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Condensed Matter and Materials Physics APS Midterm Renewal Science Case

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October 20, 2008

Committee

Sam Bader (MSD) chair	Former CMMP2010, DMP Chair
Sue Coppersmith (UW-Madison)	Condensed Matter Theory
John Freeland (APS)	X-ray Studies of Complex Materials
Pat Mooney (SFU, Canada)	Semiconductors, former IBM
Julia Phillips (SNL-ABQ)	former MRS president
Ivan Schuller (UCSD)	MRS Medalist
Gopal Shenoy (APS)	Advanced Energy Research Applications
Brian Stephenson (MSD)	*in situ* growth

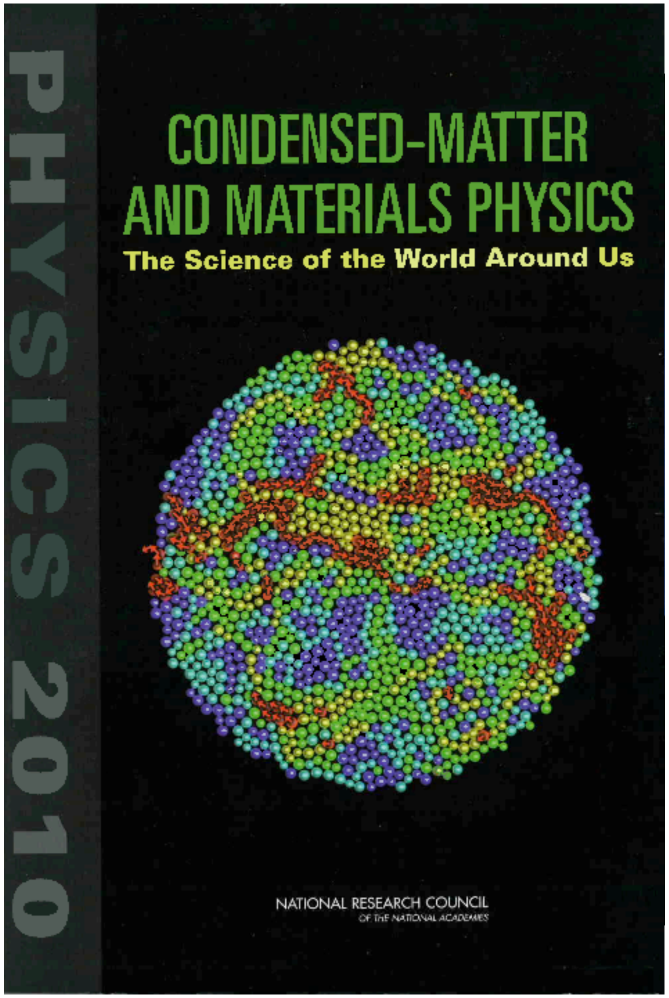
What is condensed matter and materials physics (CMMP)?

- CMMP embraces "the science of the world around us."
- It involves the *creation* of advanced materials,
- the *exploration* of their properties,
- and an *understanding* in terms of both the theoretical underpinnings of the phenomena of interest, and the structure-properties relationships exhibited.

CREATE

EXPLORE

UNDERSTAND



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?

Our Strategy

Outline exciting scientific questions and then make a general assessment of how the Advanced Photon Source can develop new research areas and infrastructure to tackle these problems

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.

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

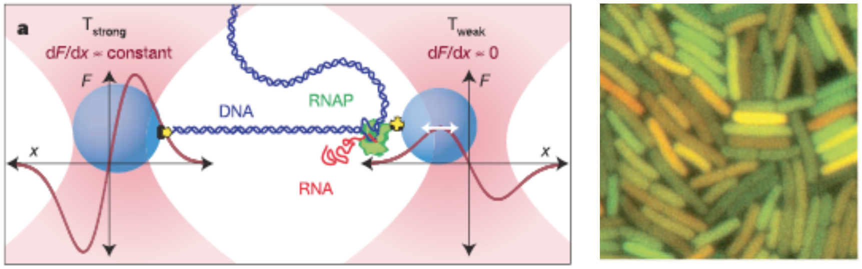
• The challenge for the future is to understand how collective phenomena emerge, to discover new ones, and to determine which microscopic details are unimportant and which are essential.

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?

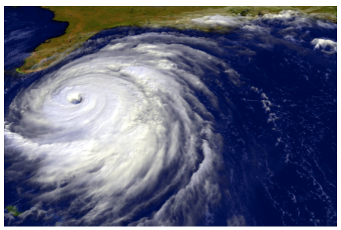
Today's physicists are learning "the facts of life" and asking new and different questions about these remarkable phenomena. Technically challenging, quantitative experiments are making precise our qualitative impressions of these phenomena. The breadth of this activity is enormous, from the dynamics 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.



