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

Final Report of the National Academies
CMMP 2010 Committee

October 18, 2007

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

Genesis

- In January 2006, the National Academies convened the CMMP 2010 Committee as part of the decadal survey of physics
  - DOE and NSF provided support for the project

- The committee was tasked as follows:
  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.

Committee membership

Mildred Dresselhaus, Co-chair, MIT
William Spencer, Co-chair, SEMATECH (retired)
Gabriel Aeppli, University College London
Samuel Bader, Argonne National Laboratory
William Bialek, Princeton University
David Bishop, Alcatel-Lucent
Anthony Cheetham, UC Santa Barbara
James Eisenstein, California Institute of Technology
Hidetoshi Fukuyama, Tokyo University of Science
Laura Garwin, Harvard University (until October 2006)
Peter Green, University of Michigan
Frances Hellman, UC Berkeley (until September 2006)
Randall Hulet, Rice University
Heinrich Jaeger, University of Chicago
Steven Kivelson, Stanford University
Andrea Liu, University of Pennsylvania
Paul McEuen, Cornell University
Karin Rabe, Rutgers University
Thomas Theis, IBM T.J. Watson Research Center

- A committee with broad membership was sought in order to critically examine the science
- Experts from inside and outside of CMMP were included
- To help frame the agenda in a broadly compelling manner, one co-chair had extensive experience within CMMP science; the other brought an external, independent perspective

Committee Work Plan and Input

- Interim report released September 14, 2006
- Four committee meetings, Facilities workshop
- 6 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)
  - APS March meeting (March 6, 2007)
- 8 Focus groups at universities and national laboratories
- Public E-mail Box: cmmp2010-input@nas.edu
  (all input received posted on committee website)
- Committee website:
  http://www7.nationalacademies.org/bpa/CMMP2010.html

Summary

- CMMP: the discovery, understanding, and exploitation of new materials and phenomena.
- Fundamental and applied research in CMMP are inherently intertwined.
- CMMP research is driven by "single investigator research groups."
- Six science challenges for the next decade were identified by the committee.
- CMMP research connects strongly to society and other science disciplines.
- Industrial laboratory research has evolved and new approaches to technological innovation are needed in its place.
- Research in CMMP is supported through federal sources and private investment.
- Federal support for CMMP research has been approximately flat over the past decade.
- State-of-the-art tools, instrumentation, and facilities are key for advancing the forefront of CMMP research.

Science Assessment

Six CMMP Science Challenges for the Next Decade

- How do complex phenomena emerge from simple ingredients?
- What is the physics of life?
- What happens far from equilibrium and why?
- What new discoveries await us in the nanoworld?
- How will the energy demands of future generations be met?
- How will the information technology revolution be extended?

How do complex phenomena emerge from simple ingredients?

Emergent phenomena are properties of a system of many interacting parts which are not properties of the individual microscopic constituents. The essence of an emergent phenomenon lies in the complex interactions between many particles. Emergent phenomena occur at all scales from the microscopic to the everyday to the astronomical. CMMP seeks to understand the connection between the microscopic and the macroscopic in systems with many interacting constituents.

- Superconductivity, the dramatic vanishing of all electrical resistance of certain materials below a critical temperature, is one of the best-known examples of emergence.

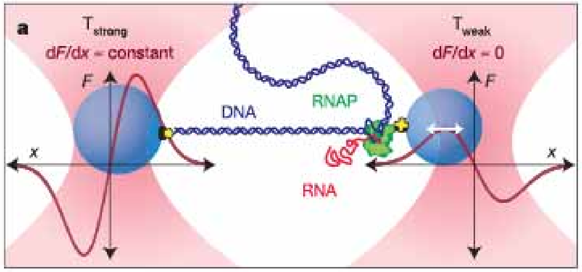
- The challenge for the future is to understand how collective phenomena emerge, to discover new ones, and to determine which microscopic details are unimportant and which are essential.

The emergent phenomenon of superconductivity plays a key role in magnetic resonance imaging (MRI), a technique that has revolutionized medicine.

What is the physics of life?

Today's physicists are learning "the facts of life" and asking new and different questions about these remarkable phenomena. Technically challenging, quantitative experiments are making precise our qualitative impressions of these phenomena. The breadth of this activity is enormous, from the dynamics of single molecules to perception and learning in the brain and from networks of biochemical reactions in single cells to the dynamics of evolution.

- The challenge is to further develop a new branch of science that combines the theoretical depth and quantitative precision of physics with the beautiful and intricate phenomena of modern biology.



