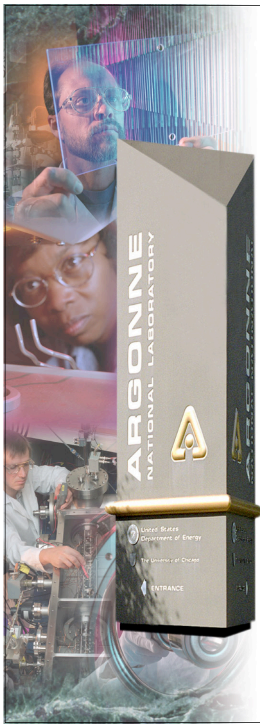


Grand Challenges in Condensed Matter and Materials Physics

Presented by

Sam Bader

at

Argonne Materials Science Division Seminar

Thursday, January 26, 2006

Argonne National Laboratory

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Office of Science
U.S. Department of Energy

Decadal Assessment and Outlook for the Field of Condensed Matter and Materials Physics (CMMP) Research

• Part of broader *Physics 2010* assessment and future outlook of the field of physics

• Conducted by the Board on Physics and Astronomy under the auspices of the National Research Council (NRC).

• The CMMP committee (~ 15 members) will prepare a report (~ two years)

• Articulate an outlook for the field

• Concentrate on compelling scientific themes.

Charge to the Committee of 15

1. Review the field - recent accomplishments, new opportunities, compelling scientific questions.
2. Identify potential future impact on other sci fields & emerging technologies.
3. How does CMMP contribute to meeting national societal needs.
4. Identify priorities for instrumentation and national user facilities.
5. How can our research enterprise realize the full potential of CMMP research?
6. Examine the research effort, compare internationally, draw conclusions.

Why Me?

- Nat'l Lab Person
- APS Div. Materials Physics
- APS Sorters' Mtg - Dec. 2003
- March Mtg 2004 - Special Evening Session
- DMP Newsletter
- NSF Proposal - Regional Workshops
- ICAM Mtg - Aspen/Snowmass, Summer 2004
- SSSC-NRC - Irvine, Oct 2004

Pioneering Science and Technology

Office of Science U.S. Department of Energy

The Quest…

Create
Explore
Understand
New Materials and Phenomena

Why…

to serve nat'l strategic missions:
- energy independence
- stimulate the economy
- healthcare innovations
- security...defense...

to enable other scientific ventures:
- lasers, x-rays, transistors, NMR
- mat'ls for space exploration
- mat'ls for particle accelerators

Defining Characteristics

Virtuosity
Curiosity
Unpredictability

- C. Slichter

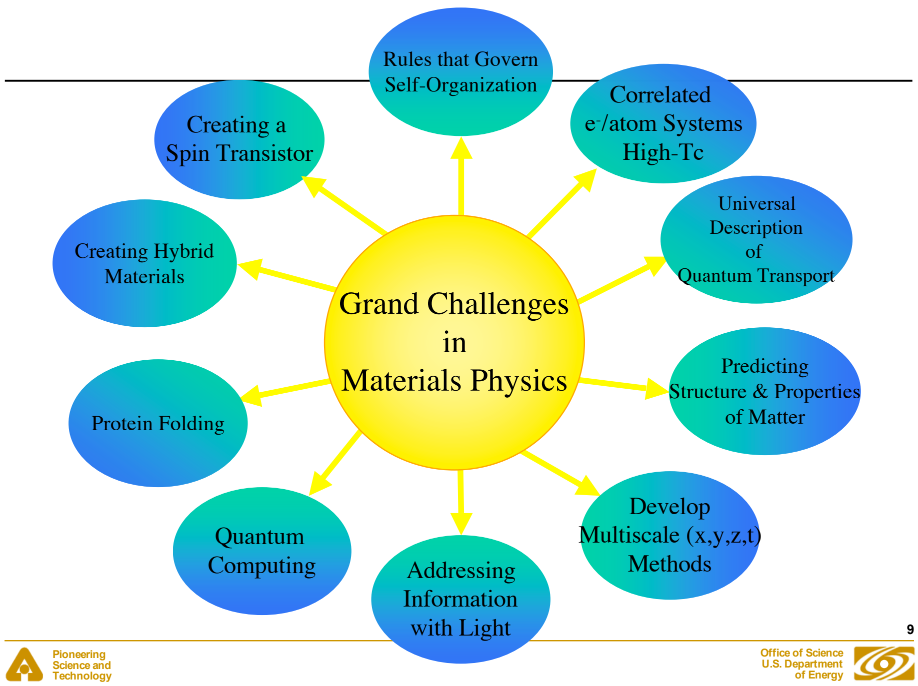
The Process

Recognition that we are a Diverse Culture:

