Report on the NASA Soft and Complex Condensed Matter Workshop

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1. Soft and Complex Condensed Matter Physics – A Definition of the field

Condensed Matter is the branch of science which deals with many particle systems and their cooperative phenomena. Other areas of physics are concerned with discovering the underlying forces governing the interactions of particles with fields or with each other. Even if these interactions were known exactly, we would still be unable to give a full description of systems consisting of more than a few particles. Nature, of course, is much more interesting, and qualitatively new phenomena arise as the number of particles and complexity of a system increases. The contribution of condensed-matter and statistical physics has been to find suitable descriptions of the "many-body problems" that occur as the complexity of the interactions between particles increases. The tools that have been developed over the past several decades in statistical mechanics, continuum mechanics, field theory, and computation have enabled some remarkable achievements in our understanding. These advances lay the foundation for what we believe is just the beginning of a very exciting and productive era for condensed matter physics as the scientific community addresses the problems of how nature organizes matter and energy at ever higher degrees of complexity, intricacy and subtlety.

What has been called "soft condensed matter" or "complex matter" deals with interacting systems where the basic units are larger than individual atoms or molecules and often have internal degrees of freedom. The size of the building blocks has many important consequences for the kinds of studies that have characterized this field. The entities and their interactions are much more variable and controllable than are the atomic and molecular constituents which are studied in the realm of solid-state or "hard condensed matter" science. For example, a particle can be fabricated with different chemistry at its surface than in its interior. Such a coating provides the particle with a flexible and tunable interaction with its neighbors or with its environment. We can design properties either to mimic those that occur naturally or produce qualitatively new structures and phases with novel static and dynamic phenomena. The increase in size scale implies an increase in the characteristic time scales as well and the two combine to make detailed observations more amenable to laboratory experiments. A good deal of fundamental research has used these materials as model systems for quantitative

measurements of many-body effects too small or too fast for observation in conventional strongly interacting systems.

The large size of the constituent particles dictates distinctive properties of the materials themselves. Because the particles are large, they are also soft. "Softness" is a statement about the elastic constants of a material which determines its stiffness, rigidity, and strength. Elastic constants are a measure of the energy density of a material. Since we are dealing with condensed phases, not gases, the interaction energy between the elementary units is much larger than the thermal energy and is similar to the interactions between the atoms that form simple liquids and solids. The big difference is that the spacing between atoms, which is on the atomic scale, is angstroms (10^{-10} m) whereas in soft materials (e.g., emulsion droplets, polymers, and colloids) it is $10^2 - 10^4$ angstroms ($10^{-8} - 10^{-6}$ m). The number density of particles is $1/(\text{length})^3$, and the energy density (energy per particle pair times number density) is therefore 10^{-6} to 10^{-12} less than it is for simple solids. Soft condensed matter systems can be as "soft" as people (who are also made from basic units, cells, on the scale of 10^{-6} m).

Not only are the materials "soft" because of their size, they are also "complex" in that many other inherent effects become important and prevent them from being amenable to a simple description. Because the constituent particles are large and made up of many atoms, they are almost always not truly *identical* to one another in contrast to the atoms and molecules studied in hard condensed matter systems. This implies that there is nearly always some degree of disorder in the system. In many cases, the disorder plays a major role in how the material behaves. This can manifest itself in the material's transport properties, its response to perturbations, as well as in the nature of its elementary excitations.

A large particle has many internal degrees of freedom. When large particles interact, these internal degrees of freedom can be excited creating dissipation. In such situations, kinetic energy may no longer be conserved even approximately. This leads the system into a new realm of dynamics and can produce structures of unexpected complexity. Likewise, dissipation is significant even in static properties where ordinary friction is important.

The size and softness also guarantee that some control parameters, such as temperature and gravity, may influence the materials of interest here in ways which are typically not significant in atomic systems. The softness combined with the building blocks' having internal degrees of freedom often result in interactions which are entropic in origin. Notions taken from statistical mechanics therefore play a special role in understanding these systems in ways that are often different from their role in describing hard condensed matter phenomena.