New questions and new methods for exploring the physics of life. Left: Optical trapping makes it possible to observe the "reading" of the genetic code by a single molecule of RNA polymerase (RNAP). Right: Genetic engineering and fluorescence microscopy are combined to observe the intrinsic noise as cells regulate the expression of individual genes; here molecular noise is translated to changes in color.

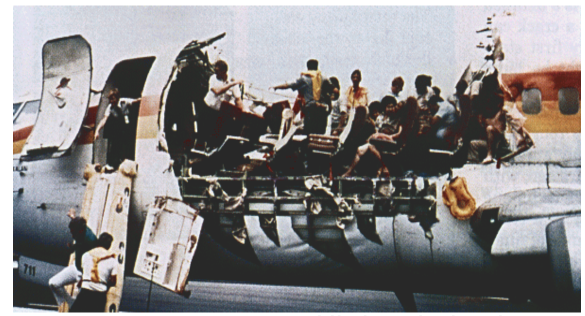
What happens far from equilibrium and why?

Much of the richness of the world around us arises from conditions far from equilibrium. Phenomena such as turbulence, earthquakes, fracture, and life itself occur only far from equilibrium. Subjecting materials to conditions far from equilibrium leads to otherwise unattainable properties.

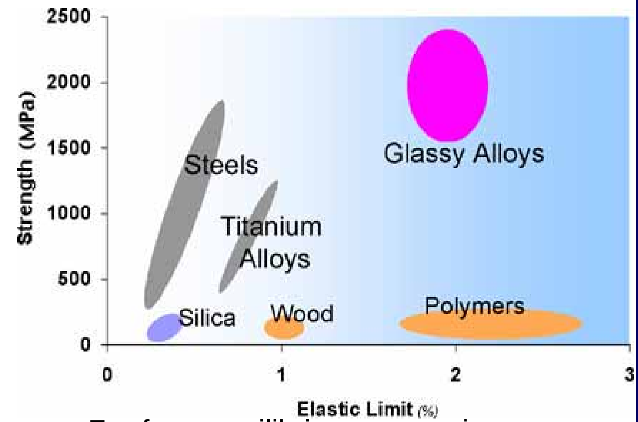
Swarming schools of fish, swirling storms and galaxies (top to bottom) are all examples of systems formed and evolving far from equilibrium.

Far-from-equilibrium behavior is emerging as one of the major challenges within CMMP and beyond:

- It is ubiquitous, occurring from the nanometer scale on up, in daily life as well as in high-tech applications.
- It connects directly to critical, national needs for the next decade, affecting a large fraction of the manufacturing base as well as our economy, climate and environment.



Control of far-from-equilibrium behavior can prevent materials fatigue and eventual fracture.



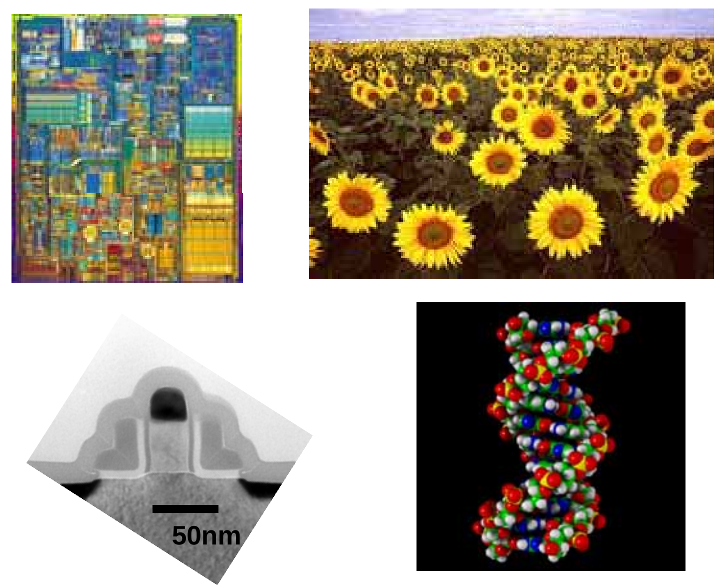
Far-from-equilibrium processing produces some of the highest strength materials (glassy metal alloys).

What new discoveries await us in the nanoworld?

"Nano" straddles the border between molecular and macroscopic: small enough to exhibit characteristics reminiscent of molecules, but large enough to be designed and controlled to meet our needs. Nanotechnology has the potential to revolutionize our lives from information technology to energy to medicine.

Key Challenges to address:

- How do we precisely construct nanoscale building blocks?
- What are the rules for assembling them into complex systems?
- How do we predict and probe the emergent properties of these systems?



