Frontiers in Correlated Matter

Scientists Discuss Intellectual Challenges of Complex Adaptive Matter

http://icam.ucop.edu

One of the great surprises about matter is that as it becomes more complex, it develops new, often unexpected classes of behavior. The rigid crystallinity of a snowflake, the levitation of superconductors, the elasticity of rubber, and the formation and stability of cells in organisms are each examples of properties that emerge from new correlations among the basic building blocks of matter. The understanding of such "correlated" matter, in which knowledge of one microscopic feature (electron, molecule, excitation, or fluctuation) allows prediction of another nearby in space or time, has strong bearing on the development of new materials, but it also continues to shed light on fundamental physics because correlations are of great interest in condensed-matter physics.

During August 5–8, 2004, leading physicists studying condensed matter convened for a conference on "Frontiers in Correlated Matter" in Snowmass, Colo. The meeting was sponsored by the Institute for Complex Adaptive Matter (ICAM), an international consortium of universities and laboratories committed to research into the principles that govern collective behavior—that is, many features acting similarly and cooperatively—in matter. ICAM conceived Frontiers in Correlated Matter as a way of bringing together leading physicists of condensed matter across a broad spectrum of research—ranging from cold "hard" quantum matter to "soft" and biological matter—to address the intellectual challenges of this frontier field and devise ways of projecting its excitement to the general public.

Each of the 25 speakers at the summit was invited to lead an interactive discussion about the questions surrounding his or her research, and as a particular challenge, the speakers were asked to describe how they would explain the quest and excitement to a 10-year-old child. Several members of the science outreach community were also invited to participate in the meeting, and in a small outreach workshop that preceded the meeting, there were several lively and optimistic series of discussions between physicists of condensed matter and members of the museum community, artists, and film-makers interested in telling the story of correlated matter (see sidebar article).

Each speaker was charged with the task of presenting 10-minute talks that emphasized the big questions and challenges behind their areas of research and served to seed a 20-minute discussion and debate that followed. This format proved highly stimulating and led to an unusually interactive and frank debate in which participants were surprised by how much new physics they learned across the spectrum of emergent-matter interests. Unlike particle physics and cosmology, condensed-matter physics, with its great diversity and scope, does not easily lend itself to a simple set of grand challenges. Nevertheless, an interesting debate on the big questions, and the best way of coupling them to the big challenges facing society today, did ensue.

Despite the appealing diversity of fundamental problems that were presented,

"Emergent Matter Project" Summit Meeting to Mount Outreach Effort

With seed support from the Richard Lounsbery Foundation, the Institute for Complex Adaptive Matter (ICAM) established the Emergent Matter Project. As one of its first activities, ICAM held a one-day educational and public outreach summit, "Telling the Emergent Matter Story," on August 4, 2004, in Snowmass, Colo. The summit was connected to the ICAM meeting on "Frontiers in Correlated Matter," which began one day after the summit. The summit brought together the leaders of ICAM (Greg Boebinger, Daniel Cox, Al Hurd, Bob Laughlin, David Pines, and Peter Wolynes), the American Physical Society (Sam Bader, Marvin Cohen, and Myriam Sarachik), the Materials Research Society (Shenda Baker and Betsy Fleischer), the National Academies—National Research Council (Pierre Hohenberg and Marc Kastner), and the National Science Foundation (Lance Haworth), along with leaders of science museums (Barry Aprison, Museum of Science and Industry; Hooley MacLaughlin, Ontario Science Centre; and Rob Semper, Exploratorium), a science documentary film-maker (Linda Feferman), a physics-in-theater expert (Brian Schwartz), a science illustrator and exhibit developer (Tom Rockwell), an outreach grant expert (Carol Inman), and a U.S. congressional staff member (Eric Werwa of Rep. Mike Honda's office).

Following talks by Laughlin (Stanford University), George Whitesides (Harvard University), Seamus Davis (Cornell University), and Piers Coleman (Rutgers University), who gave examples of the search for organizing principles responsible for emergent behavior in matter, and by Leo Kadanoff (University of Chicago) on his museum outreach efforts, the participants gave brief talks on mechanisms for public and educational outreach. There was lively discussion throughout the day; it led to a consensus that it is timely and important to form an ICAM-led alliance (involving the workshop participants and many others) that will mount a major educational and public outreach effort devoted to emergent behavior in matter.