Many of these properties are shared by the objects and natural phenomena that we observe in everyday life. One of the reasons is the natural fit between the size and strengths of the interactions we study and the basic units of biology -- cells and their constituents. In some sense soft and complex condensed matter is the physics of biology, the physics of life. Presently, we are poised between understanding the elementary interactions in well-defined systems on the one hand and attacking the more complex problems of interdependent networks, and the time and spatial evolution of driven multicomponent systems on the other. This again suggests a strong synergy with biology.

Thus the systems that we are interested in here, because of the large size of their constituent particles, tend to be soft, slow to relax, disordered, and dissipative. As we will discuss below, this implies that such systems are easily driven out of equilibrium and into regions where nonlinear effects are dominant. Studying these materials probes into many of the regions of physics about which we are currently most ignorant.

a. Systems

At present there are many research groups in the international community who consider that they are doing "soft condensed matter" or "complex matter" science. There are significant contributions from physics, chemistry, biology and engineering. This leads to an exciting mix of perspectives with different kinds of questions being asked. There is much activity in the field of "complex fluids", where colloids, dusty plasmas, emulsions, foams, copolymers, and micellar systems exhibit similar ordering, rheological, and transport phenomena. However, each of these systems has its distinct characteristics, applications, and science. Granular materials have reemerged as an exciting area for scientific as well as applied investigation. Liquid crystals have long been studied for

their applications, even more important in the display age, and for their basic insights into understanding broken symmetry and elasticity. Polymers are ubiquitous in everyday life, in the economy and in biology. Study of polymers has led to new materials as well as insights and concepts, such as scaling, self avoidance and entanglement that have proven useful in diverse scientific areas. In general, these systems bridge the size scale from angstroms to meters and require an understanding of interactions from the quantum to the classical. Control parameters range from elementary electromagnetic fields to flow, stress and strain, boundary conditions, gravity and temperature. Manipulation can be accomplished on the single- or multiple- particle level all the way up to global perturbations of the system. Soft and complex condensed matter is the natural field which connects the microscopic and macroscopic worlds.

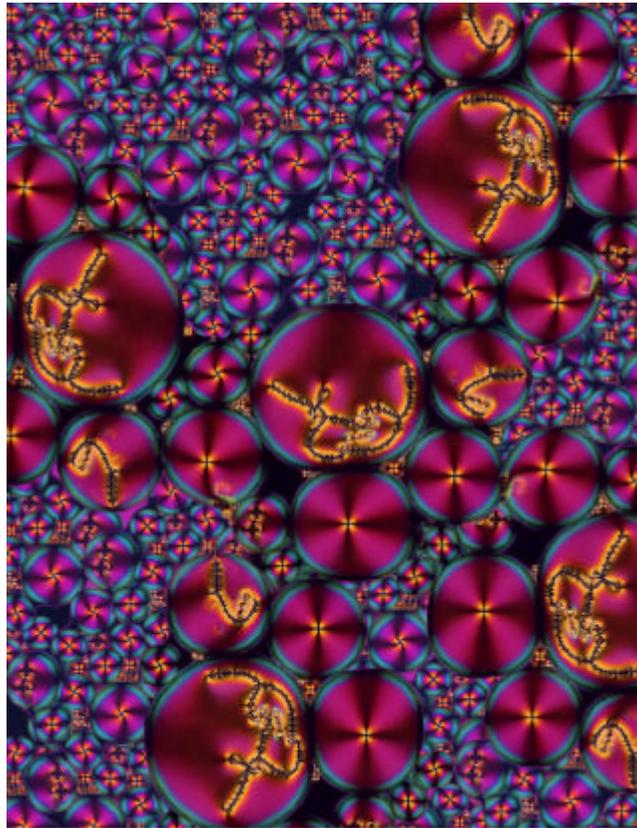Figure 1. Emulsion of nematic liquid crystal droplets with intrinsic defects. From the front-cover of Science: "Novel colloidal interactions in anisotropic fluids," P. Poulin, H. Stark, T. C. Lubensky, and D. A. Weitz, Science **275**, 1770 (1997).