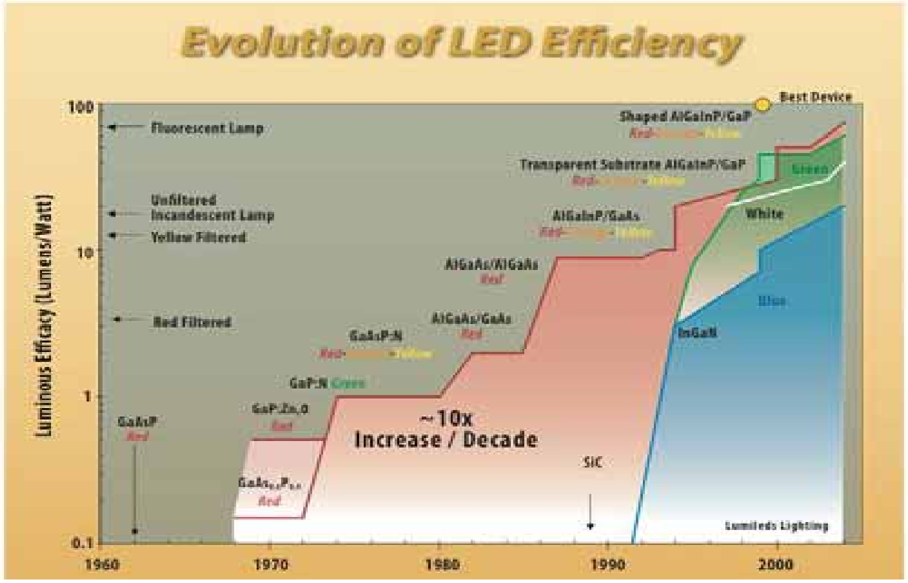
The first human nanotechnology—the modern integrated circuit (upper left), constructed from billions of individual transistors like the one shown (lower left). An example of Nature's nanotechnology—a field of sunflowers (upper right), constructed from nanoscale building blocks like DNA (lower right).

How will the energy demands of future generations be met?

The ever-increasing demand for energy coupled with related concerns about climate change make the supply and security of energy one of society's greatest challenges. The CMMP community has multiple opportunities to contribute in this area, but there are no over-arching technologies, easy solutions or magic bullets.

Priority research areas include:

- Photovoltaic cells and solar technologies
- Fuel cells and hydrogen storage
- Biocatalysis for water splitting
- Enhanced thermoelectric materials
- Rechargeable batteries and supercapacitors
- Solid-state lighting
- New materials for nuclear energy
- Catalytic processes for biofuel technologies
- Functional nanoparticles for smart materials
- New superconductors for power transmission
- Novel materials for low power computing



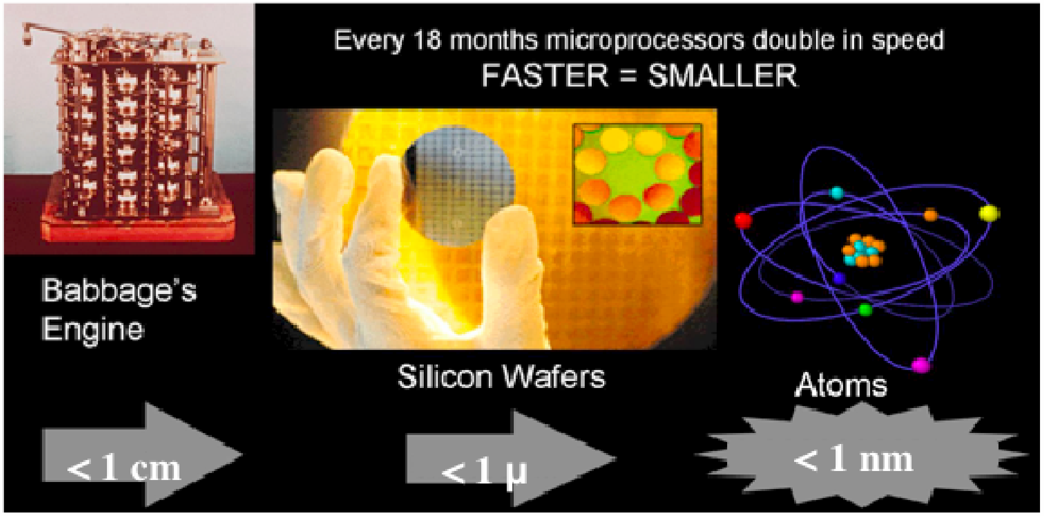
Light emitting diodes (LEDs) continue to improve in efficiency and hold strong promise for future lighting applications. LED lighting has the potential to reduce overall electricity consumption in the U.S. by about 13% over the next 20 years.