Several projects were considered. One idea is to develop museum-quality exhibitions for the Museum of Science and Industry (Chicago), the Exploratorium (San Francisco), the Ontario Science Centre (Toronto), and others that could be used as a basis for an interactive virtual museum on an ICAM Web site.

Another project involves developing a video on emergent behavior in matter for the ICAM Web site. The video could be used in preparing a television series through major educational television producers (e.g., NOVA, Public Broadcasting Service, and the Discovery Channel), with funding from the National Science Foundation and/or the Sloan Foundation.

To develop an educational outreach network on emergent matter, scientists at ICAM branches and elsewhere could collaborate on the development of new curricula at the college level. The focus of this project would be to provide a library of pedagogical materials dealing with emergent behavior in matter. ICAM would then establish a Web site devoted to curriculum reform to help faculty members, who are designing new courses, to exchange views.

Updates on the Emergent Matter Project will be posted on the ICAM Web site, http://icam.ucop.edu.

there were a number of fascinating common themes. Many participants expressed the view that major generational advances in materials research depend critically on a freedom to pursue experiment over wide regions of parameter space without a view to immediate application; that without this freedom, it is impossible to develop the intellectual framework required to understand and develop new classes of material behavior. Z. Fisk (University of California, Davis) described how insights into the strongly correlated *d*-electron oxide materials were being gained from parallel studies of *f*-electron materials. M. Cates (University of Edinburgh, Scotland) described how his group's efforts in understanding the formation and development of vesicles in colloidal biomatter benefited immensely from the study of systems that lie far outside the parameter ranges found in biology.

The meeting presented exciting problems for physicists working on the behavior of matter. In general, the work focused on newer kinds of materials than familiar liquids, gases, and solids. About a third of the meeting concerned quantum, or "hard," condensed matter. S. Davis (Cornell University) illustrated the seemingly unbounded potential for discovery of new types of quantum matter, showing tunneling spectroscopy measurements that suggest that electrons in certain high-temperature superconductors form a new kind of "supersolid" (see Figure 1), a crystal of electron pairs that simultaneously possesses the zero-resistance properties of a superconductor. Another major topic was quantum phase transitions, which occur when a finite temperature phase transition is suppressed to zero. These were likened to a kind of "black hole singularity" in the materials phase diagram because of their profound abilities to transform the properties of the material across a wide range of temperatures near to the quantum phase transition. G. Lonzarich (Cambridge University) and F. Steglich (Max Planck Institute of Chemical Physics, Dresden) showed many examples of how magnetic quantum phase transitions transform materials, giving rise to new kinds of strange metals and often inducing superconductivity. An understanding of this area may herald a fusion of ideas from statistical mechanics and correlated electron physics.

One broad class of research looked at how materials could fall into jammed configurations in which they would move very slowly, remember their past, and maintain interesting structures over long periods of time. T. Witten (University of Chicago) demonstrated the memory in a crumpled piece of paper (see Figure 2). This paper can have sharp corners and folds that remain even after one tries to straighten out the paper. The corners represent an energy focusing, and provide an example of how small objects may form from large ones. This problem is presented in a much larger context as parts of the study of the development of structures in the motion of fluids and elastic systems. A sheet of plastic, like a plastic bag, can—when ripped—produce a riffled structure with riffles of all sizes included. Fluids can be made to come to a point forming very thin necks. Witten speculated that there may be a whole new science of matter singularities connected with these observations.