- One Umbrella? - i.e. nano...
- Feet on the Ground - Head in the Clouds

Distillation:

- satisfy ourselves - Introspection
- satisfy our sponsors
- relate to the community at large



Working list of challenging questions:

1. What are the rules that govern phase separation (i.e. stripes)? What are the rules that govern self-organization (i.e. hierarchical assembly)?
2. How does one describe materials whose electrons are neither perfectly localized nor fully itinerant (i.e. correlated electron systems)?
3. Is there a universal description of quantum transport, including spin transport, ballistic transport, molecular transport, Kondo...?
4. Can one predict the structure and properties of matter from a knowledge of the atomic constituents alone?
5. Is it possible to develop multi-scale methods (both in time and space) to predict the properties of matter?
6. How does one address information with light?
7. What are the ramifications of quantum entanglement and coherency in computation?
8. What is the theory of high-Tc superconductivity? What interactions can successfully pair electrons?
9. Can we integrate materials whose properties tend to be mutually exclusive, such as "ferromagnetic and superconducting," "photonic and semiconducting" and "bio and inorganic"?
10. Can one find nearly 100% spin polarized electron sources and retain interfacial control? Can one create a spin transistor with gain to enable spintronic applications? Can one find magnetic semiconductors that operate well above room temperature?

http://www7.nationalacademies.org/bpa/Bader_CMMP2010_Challenges.pdf

1. What are the rules that govern phase separation (*i.e.* stripes)?
   What are the rules that govern self-organization (*i.e.* hierarchical assembly)?

Self-assembly, defined as the autonomous organization of components into patterns or structures, is rapidly emerging as a major topic of critical interest. Self-assembly occurs on length scales that extend from the molecular to the cosmic. Self-assembly provides pathways to create new nanoscale materials from the bottom up that transcend the spatial limits of lithographic patterning, and is implicated as a universal feature in the physics of many complex systems, such as oxide superconductors. The thermodynamic and kinetic rules that govern self assembly, and the underlying structural and electronic properties, need to be understood in order to harness self assembly to create a new generation of advanced materials and hierarchically organized systems, as well as to get a better physical understanding of living systems. For example, how does the surface topology influence morphology?

http://www7.nationalacademies.org/bpa/sssc_committee.html

Alternate list of challenging questions Compiled by Nemanich, Sayers, and Ade:

1. Establish the energetics, kinetics and dynamics of nanoscale phenomena and self assembly.
2. Developing new approaches to precisely fabricate and engineer macroscopic materials with nanometer scale precision.
3. To develop near frictionless surfaces that are adaptive and allow sliding motion in a wide range of environments.
4. To develop the materials for the next generations of digital electronics.
5. To develop approaches to fabricate molecular patterns on solid surfaces for bio and chemical sensing applications.
6. Developing new materials for energy transfer, conversion, and storage.
7. Developing materials to enable optoelectronics from the IR (or terahertz) to X-ray.
8. Materials characterization at the nanometer scale and at times less than a femtosecond.
9. Developing nanostructures to achieve unique functionality. Developing approaches to integrate 10**15 nanostructures to achieve unique functionality.
10. Producing crystalline materials with defect densities that approach zero. Producing amorphous materials with defect densities that approach zero. Producing interfaces between materials with defect densities that approach zero.

Paul Canfield's Definition of CMP

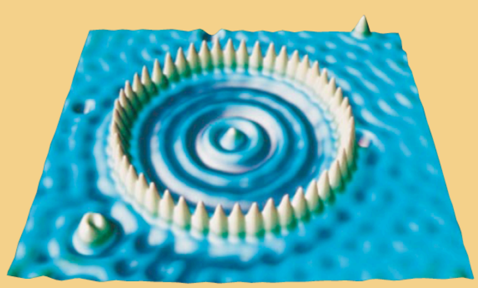
Condensed Matter Physics is the **discovery, understanding and control** of new materials and phenomena by experimental, computational and / or theoretical means.

Discovery can take place as a result of detailed experimental, theoretical, or computational efforts, or as a result of a well interpreted chance event.

Understanding is gained by careful research and analysis and often first takes place at an empirical level. Over time, as experimental and theoretical knowledge grows, understanding can evolve to a deep and profoundly detailed level.

Control of a new material or phenomenon can range from the ability to predict response or events based on an empirical or theoretical knowledge to the ability to manipulate the material or phenomenon in the form of a product or tool.