How will the information technology revolution be extended?

IT represents a watershed event in modern history: half the U.S. economy's productivity growth is due to IT. But fundamental limits of conventional devices will soon be approached. New devices based on new materials and new physics are needed. Fundamental physics and can again play a central role in the evolution of IT.

There are many routes to increased data storage, but the greatest research challenge for the future is to replace the silicon field effect transistor with new logic device concepts. What's next?

- •Organic Electronics?
- •Moletronics?
- •Spintronics?
- •Plasmonics?
- •Quantum Computing?



Past, present, and future of information technology, from Babbage's mechanical computer, to the silicon era, to perhaps atomic- and molecular-level systems in the future.

Policy Assessment

Breadth of CMMP Research

- Societal impact
  - Education
  - Economy
  - Energy
  - Medicine

- Science impact
  - Atomic, molecular, and optical physics
  - Nuclear and particle physics
  - Astrophysics
  - Chemistry
  - Biology
  - Computer science

Education

- Three challenges:
  - Education of the next generation of CMMP researchers
  - Attracting talented students to the field
  - Increasing the scientific literacy of the general public and school-age children
- The CMMP community needs to extend educational efforts to the public and student populations at all levels.

Industrial Laboratories

- In the past, many important scientific discoveries and key technological innovations occurred at the industrial laboratories.

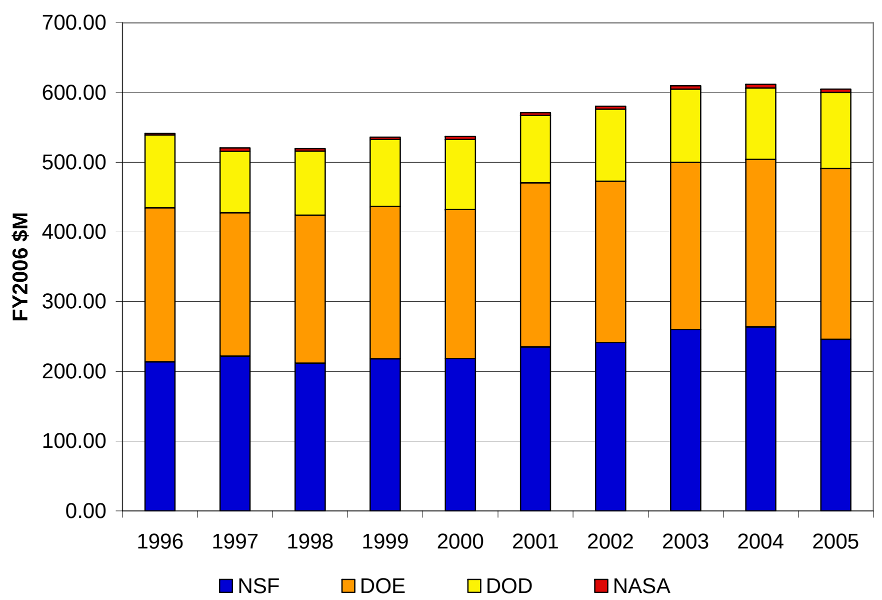
Activity	**Corporate Sponsor**	**Name & Nobel Prize Date**
Surface Chemistry	GE Labs	Langmuir, 1932
Electron Diffraction	Bell Labs	Davisson and Thomson, 1937
Transistor	Bell Labs	Bardeen, Brattain, and Shockley, 1956
Maser-Laser	Bell Labs/Columbia	Townes, Basov, and Prokhorov, 1964
Quantum Tunnel Junctions	IBM/GE Labs	Esaki and Giaever, 1973
Theory of Disordered Materials	Bell Labs	Anderson, Mott, and van Vleck, 1977
Cosmic Microwave Background Radiation	Bell Labs	Penzias and Wilson, 1978
Scanning Tunneling Microscopy	IBM	Binnig and Rohrer, 1986
High Temperature Superconductivity	IBM	Bednorz and Muller, 1987
Quantum Hall Effect	Bell Labs	Laughlin, Stormer, and Tsui, 1998
Integrated Circuit	Texas Instruments	Kilby, 2000