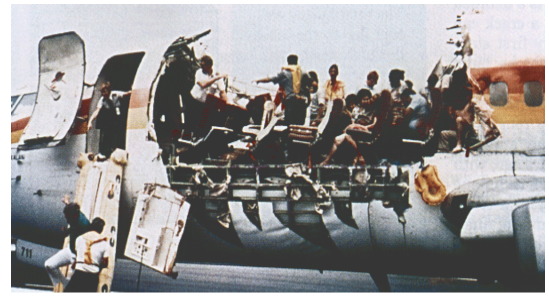
New questions and new methods for exploring the physics of life. Left: Optical trapping makes it possible to observe the "reading" of the genetic code by a single molecule of RNA polymerase (RNAP) Right: Genetic engineering and fluorescence microscopy are combined to observe the intrinsic noise as cells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

What happens far from equilibrium and why?

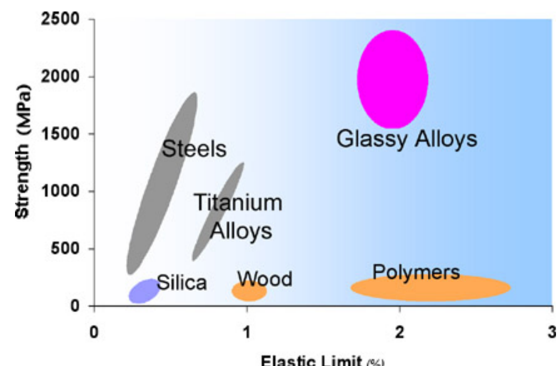


Swarming schools of fish, swirling storms and galaxies (top to bottom) are all examples of systems formed and evolving far from equilibrium.

- 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.



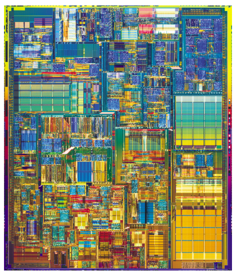
Far-from-equilibrium processing produces some of the highest strength materials (glassy metal alloys).

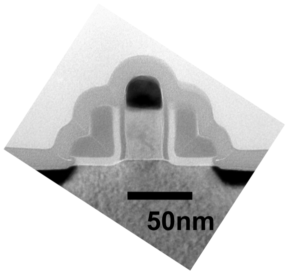
What new discoveries await us in the nanoworld?

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?

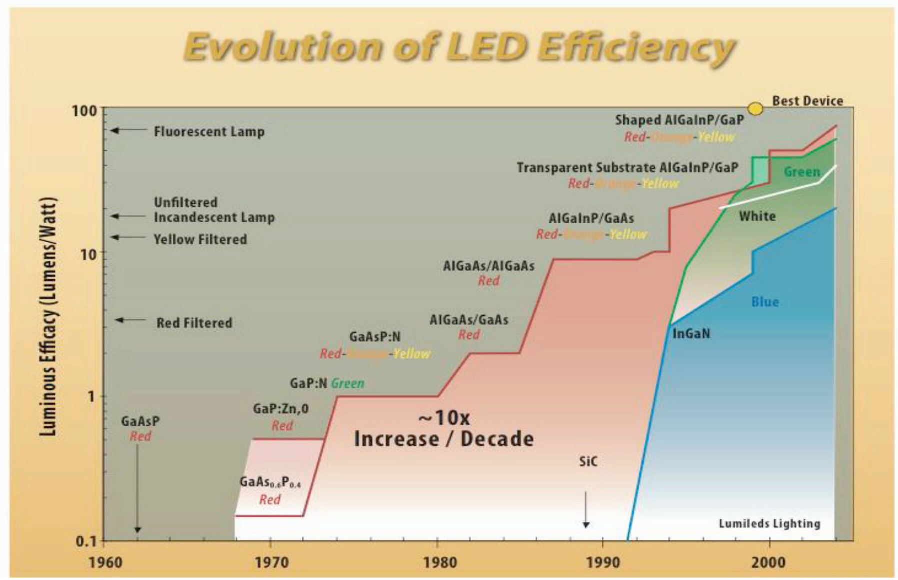




How will the energy demands of future generations be met?