b. Phenomena

The number of research groups that identify themselves with the field of soft and complex condensed matter systems through the phenomena they study is large, wide-ranging and varied. Since the materials are soft, disordered, dissipative, and slowly relaxing their response to even the moderate forces encountered in everyday life and in laboratories takes them out of the "simple" small perturbation regime. Science has made tremendous strides in understanding equilibrium and near-equilibrium thermodynamics, elasticity theory, chemical reaction theory, fluid and statistical mechanics. The systems we study here often cannot be described in such simple terms. As a result, much of the present interest centers on a set of "nons": non-equilibrium, non-linear, non-ordered, non-local and non-ergodic systems to itemize a few. The phenomena encompass diverse yet related fields from crack propagation (in otherwise hard condensed matter systems), earthquakes, turbulence, chaos, granular flow, multi-phase flow, singular flows in "simple" fluid systems, glass formation, aperiodic and novel forms of order, pattern formation, self-assembly, self-organization, and biology.

One of the unifying aspects of this research is the search for new mathematical and computational ways of solving the increasingly complex nonlinear partial differential equations that can be written down for the different systems. In some systems, we have not yet even found the appropriate continuum equations to solve. Many of the processes involve networks with
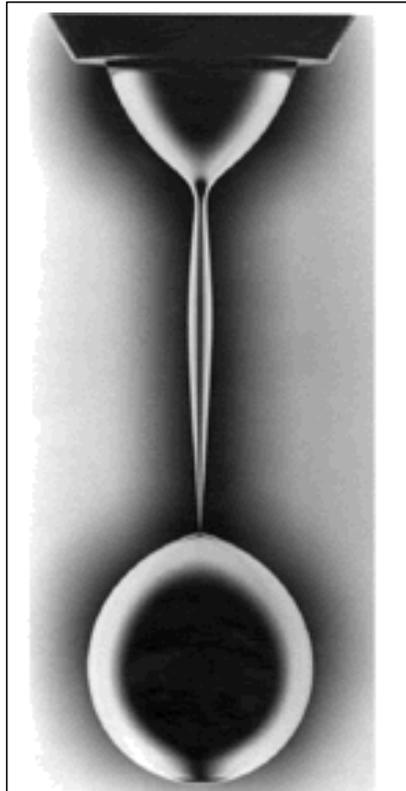
Figure 2. This photograph shows a drop in the process of breaking apart. During the breakup process, the curvature of the neck, and therefore also the surface tension pressure, diverges. In this case, the drop is glycerin dripping through a polydimethylsiloxane (PDMS) oil. The glycerol has a viscosity of 9.5 St and the PDMS has a viscosity of 10 St. The nozzle diameter is 0.48 cm. From: I. Cohen, M. P. Brenner, J. Eggers, and S. R. Nagel, "Two Fluid Drop Snap-Off Problem: Experiments and Theory" Phys. Rev. Letts. **83,** 1147 (1999).

chemical and physical reactions, competing assembly paths, and simultaneous organization and time evolution. Since we are interested not only in understanding the basic science but also in creating new and useful materials and uncovering new phenomena, the evolution is often guided and driven rather than left to evolve on its own. Thus, the science of soft and complex matter is highly interdisciplinary and requires input from all of the experimental sciences, mathematics and engineering fields.

c. Impact

While soft and complex matter has a great deal to contribute to our understanding of basic questions in the physical and life sciences, it also has substantial impact on the economy. Industries as diverse as food, chemicals, oil, cosmetics, pharmaceuticals, and plastics rely on the ability to discover, create, extract, and control soft materials and to process them into useful forms. Granular and fluid flow through natural and industrial environments are part of present and emerging technologies. The direct contributions of these materials and processes accounts for 4.9 % of the GDP and 31 % of the manufacturing output of the U.S. alone (~$850 Billion/year). Direct and indirect contributions to construction, textile, printing and electronics industries raise the value even further.

Figure 3. This image shows the force network with a real pile of granular material subject to gravity. The image was obtained using photoelasticity. Particles that are red are subject to the largest forces and those colored blue to the smallest forces. The arch-like structure of the red-colored particles means that forces are being carried on buttress-like structures, with the result that the force at the bottom of the pile is a local minimum. J. Geng, R. P. Behringer, and D. Howell, Memory in two-dimensional heap experiments, Phys. Rev. E, **64**, 060301(R) (2001).