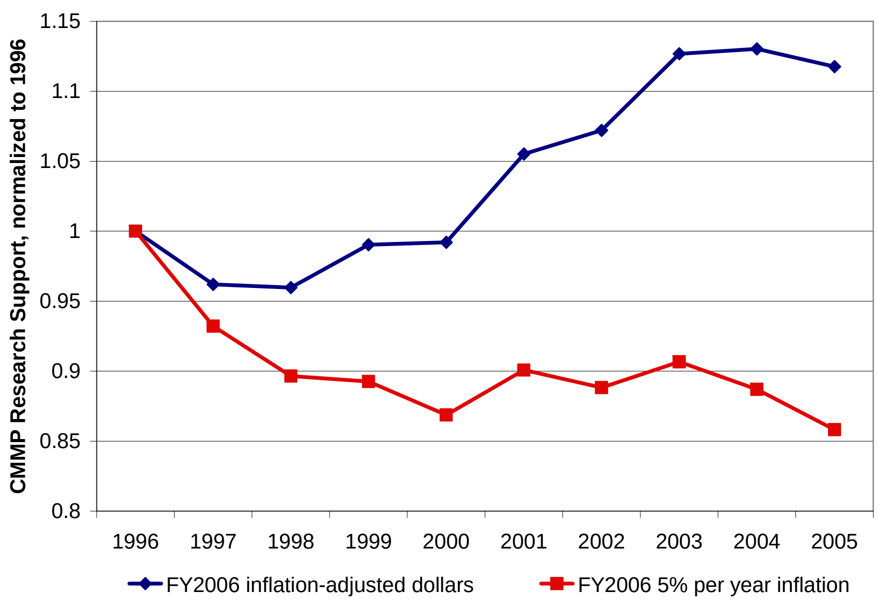
Industrial Laboratories

- The industrial laboratories served as incubators for today's academic and corporate leaders.
- In the U.S., industrial laboratories are now focused on much shorter-term research and development goals, with little emphasis on fundamental, basic research.
- New approaches to technological innovation are needed in the U.S.

Investment in CMMP Research

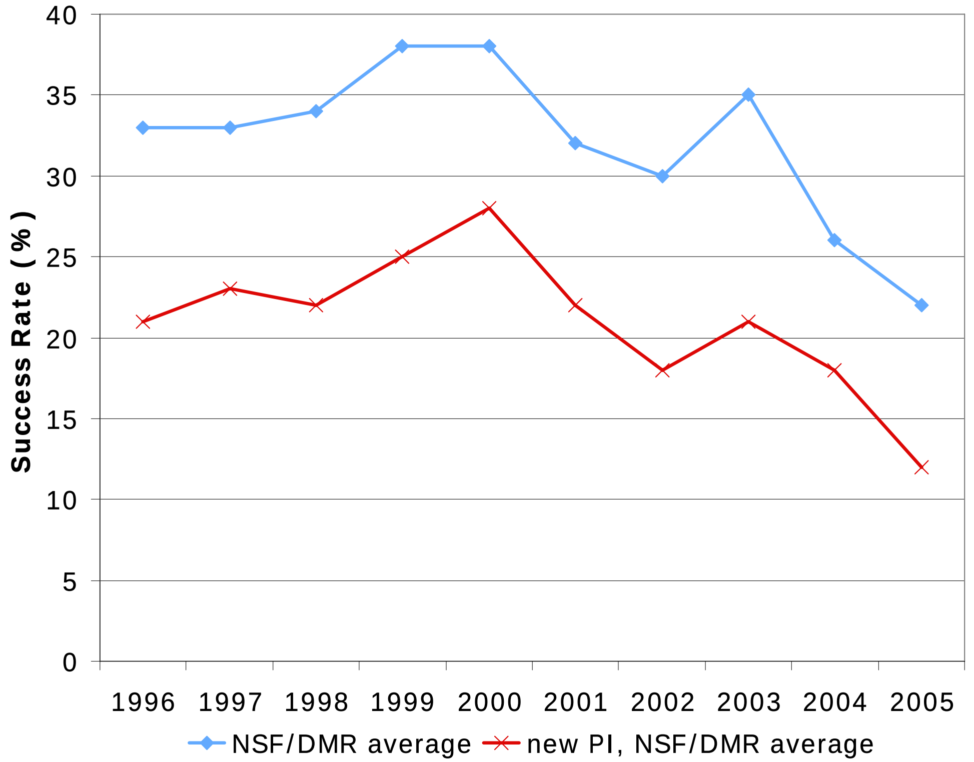
- Federal research funding for CMMP has been approximately flat in the U.S. in inflation-adjusted dollars over the past decade.
- The buying power has decreased by about 15% over the past decade.
- Other parts of the world are investing heavily in CMMP research and development.