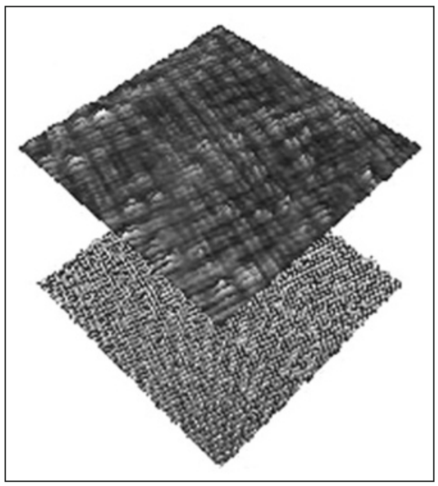

Figure 1. Scanning tunneling microscope image showing the formation of an electronic crystal that coexists with electronic superconductivity—a possible "supersolid." (Courtesy of S. Davis.)

Figure 2. A crumpled piece of paper illustrates the open problem of understanding the development of memory and the focusing of energy in correlated matter.

Another class of work focused on the forms and groupings of molecules in biological systems and how those structures affect dynamical properties and biological functioning. Several of the participants discussed how ideas of condensed matter are starting to shape problems of biological complexity. R. Goldstein (University of Arizona) described how fluids acquire new structure and develop new flow patterns in response to the forces derived from the flagella of bacteria (see Figure 3). Understanding such "live fluids," he said, will require an innovative fusion of ideas from biology and fluid dynamics.

G. Whitesides (Harvard University) observed that life, and that cells are just one of many complex systems that populate the world, including weather and economic systems, large networks such as the human nervous system, computers, information systems, and energy distribution grids. The ability to understand and control the complex behavior of these systems, he argued, is a central problem in science and engineering. Whitesides expressed optimism that biology is slowly developing the kinds of reproducible experiments that will bring it into the realm of physics. In physics and chemistry, he said, we are accustomed to sets of rules and laws that govern our understanding—Newton's laws, Arrhenius' laws, and the application of statistical mechanics, for example. But what, he asked, are the rules for biology? The answer, according to Whitesides, will lie in discovering the principles that regulate and describe complex networks.

The meeting ended with a wide-ranging discussion about the big questions of correlated matter. A list of "millennium questions in physics" proposed by string theorists four years ago attracted wide media attention, yet not a single one concerned the challenges of condensed matter. Despite the profound impact that condensed-matter physics has had on fundamental science—notably its role in generating concepts that have influenced particle physics, cosmology, biology, and computer science—in the public eye, it is seen as a primarily technological activity. There is clearly a set of big questions that convey the aspirations of this frontier field, but still some participants expressed reservations. L. Kadanoff (University of Chicago) and M. Brenner (Harvard University) cautioned that many breakthroughs come from the little questions that lead to big answers. P. Hohenberg (New York University) expressed the need to divide such questions into "inreach" questions—more detailed issues that can be used to inspire research and attract bright students—from "outreach" questions that are broadly stated for the general public. Following are the 11 big questions that were tentatively discussed:

1. What fundamentally new classes of matter await discovery?

2. What is the origin of high-temperature superconductivity, and is room-temperature superconductivity feasible?

3. What new principles of the cosmos can be discovered from condensed matter in the laboratory?

4. What principles govern the organization of matter away from equilibrium?

5. What is the nature of strange metals?

6. Is quantum computation feasible?

7. Why do glasses not flow like liquids?

8. How do singularities form in collective matter and in space-time?

9. Can statistical mechanics be applied to a system as complex as the living cell?

10. What principles govern the flow of granular materials?

11. What are the physical principles of biological self-organization?

Figure 3. A bacteria-induced fluid convection pattern in a half-inch-diameter fluid drop. (Courtesy of R. Goldstein.)

A commentary on each question can be viewed on the Web at http://frontiers.physics.rutgers.edu. Some of the discussion material also listed on this Web site will be used in a series of town meetings planned by the American Physical Society to discuss the outreach and future directions of condensed-matter research.

The eclectic mix of topics and the interactive quality of the ICAM meeting proved surprisingly stimulating to all participants. Buoyed by the success, ICAM plans to hold another meeting, focusing more tightly on frontier aspects of materials research, in 2005.

The meeting was organized by Piers Coleman (Rutgers University), Elihu Abrahams (Rutgers University), Paul Chaikin (Princeton University), Sidney Nagel (University of Chicago), Greg Boebinger (Los Alamos National Laboratory), and Hans Frauenfelder (Los Alamos National Laboratory).