2. Outstanding Questions

While each material and phenomenon has problems and questions requiring specific new insights and explanations, we can identify some "Big Questions" with a universality and commonality that transcends particular systems. Specific questions involve, for example, the rheology of particular complex fluids. The distinctive geometry of the entangled elementary units required a new insight, reptation, to understand diffusion and viscosity of polymers. Likewise, the surface tension, Laplace pressure and packing constraints were concepts needed to understand the response of emulsions and foams. While both sets of studies contribute to our general understanding of interacting many-particle systems, they are specific.

On the other hand, the onset of rigidity, a finite resistance to shear, appears as a more universal phenomenon observed in many systems and hence may portend a yet deeper and more universal explanation. The specific questions naturally tend to be the ones that occupy most of the effort in our investigations. However, it is worthwhile to see whether we can get a larger picture of what might be universal. This was one of the aims of this workshop. What interested us were problems that might best be answered by studies of soft and complex matter or those that were generic to the field. Below, we discuss a consensus view of some "Big Questions". It is nowhere near exhaustive, it is just an attempt.

a. Rigidity

We know from experience that materials can flow, like a simple liquid, or resist shear, like a solid, and that there can be a transition between the two states when a control parameter such as temperature or density is changed. Rigidity is characterized by the existence of a finite shear modulus at long times. The properties of the two states and their transition is related to a host of other phenomena such as conducting/insulating and resistive/superconducting transitions. In the case of crystalline solids, and in superconductors, rigidity is related to an ordered state, broken symmetry, and to the trapping of particular defects (dislocations and vortices) related to the ordered state. However, there are disordered systems (or ones for which we have not yet discovered the appropriate form of order) that are also rigid. Molecular glasses, polymer gels and sandpiles do not flow appreciably when slightly pushed even though they are disordered.

Finding and understanding the relationship between the causes of the rigidity in these different systems would solve an old -- indeed ancient -- fundamental problem.

a1. Glass Transitions

The rigidity transition discussed above has often been associated with the formation of a glass state, a state with rigidity but no long-range order. This has been cited as one of the outstanding unsolved problems in physics over the past several decades. Attempts to dent this problem have been made by studying various model systems such as disordered magnets (e.g., spin glasses), and some progress has been made. Such spin-glass systems have quenched, or externally imposed, disorder. Over the past two decades, colloidal glasses have emerged as valuable source of needed insight and answers. Colloids exhibit a glass transition as the particle density or interaction strength is increased. Here the disorder, evolving naturally from the dynamics, is frozen in. This change in the nature of the disorder may put them into a very different category from their spin glass cousins. The structural glass transition is characterized by a diverging viscosity, the appearance of a shear modulus, the absence of diffusion, and the onset of aging effects (memory of the thermal history of the glass as well as the time at which the glass was formed). All of these are properties observed in conventional and spin glasses. Recent research has uncovered the evolution of dynamic heterogeneities as the glass transition is approached. Signatures of the glass state can be found in the high-frequency response on many different systems, including spin glasses. In structural glasses, there are also signatures of the disorder in the Boson peak and in the density of vibrational states. None of these phenomena are well understood. The advantage of the colloidal system is that the particles and their interactions are controllable and that their size and time scales are compatible with real-space and real-time observations. There are presently models, mode coupling and beyond, which are being rigorously tested by light scattering, optical microscopy, micro- and macro-rheology and computer simulations.