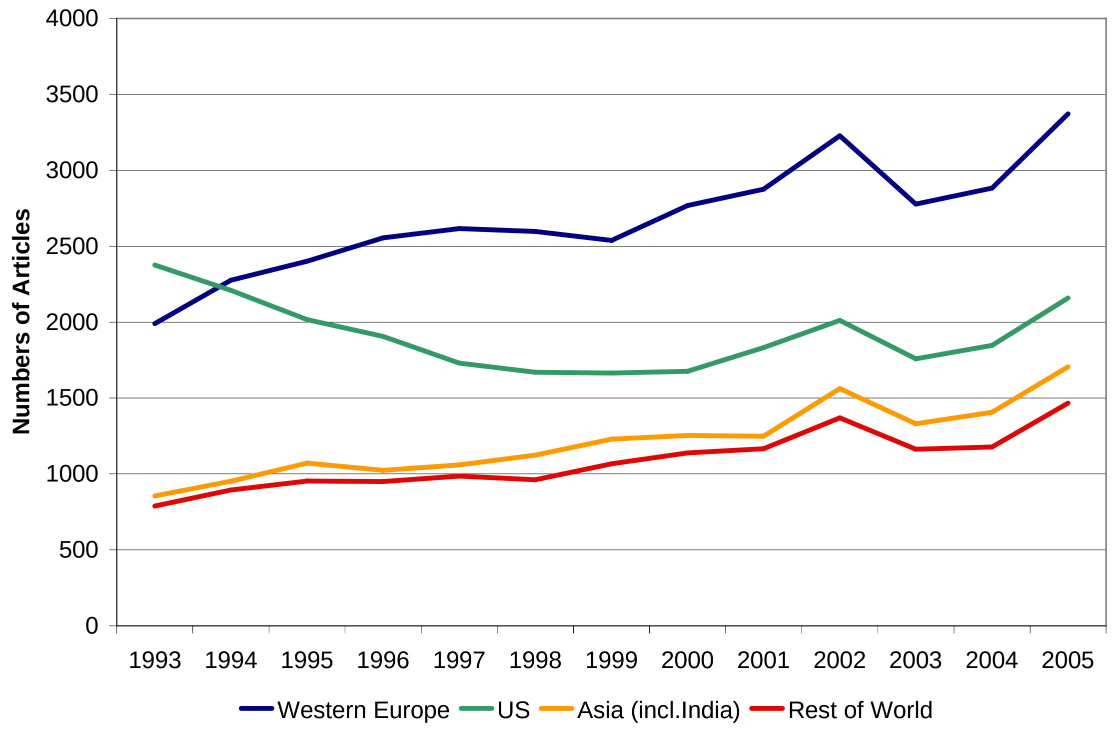
CMMP Research Proposal Success Rates

- Low success rates for funding of research proposals reveal hidden “overhead” of writing and reviewing proposals, lowering the efficiency of the scientific community and lowering the morale of new investigators.



Publications in CMMP Research

- U.S. leadership in CMMP articles published in leading journals, Physical Review B (PRB) and Physical Review E (PRE), is eroding.
- The U.S. share of total publications has fallen from 40% in 1993 to 25% in 2005.



Warning Signs

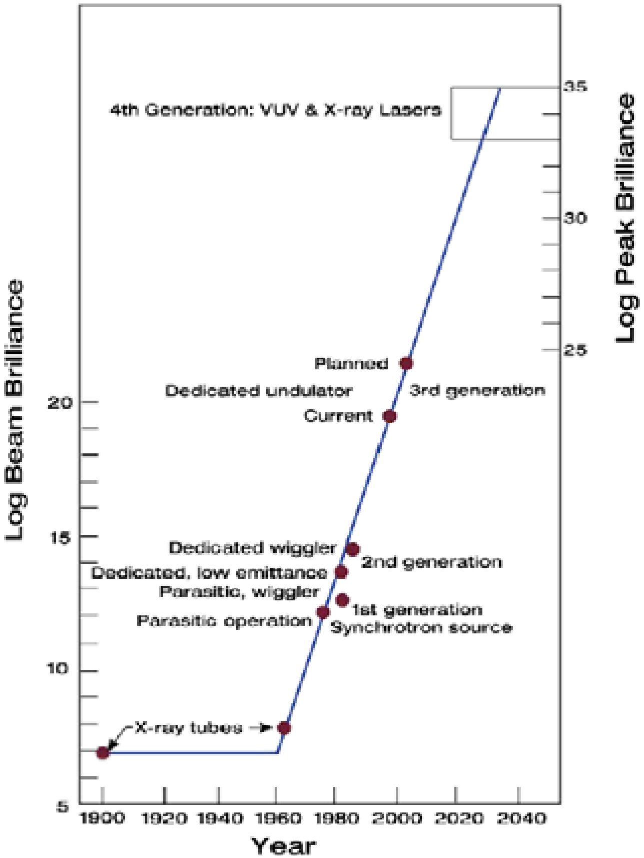
- With the changing focus of industrial research laboratories and increasing investments abroad, US leadership in CMMP is uncertain
- Flat funding of CMMP over the last decade
- US is not participating well in the world growth of the field
- Recent advances and discoveries in CMMP occurring elsewhere

