand how collective phenomena emerge, to discover new ones, and to determine which microscopic details are unimportant and which are essential.

2. 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 harm to the environment. 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 require urgent attention. 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 the ability 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.

3. 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. Researchers are just beginning to see how understanding of materials can be extended to living systems and to recognize the organizing principles that govern living matter. Already, 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.

4. What happens far from equilibrium and why?

Isolated systems evolve toward 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 such systems. Breakthroughs in this area of CMMP research would affect virtually every discipline in the physical sciences, the life sciences, and engineering.

5. What new discoveries await us in the nanoworld?

Nanometer-scale materials straddle the border between the molecular and the macroscopic. 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 do 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.

6. 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 constitute condensed-matter systems is central to the CMMP enterprise. 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 largescale 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 CMMP, 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.

7. How do we revolutionize the information age?

Extrapolation of Moore’s law suggests that, in the next 20 to 30 years, electronic circuit elements will shrink to the size of single atoms. 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.

8. How can we inspire and teach others?

CMMP describes and shapes the world we see. Yet few people ponder the quantum mysteries of the magnet on their refrigerator, or realize that 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 present an increasing danger to our nation’s economic security and are most dramatically reflected in the current crisis in primary and secondary school science education. We must now extend our educational efforts not only to improve general scientific literacy but also to 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.

In the full report, the committee will discuss these scientific challenges for CMMP in a larger context, cognizant of the fact that future advances are often triggered by unexpected discoveries. It will address a number of questions, including the following: How should CMMP research by single investigators be supported to keep it focused on moving toward these goals? 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?

The committee will further examine the increasingly interdisciplinary nature of CMMP, evident as a common thread running through the challenges presented here. Interdisciplinarity has been one of CMMP's major strengths from the beginning and is a continuing sign of its vitality as a field. More than 50 years ago, physicists exploring the diffraction of x-rays in condensed matter turned to biological molecules and initiated the field of molecular biology. Biology and chemistry, in turn, have stimulated new areas of research in CMMP. Ideas from the theory of phase transitions in condensed-matter physics underlie current understanding of the fundamental interactions in the universe, while CMMP imaging and detection techniques have enabled great advances in particle physics and astronomy. Bose-Einstein condensation, first observed in superfluids and superconductors, has now been realized in atomic systems, revitalizing the connection between CMMP and atomic physics. In the past few decades, soft-matter physics has grown into a vibrant field, linking CMMP with chemistry, engineering, and biology. Nanoscience is further blurring the boundaries with these fields, and with atomic physics. Approaches originating in CMMP are being applied to systems as diverse as the human genome, the World Wide Web, and the economy. We must continue to foster interdisciplinarity, even as we nurture core research in CMMP, which often has unanticipated impacts on other fields.

As the committee lays the foundation for its recommendations for the effective organization and support of CMMP research in the United States, it will look back to the history of past successes, and, most importantly, examine the current position and likely future of U.S. research and technological innovation relative to the rest of the world. Here, the news is not good: domestic funding for basic research in CMMP has been essentially flat for the past decade. The field is growing, as evidenced by the increase in total publications, but the U.S. output remains flat, as shown in Figure 1. CMMP is an important area because of its tight coupling to society, economic growth, and national objectives, as described above. To remain among the world leaders in CMMP,[2] the

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[2] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Science, Technology, and the Federal Government: National Goals for a New Era*, National Academy Press, Washington, D.C., 1993, pp. 18-20.

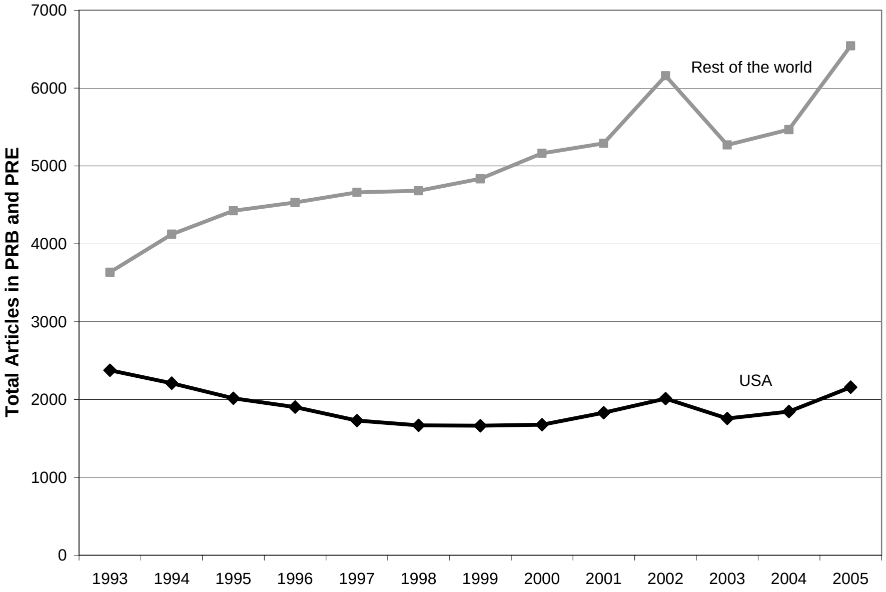

FIGURE 1 U.S. leadership in CMMP articles published in two leading journals, *Physical Review B* (PRB) and *Physical Review E* (PRE), is eroding.

United States should be participating more fully in the growth of the field. To appreciate the magnitude of the problem, one must recognize the inertia in the system: the U.S. research community still benefits from the science conducted and the scientists trained years ago; the lower levels of current funding will have increasing impact in the future. When considering key recent advances in fundamental CMMP, this effect may already be more pronounced than is currently appreciated. For instance, foreign researchers have led the charge in the discovery of new types of superconductors and advanced magnetic materials. In these important areas, the United States may already be falling behind.

The challenges presented in this interim report outline some of the exciting questions that will drive the continued vitality and growth of CMMP in the coming decades. The fundamental scientific questions, the close interplay between theoretical and experimental research, and the technological applications that will contribute to solving important societal problems all drive enthusiasm in the field. Attracted by such compelling research opportunities, more starting graduate students in U.S. programs choose CMMP than any other single subfield of physics. These young minds are our future as we face the challenge to transform from 20th-century ways of organizing and supporting CMMP research to a sustainable 21st-century model responsive to developments in the field, societal needs, and fiscal realities. With sufficient resources, the United States will strengthen an indispensable component of the nation’s capacity for economic competitiveness—its leadership in CMMP basic research.