The questions to be resolved include which theories "work", what underlies some of the remarkable aging phenomena observed in the glassy state, what is universal about the glass transition and what are the characteristic properties of the glassy state itself that distinguishes it from the crystalline one. The colloidal glass transition is a good model

for studying some of these behaviors. Tied up with these questions are whether there are fundamental relations between ergodicity (more below), diffusion, aging, and rigidity.

a2. Jamming

In the spirit of universality, a new concept has been proposed within the past five years which seeks to unite some of the properties of the glass state to that of granular material. The idea is that the immobile, rigid state is "jammed" -- the individual particles are constrained by their neighbors. One of the interesting predictions of this model is a jamming phase diagram involving temperature, density, and stress. Increasing temperature or stress or decreasing density takes you out of the jammed state and allows flow. Thus, we can gain some intuition about the glass state from what we observe in sand piles and, likewise, learn more about granular matter and foams from studies of glasses. For example, the glass state should be destroyed by shear; it should have a yield stress. Similarly, the jammed granular system can begin to flow by the injection of kinetic energy (akin to increasing the temperature). Early experiments suggest that the topology, if not the detailed geometry of the jamming phase boundary, is similar for colloidal glass and sand. What awaits is further development and predictions from this idea and critical experimental and simulational tests.

a3. Ergodicity Breaking

Gases and liquids consist of particles that diffuse arbitrary distances. Over a relatively short period of time, the system explores a representative sample of all of its possible configurations. An average over configurations is then the same as a time average. Measurements yield the time average, while equilibrium statistical mechanics calculates the configuration (ensemble) average. Closely associated with the glass transition and jamming is the absence of diffusion, dynamic or kinetic arrest, and the loss of ergodicity, particles explore only their local environment, and their configuration is frozen. We understand how this happens in ordered systems (in a crystal, atoms are energetically allowed to switch positions at arbitrary distances, but they never do), but the reason is less clear in a glass. Intimately connected with the absence of ergodicity is the presence of time dependence, i.e., aging, of many properties of the system. Again, the
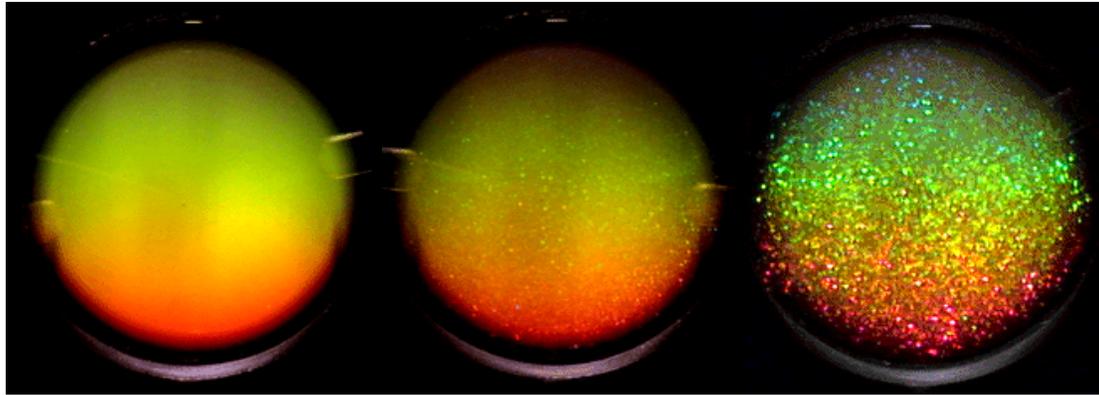
Figure 4. Colloids as a model system for the study of crystal nucleation and growth from a metastable liquid. Homogenization, nucleation and crystallization in µg for sample 3 of the PHaSE flight experiment. From a front-cover hologram on Applied Optics, published as a companion to the paper by Z. Cheng, J. Zhu, W. B. Russel, W. V. Meyer, and P. M. Chaikin, "Colloidal hard sphere crystallization kinetics in microgravity and normal gravity," Appl. Opt. **40**, No. 24, 4146-4151 (2001).

seemingly direct relationships between ergodicity, rigidity, kinetic arrest, diffusion, aging, and the glass/jamming transition await further insight and investigation.