CMMP 2010 Facilities Workshop

- Convened government and scientific stakeholders 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 was to generate ideas and (some) consensus on the facilities priorities of the CMMP community (a charge to the committee)
- Plenary speakers; four concurrent breakout sessions on light sources, neutron sources, magnetic fields and electron microscopy, and cross-cutting facilities (nano, materials synthesis); breakout session reports at the end of the meeting
- Attendance: 6 committee members, 30 invited speakers, 38 registered attendees
- *There is a need for ongoing input from the community concerning priorities for future facilities.*

Tools, Instrumentation, and Facilities for CMMP Research

- CMMP researchers develop new tools and instrumentation for use by scientists in many disciplines.
- Measurement techniques designed to probe the properties of matter at smaller length, time, or energy scales, or with greater quantitative resolution and sensitivity, advance the forefront of CMMP research.
- There are new opportunities and needs for facilities locally, regionally, and nationally.



With increases in X-ray brilliance over the last century, synchrotron sources of increasing capability were developed. With careful planning, advanced 3rd and 4th generation synchrotron sources being developed now will afford access to frontier physics research.

Recommendations (1)
Realizing the Benefits of CMMP for the Nation

1. Basic research in CMMP contributes to the economic strength and leadership of the United States. The following three recommendations are aimed at ensuring scientific progress on the challenges identified in this report and continued technological innovation to benefit the United States.

   - Strong support should be maintained for individual and small groups of investigators, which are historically the primary source of innovation in CMMP. The ratio of support for individual and small groups of investigators relative to centers and facilities should not decline in the next decade.
   - The average success rates in funding proposals should be increased to over 30% in five years to give junior scientists the opportunity to obtain results before the tenure decision, and to enable presently-funded researchers to maintain continuity in their research programs.
   - The size of grants to individual and small groups of investigators should be increased to maintain the buying power of the average grant and to retain scientific talent in the U.S.

Recommendations (2)
Organization of the CMMP Research Community

2. Funding agencies should develop more effective approaches toward nurturing emerging interdisciplinary areas for which no established reviewer base now exists. The CMMP community should organize sessions at national meetings to engage funding agencies and the community in a dialogue on best practices for proposal review and for the support of these non-traditional, rapidly-evolving areas.
3. Outreach, K-12, and undergraduate science education initiatives should be supported via supplemental or stand-alone grants administered by separate NSF and Department of Education programs, instead of through individual research grant awards. In the present system, the quality of outreach programs is a criterion in the evaluation of NSF/DMR research grants. The present approach confuses two conceptually distinct goals to the point where neither is optimally served. The funding agencies and research community both want outreach programs to succeed, and they should confer to determine how best to implement this effort.
4. The CMMP community should work to improve the representation of women and underrepresented minorities in CMMP through mentoring; providing flexible working conditions, daycare opportunities and viable career paths; and developing outreach programs to students and the public aimed at increasing the pipeline.

Recommendations (3)
Economic Impact and Basic Research

5. OSTP should convene a study with participation from DOE, DOD, NSF, NIST, the physics community, and corporate America to evaluate the performance of R&D activities that might replace the basic science previously done by the large industrial laboratories, and the contributions that these laboratories made to the training of future scientific leaders and educators. This next decade will involve a series of new approaches to long-term research and development designed to recapture the ability to work on large difficult projects based on fundamental CMMP research. Such an evaluation should be an ongoing activity of OSTP since it may be several years before the performance of these activities can be adequately evaluated.

6. The DOE and NSF should develop distributed national facilities in support of the design, discovery, and growth of new materials for both fundamental and applied CMMP research. A current NRC study on an “Assessment of and Outlook for New Materials Synthesis and Crystal Growth” should make detailed recommendations on how to best support this need.