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

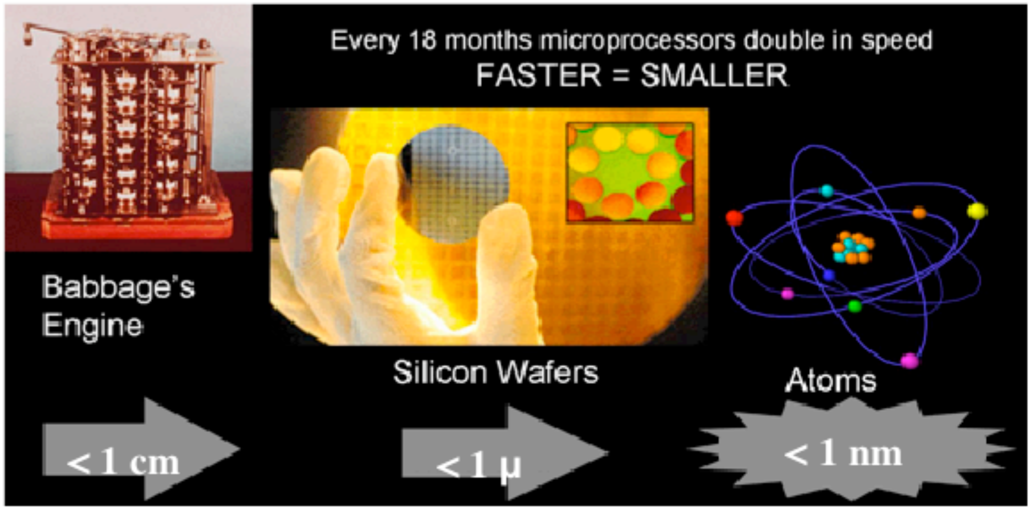


How will the information technology revolution be extended?

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.

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.

How can APS tackle these problems?

What is needed?

New approach to how experiments are undertaken at large scale user facilities!

Bring the lab to the synchrotron!

Multi-Scale Studies

Atomic to Mesoscopic to Macroscopic

X-rays to Optical

psec to seconds

How To Meet The Needs?

- Enable long term access (1-3 years) in order to merge the expertise of scientific collaborators with those of x-ray scientists

- Expansion in facilities to bring widely applicable, powerful hard x-ray synchrotron techniques such as high resolution scattering coherent imaging, and spectroscopy to bear on a greater variety of materials and processes.

- An appropriate balance of facilities for specialized, high performance, niche techniques (*e.g*. inelastic scattering, magnetic scattering, ultra-fast, and coherent x-ray techniques).

- Theory!!!

What Types of Infrastructure Is Required?

- Multiple, Ancillary and Complementary Probes
  - bulk property measurements and external stimulation (e.g. lasers, fields)
- Combinations of Extreme Environments (Static and Dynamic)
  - Temperatures, Pressures, Fields, ...
- ***in-situ*** Studies: Processing
  - catalysis, chemical reaction dynamics, ...
- ***in-situ*** Studies: Materials Synthesis
  - crystals, films, foams, glasses, proteins, polymers, heterostructures and interfaces, 0D, 1D, 2D, 3D quantum structures, soft-hard matter interfaces, ...
- Portable systems to provide capabilities to multiple beamlines
- Integrated lab space for offline setup of experiments.

X-ray Source Properties

- A range of spatial resolutions extending to ~1 nm for imaging and probing with various x- ray contrast mechanisms (absorption, phase contrast, diffraction, fluorescence, spectroscopy, polarization).

- A range of temporal resolutions extending to ~1 ps to probe rapid dynamics and non- equilibrium phenomena.

Spatio-Temporal Studies!

Enhanced angular density and peak density of photons (flux/nm^2 and flux/ps)

↓

Longer undulators and higher stored current

Breakout Session

2:00 pm	Welcome and Charge – John Freeland (APS)
2:10 pm	Why add *in situ* Oxide MBE to the APS? – Darrell Schlom (Cornell)
2:30 pm	Discussion
2:40 pm	Dynamic Compression of Condensed Matter: Need for Real Time Microscopic Measurements – Yogendra M. Gupta (Washington State University)
3:00 pm	Discussion
3:10 pm	Break
3:20 pm	Using X-ray dichroism to find hidden order– Mike Norman (Argonne National Laboratory)
3:35 pm	Discussion
3:45 pm	ESRF Upgrade - Carsten Detlefs (ESRF)
3:55 pm	Open session (5 min. presentations)

- Jeff Terry – IIT – Hard x-ray photoemission
- Dave Keavney – APS – Precision XMCD
- Volker Rose (APS) – X-ray microscopy
- Zahir Islam – APS – Pulsed magnetic fields
- Michel van Veenendaal – APS/NIU – Theory

4:45 pm	Wrap-up
5:00 pm	End

Conclusions

CMMP is a field of rich physics spanning across many disciplines

Harnessing the APS will provide crucial insight into these problems

What's Next?

Formulate detailed plans for these next generation experiments