THE PHYSICS OF MATERIALS



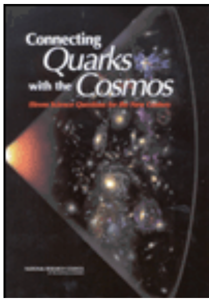
How Science Improves Our Lives

ICAM: questions on the origins of collective behavior in matter

1. *What fundamentally new classes of matter await discovery?*
2. *What is the origin of high temperature superconductivity?*
3. *What is the nature of strange metals?*
4. *What new principles of the cosmos can be discovered from a study of condensed matter?*
5. *Is quantum computation feasible?*
6. *Why don't glasses flow like liquids?*
7. *What principles govern the organization of matter away from equilibrium?*
8. *Can statistical mechanics be applied to a system as complex as the living cell?*
9. *How do singularities form in collective matter and in spacetime?*
10. *What principles govern the flow of granular materials?*
11. *What are the physical principles of biological self-organization?*

Tony Leggett: Great Questions and Challenges to CMMP

1. Why do all amorphous matls behave in the same way below 1 K?
2. Can we build a robust room-temperature superconductor? How?
3. Does quantum mechanics fail at some level of size/complexity/organization?
4. If no to the last, are there any *a priori* limits on the degree of coherence we can attain with macroscopic degrees of freedom (*e.g.*, SQUIDs)?
5. Is there a universal origin to 1/f noise?
6. Does nature exploit the phenomenon of entanglement, *e.g.*, in biological processes?
7. Are there completely new types of order to be found in condensed-matter systems?



Connecting Quarks with the Cosmos

Committee on the Physics of the Universe

NRC, NAS Press

- Advances by physicists & astronomers intertwine the very large & very small.
- The report identifies 11 key questions that can be answered in the next decade.
- It urges a new cross-disciplinary research strategy to address these questions.
- Seven recommendations with priorities to realize these scientific opportunities.

Questions from "Connecting Quarks with the Cosmos"

1. What is dark matter?
2. What is the nature of dark energy?
3. How did the universe begin?
4. Did Einstein have the last word on gravity?
5. What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
6. How do cosmic accelerators work and what are they accelerating?
7. Are protons unstable?
8. What are the new states of matter at exceedingly high density and temperature?
9. Are there additional space-time dimensions?
10. How were elements from iron to uranium made?
11. Is a new theory of matter and light needed at the highest energies?

A sampling of Gross's Q's - UCSB Theory Institute (NYT 10/04)

1. What is the dark matter that envelopes the visible galaxies?
2. Was there a time before the Big Bang, or is time an emergent concept deriving from something more fundamental that we don't know yet?
3. Can we measure the onset of consciousness in an infant?
4. Can the theory of evolution be made quantitative and predictable?
5. Is quantum mechanics the ultimate description of nature?
6. Can we understand big things by understanding little things?
7. When will computers become creative theoretical physicists? And how will we train them?
8. Will physics still continue to be important?

NAS Discussion (continued)

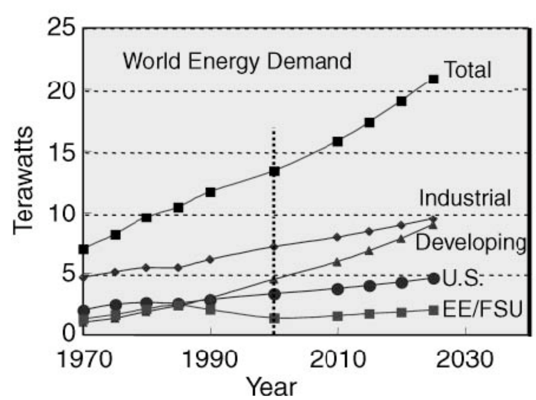
- How can the nation create a system that supports the synthesis of new materials?
- What problems can be solved using advanced computation, and what are its limitations and technical requirements?
- What are the prospects for new technologies emerging from CMMP that could ameliorate the problems associated with global energy consumption?
- What types of new capabilities in sensing, imaging, and characterizing condensed matter will be needed to advance both physical sciences and life sciences?
- What new large and small facilities will be needed to solve the great problems of CMMP?
- As problems become increasingly complex, how will the nation provide access to critical facilities and what mechanisms will be needed to nurture interdisciplinary collaborations?
- Given the changing landscape for manufacturing in the world, how can CMMP have the greatest positive impact on society? Will understanding of new materials and phenomena be needed and if so which ones? Given the shortened time horizon of industrial R&D what should be the role of government and university research?