Recommendations (4)

Advanced Facilities and Tools for CMMP Research

7. State-of-the-art instrumentation and facilities are critical to CMMP and will be even more critical during the next decade. The committee's top priority recommendations for instrumentation and facilities follow below. The committee also recommends action on the priorities for mid-scale instrumentation identified in a recent National Research Council report.[1] Further recommendations on light sources, neutron sources, electron microscopy, magnetic field facilities, and nanocenters can be found in Chapter 11.
   - DOE and NSF, partnering with NIH and NIST, should create a consortium[2] focused on research and development needs required for next generation light sources. The consortium, with an independent chairman, should include stakeholders from universities, industry, and government (both laboratories and agencies). The consortium should formulate a light source technology roadmap and make recommendations on the R&D needed to reach milestones on the roadmap for a new generation of light sources, such as seeded x-ray free electron lasers, energy-recovery linac driven devices, and other promising concepts. The consortium should also take into account cost containment and internationalization of research facilities. The sponsoring agencies of the consortium should fund the R&D needed to reach the milestones on the roadmap.
   - DOE should complete the instrument suite for the Spallation Neutron Source (SNS), together with the provision of state-of-the-art ancillary equipment for these instruments in order to gain the maximum benefit from the recent investment in the SNS.
   - DOE and NSF should support CMMP community needs for electron microscopy instrumentation at universities on a competitive basis. Cutting edge electron microscopy technique development (such as the DOE TEAM project) should be continued to fully re-establish U.S. competitiveness in developing the next generation of electron microscopes.
   - The NSF should continue the support of the National High Magnetic Field Laboratory and high magnetic field instrumentation development following the priorities recommended by the recent NRC report on Opportunities in High Magnetic Field Science.[3]

1. National Research Council, *Midsize Facilities: The Infrastructure for Materials Research*, Washington, D.C., The National Academies Press, 2006.
2. The committee used the term "consortium" in the sense of a partnership among the stakeholders described in the recommendation for developing a light source technology roadmap. The committee expects that the "consortium" will follow federal rules for providing advice to federal agencies.
3. National Research Council, *Opportunities in High Magnetic Field Science*, Washington, D.C., The National Academies Press, 2005.

Looking Back, Moving Forward

Final Report (Slide from Fall 2006 SSSC Meeting)

- Will be released in spring 2007 (we made our deadline)
- 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? (the logic and approach was addressed)
  - How can we promote and reward high-risk, high-creativity research? (the logic and approach was addressed)
  - How can we tackle larger-scale, longer-term problems that require the coordinated work of large teams? (big interest in government, needs more discussion)
  - What are the future instrumentation and facility needs for CMMP? (addressed by the CMMP Facilities Workshop)
  - 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? (address in part)
  - 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? (addressed in part)

Some difficulties encountered with the interim report and the final 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.

Dissemination Activities

- Initial round of DC briefings on June 8, 2007
  - Senate Energy staff, OSTP/OMB, NSF/DOE, House Science and Technology Committee staff
- Briefing to the Executive Committee of the AIP Governing Board on both the interim report and the final report.
- Second round of DC briefings on November 7, 2007
  - Ray Orbach, DOE Under Secretary for Science; Jack Marburger, OSTP Director; House and Senate Appropriations staff
- Write-ups on the report:
  - EurekAlert (June 12, 2007)
  - FirstScience.com (June 12, 2007)
  - The A to Z of Materials (June 14, 2007)
  - ars technica (June 15, 2007)
  - FYI, American Institute of Physics (June 21, 2007)
  - DCMP Newsletter, American Physical Society (Summer 2007)
  - MRS Bulletin (Forthcoming)

DOE Basic Energy Sciences Advisory Committee: Impact of CMMP 2010???

- Charge to BESAC (September 20, 2007):
  - Consider the characteristics of the next generation light sources that will address the scientific and technological challenges put for in the Basic Research Needs workshops reports and the BESAC Grand Challenge study and that will enable new and innovative ways of probing our material world in the 21st Century.
  - The characteristics to be specified are the standard ones used to describe light sources: wavelength, flux, brightness, emittance, coherence, pulse length, potential instrument suite, availability and reliability of the entire system, and user accessibility. The charge excludes consideration of the many specific pre-proposals or proposals for light sources that are currently being discussed in the community. However, the capabilities of various types of light sources (including lasers, storage-ring-based and linac-based light sources, or other types of light sources) should be evaluated against the preferred characteristics of the new light sources. Both upgrades and new facility concepts may be considered in this context.
  - The work of the BESAC subcommittee should be reported to BESAC at its summer 2008 meeting.