b. Self-Assembly and Pattern Formation

Natural objects self-assemble in ways that we are just beginning to understand. In the simplest case, crystals form perfectly ordered arrays of atoms from melt or solution. In soft and complex matter science, we have used self-assembly to create periodic and other patterns and objects from polymer blends, diblock copolymers, colloids, and micellar systems in three dimensions, as well as arbitrary shapes in two dimensions. Biology, of course, uses self-assembly in more clever and intricate ways. One of the forefront research areas and "big questions" which emerged from this workshop was the study of self-assembly not only as a means of forming exciting new materials and devices but more importantly as a ***process***. Is there something more than just making biomimetic materials which we can learn from nature and adapt in more general ways? Cracking this problem may prove a fundamental contribution to the sciences of complex driven systems as well as to biology itself. What is needed for understanding the process is an effort directed at understanding the complex free-energy landscapes, the kinetics and dynamics of the self-assembly process, the templating processes, and the role of time and spatially dependent fields in directing/controlling the process. What is unique here is the attempt

to understand, and ultimately to control, a system that is chemically reacting and physically interacting, evolving in composition and morphology as time progresses. Can one predict the final states and/or the complete time evolution of such complex phenomena? To understand such systems requires rapid real-time and real-space characterization and analysis.

Once the process is understood we should be able to scale up or down the amount and size of the self-assembled materials. Soft and complex matter science is the natural home for these studies due to the size, designability and internal degrees of freedom of the basic building blocks with which we are familiar.

The technological importance of this area is very large. Most presently assembled systems are planar or in several layers. As the complexity and number of interdependent units of devices increase, the time to assemble them serially and the ability to access the regions to be assembled becomes a larger problem. Self-assembly will allow advances that take us from layered structures to dense, fully three dimensional machines, biological and chemical reactors and sensors, and optoelectronic devices from the nanoscale to macroscopic.

c. Networks

The transfer of information in space and time is responsible for all of the correlations we observe. The networks which transfer this information can be physical, chemical, temporal or any combination of these. The basic idea is that information, force, momentum, reactivity are transferred from one point in space-time to another via a sequence of connected steps. The spatial connectivity (often related to the dimensionality) of a system has well-understood effects on rigidity and transitions in physically interacting systems. However in complex, driven, time-dependent systems, understanding that the system is an interconnected network becomes an increasingly important concern. In particular, a question arises as to the efficiency and stability of a network as its complexity and interconnectivity increases or decreases. What are the effects of fluctuations and finite number on the stability of a network? How can it be stabilized?

This is again a problem germane to biology. Cells and species are based largely on very complex networks of DNA, RNA, and proteins. They respond to stimuli and

exhibit control and feedback. They seem to be quite robust to some perturbations, but respond catastrophically (they die) to others.

d. Origins of Dissipation

Another ancient problem in science at large is the origin of friction and dissipation. Although we teach friction in our most elementary physics courses, we are only beginning to understand it at a microscopic level. The studies of friction are related to those concerning lubrication in confined geometries. Yet almost all of our dynamic and kinetic theories rely on the idea of some energy dissipation. Many equilibrium structures require the additional frictional constraints to define the configuration. Specific models for friction and dissipation have been advanced for specific systems, but there is a sense that the phenomena must have a more universal character yet to be uncovered.

e. Driven Dynamics and Effective Temperature

In equilibrium or near-equilibrium systems thermodynamics/statistical mechanics tell us the rules for computing the system properties and what free energy to minimize. Highly nonequilibrium phenomena lack such well established governing principles. At present we can only use forces and conservation laws for momenta, mass, entropy, and energy flow to obtain equations, perform simulations and guide our intuition. The development of a new statistical mechanics for driven, dissipative, dynamical systems is an ultimate goal. There has been some progress at intermediate steps.

Systems driven far from equilibrium often exhibit chaotic behavior which is reminiscent of the collisions we have learned to associate with the thermal motion of particles in a gas. It has always been tempting to associate random motion with an effective temperature, the implication being that we might then apply equipartition and thermodynamics using the effective temperature rather than using the actual temperature. In driven dissipative systems, there is no fluctuation-dissipation theorem (as we have for truly thermal equilibrium systems) to relate the random forces to the dissipation. What is interesting here is that much evidence suggests that effective temperature can be a useful concept in some instances, e.g. monodispersed fluidized granular systems, while in other

cases, such as in bidispersed systems, it cannot explain the non-equipartition of energy. When applied to living cells, it is wrong by orders of magnitude.