Preliminary Questions Developed by BESAC for all of BES

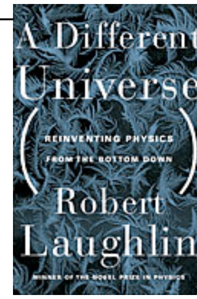
1. What are the fundamental phases of matter (no longer just solid, liquid, and gas, but also liquid crystals [many phases], plasmas, BEC, superfluidity, superconductivity, ferromagnetic/paramagetic materials, and more); can we understand, model, predict, and harness phase transitions; and what are the implications for other fields of science?
2. Why does the quasiparticle construct – the "standard model" of condensed matter physics – fail for large classes of materials, and what is beyond the standard model?
3. What is the nature of the chemical bond (revisited)? How do the strong and weak interatomic forces, acting in concert, guide reactivity and molecular rearrangements/folding?
4. How do electrons, atoms, molecules, cells, and organisms naturally communicate between and among one another, and over what distances do communications occur? Can we predict how communication affects the evolution of things on all scales? Can we harness the properties of elementary particles, atoms, and molecules to create fundamentally new ways to store, manipulate, and transmit information?
5. Are there as-yet-undiscovered organizing principles at the nanoscopic and mesoscopic scales, intermediate between atomic and macroscopic dimensions?
6. To what extent are reductionist approaches to phenomena limited, and where limits exist, what is to be done? Can we predict and control emergent properties?
7. What are the molecular origins of the evolution of life? Can this understanding guide future synthesis paths and functional synthetic diversity?

There is No Shortage of Good Questions

The challenge is to use them to weave a powerful story.



Robert Laughlin: *A Different Universe*



From Age of Reductionism to the Age of Emergence

Is there a transition from the age of physics to the age of biology?

But instead: "What we are seeing is a transformation of worldview in which the objective of understanding nature by breaking it down into ever smaller parts is supplanted by the objective of understanding how nature organizes itself." p. 76

"…a time when the search for ultimate causes of things shifts from the behavior of the parts to the behavior of the collective."

…there can be no doubt that the dominant paradigm now is organizational.

….. the search for a single ultimate truth…[has] ended…
nature is revealed as an enormous tower of truths…like Columbus or Marco Polo, we set out to explore a new country but instead discovered a new world." p. 208

The End of the Age of Reductionism

"Is Einstein relevant anymore?...

but the deeper sense of the question..[is]..whether fundamental things still matter and whether there are any more of them left to discover. p. 217

"…there is much, much more yet to come." p. 218 "We live not at the end of discovery, but at the end of reductionism…This is not to say that microscopic law is wrong…but only rendered irrelevant in many circumstances by its children and its children's children, the higher organizational laws of the world. p. 221 (end)

The Age of Emergence

"Emergence means complex organizational structure growing out of simple rules.

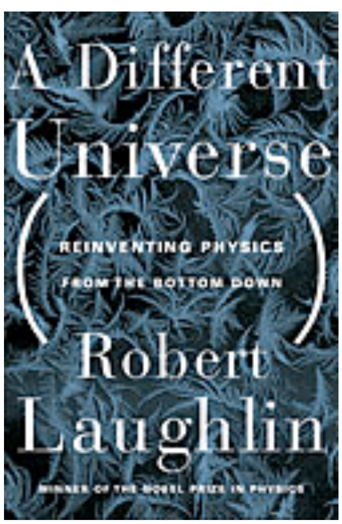
Emergence means stable inevitability in the way certain things are.

Emergence means unpredictability, in the sense of small events causing great and qualitative changes in larger ones.

Emergence means the fundamental impossibility of control.

Emergence is a law of nature to which humans are subservient."
pp. 200-201.

Can we agree on what's important?



"The concept of emergence, touted as a revolutionary new paradigm, turns out at the end of the day to be little more than a catchall label for a miscellaneous collections of things we all understood perfectly well already. As an explanatory or even heuristic principle in its own right, 'emergence' is completely vacuous."

-Tony Leggett

***Physics Today*, 10/05**

Laughlin Unplugged

"String theory is … fun to think about [but]…has no practical utility,…other than to sustain the myth of the ultimate theory. There is no experimental evidence for strings in nature,… it is instead the tragic consequence of an obsolete belief system – in which emergence plays no role…" pp. 211-212

"While our knowledge of the nanoscale is exploding almost incomprehensibly at the moment, nearly all of it is deeply unimportant. Predicting great new technologies from this situation is like predicting lasers from the existence of Christmas ornaments." p. 135

P. W. Anderson on Laughlin's ideas

A Different Universe is a book about what physics really is;

it is not only unique, it is an almost indispensable counterbalance to the recent proliferation of books by Brian Greene, Stephen Hawking and their fellows, who promulgate the idea that physics is a science predominantly of deep, quasi-theological speculations about the ultimate nature of things.

The Challenge Ahead

I hope that this stimulates thought, discussion and new ideas,
new ways to look at who we are and why what we do is essential.

Most important would be if we can use this process to expand the funding pot, rather than just each trying to get a bigger piece of the pie in a zero-sum scenario.

Can we educate and influence science policymakers?

Can we make our quest compelling in the popular press to capture the imagination of the general public?