PIERS COLEMAN
Organizer, ICAM:
Frontiers in Correlated Matter

4th International Conference on Synchrotron Radiation in Materials Science Held in Grenoble

The 4th International Conference on Synchrotron Radiation in Materials Science was held August 23–25, 2004, in Grenoble, France. The main organizer was the European Synchrotron Radiation Facility (ESRF) with co-organizers from Université Joseph Fourier, Institut Laue Langevin (ILL), and the CNRS Crystallography Laboratory. Neville Greaves, University of Wales, U.K., chaired an international advisory committee, and Åke Kvick, ESRF, France, chaired the local organizing committee. More than 230 participants from 30 countries attended the meeting.

The 4th International Conference on Synchrotron Radiation in Materials Science was held August 23–25, 2004, in Grenoble, France. More than 230 participants from 30 countries attended the conference.

The conference gave a broad overview of the latest developments in the field, where the main topics were semiconductors, surfaces and interfaces, magnetic materials, clusters, engineering materials, biomaterials and polymers, glasses and amorphous materials, nanostructures, high pressure, catalysis and archaeological materials, and instrumentation and techniques. The proceedings will be published as refereed articles in a special issue of *Nuclear Instruments and Methods B*.

The conference illustrated rapid progress in a variety of areas of materials science. It was noted that the use of high-energy photons, *in situ* studies, time-resolved investigations, and a combination of methods are increasingly important. The use of high-energy photons (>50 keV), for instance, has several advantages: higher spatial resolution, smaller correction terms for absorption, and large penetration depth, allowing bulk studies and investigations in absorbing sample environments. Examples were given for medium-range structural studies of glasses and superconductors using high-resolution pair-distribution functions. High-energy x-rays are now also used to obtain unparalled nondestructive information on crack mechanisms, grains, grain boundaries, and stress/strain relationships. Also at this meeting, the number of x-ray methods that were quantitative, where formerly they were qualitative, was a welcome development. For example, there are now better approaches to handling diffraction by nanostructures, imaging strain and deformation in engineering materials, and characterizing complex technological materials.

Several speakers described the importance of time-resolved studies in areas such as thin-film growth, ion exchange and amorphization in zeolites, switching mechanisms in smectic liquid crystals, cement hydration, and grain growth. Several examples of combining synchrotron radiation methods with neutron radiation studies were given. This was evident particularly for polymer studies, where small-angle scattering and wide-angle scattering were combined to elucidate structure, properties, and processing relationships.

High-pressure studies are another area where a combination of techniques is gaining momentum, and in particular, spectroscopic studies such as high-pressure emission, inelastic, and nuclear resonant techniques will give valuable information on electron structure and phonon dynamics in addition to the well-established diffraction methods that provide structural information.

SRMS-4 drew the attention of young researchers.

Åke Kvick (European Synchrotron Radiation Facility, France) chaired the local organizing committee of the 4th International Conference on Synchrotron Radiation in Materials Science.

A good case was made for the use of high-energy photoemission (6 keV), where now it is possible to sample depths of more than 60 Å for alloys. In studies of the distribution of oxide as a function of depth, measurements were made of Si/Al_2O_3 and Zi/HfO_2 on a Si(100) substrate to learn if there is a SiO_2 layer. Remarkably, the group was able to demonstrate that for Si/Al_2O_3, there was less than one monolayer of SiO_2 present.

From the emerging nanostructures field, an example was given on how a combination of information theory, maximum entropy methods, and high-resolution powder data could provide information on metal atoms in fullerene cages and gas molecules absorbed in nanochannel microporous compounds.

In addition to the scientific sessions, there was a social program that included a conference dinner, where the attendees rode to the Bastille in the famous Grenoble "bubbles" and then dined on local delicacies including an ice cream dessert flavored with Chartreuse. There was also a preconference excursion, a musical concert, and a reception at the Grenoble mayor's office. Support from the ESRF, the ILL, the University of Grenoble, the Mayor of Grenoble, and Conseil General de l'Isere was much appreciated.

ÅKE KVICK
Chair, SRMS-4 Organizing Committee