The question then is when an effective temperature is a reasonable concept, how can one determine its value, and how well does the analogy to temperature hold. In trying to answer that question, there has been a growing emphasis on measuring the fluctuations of a variety of variables in a system in addition to their average properties.

Related to these questions is the basic question about how should one take averages in systems far from equilibrium. The existence of a temperature defines an ensemble over which one should average. In systems without a well-defined temperature, how should one take averages?

3. Interface with biology

Life is soft, out of equilibrium, nonlinear, disordered and certainly complex. Since cells, plants, and animals are dynamic, dissipative systems composed of many strongly interacting complex units, they have many of the same properties as the systems we have described above. There is not a sharp division between biology and soft and complex matter. Rather there is an increasingly strong exchange of ideas, techniques, and materials.

For some time, the contribution of condensed matter studies was to provide a better understanding of the materials science of cells, tissues and biomatter. But increasingly, the dynamics, complexity, and networking problems have become part of the field as, for example, in the self-assembly process discussed above. Of course, the complexity of the physical and chemical networks in even the simplest biological systems dwarfs the complexity and number of paths in the systems we study. However, there may be some value in working from the bottom up, with a simple system, and seeing the effects of increasing complexity rather than deconstructing a cell and working from the top down. Animate systems differ from inanimate ones in other significant ways including their reproductive ability and the fact that they have a history bequeathing both useful and useless elements left over from evolution.

There has been, and continues to be, a strong overlap in interests in studying the mechanics of living systems. These range from understanding how proteins fold, to how motors work, to the internal rheology of cells, to how sound is transduced, to how cellular

systems respond to chemical, mechanical and electrical stimuli. Some difference in culture exists as to whether phenomena are, or should be, universal rather than specific. Are there guiding principles, or does each species solve the same problem in different ways? There seems to be evidence to support both views. Protein motors appear to be quite different but many are amenable to a unifying description in terms of athermal ratchets.

Areas of strong overlap include both processes -- self-assembly, pattern formation, networks, dynamics of driven dissipative systems; and materials -- membranes, surfactants, emulsions, colloids, polymers, liquid crystals. Much of the material studied in soft and complex matter is organic, and much has been produced naturally from living things.

Biotechnology is a rapidly developing field both academically / scientifically and as an industry. Soft and complex condensed matter science is an essential component of biotech companies providing the enabling techniques, materials, processes and instrumentation. Manipulation, physical and chemical characterization, sorting, separating, and identifying sub-micron scale objects is a mainstay of the soft and complex matter field.

Biological puzzles, in which condensed-matter science should provide some answers, include mechanical, chemical and electrical functions, cell adhesion, motility, bio-informatics, and growth. Less certain but intriguing are whether soft and complex matter can contribute to understanding morphogenesis, evolution and pre-biotic evolution, the emergence of diversity, memory, thought, and consciousness – the ultimate emergent phenomenon.

Another distinction of biological systems from those we normally study is the role of fluctuations and diversity. We tend to aim for systems where all the building blocks are identical. Cells are not. Often, with a few of each type of protein per cell and large variations in the number between cells, they are able either to perform the same function in some instances, or to differentiate in others. It would be tremendously useful to understand the feedback and control mechanisms and reproduce them in non-biological materials. It would be interesting to make our systems such that they are identical in some aspect, e.g. size, but distinct and possibly reactive and/or addressable in others, e.g.

chemical or dye content. Combinatorics would allow the formation of colloids, micelles or emulsion droplets in macroscopic quantities each with a separate label by modifying a tiny fraction of the billion molecules in each unit. As our understanding of biology and soft and complex matter systems progresses we will move beyond "model" systems and explore systems of greater diversity and complexity.

4. The role of m-gravity

Many of the outstanding questions that we aim to answer: rigidity, self-assembly, stability and evolution of networks, involve the large scale, long time behavior of materials and systems. Gravitational forces and stresses tend to obfuscate these behaviors. In many cases they turn the advantages of soft systems, their size and internal degrees of freedom, against us. This is especially true when we want to model atomic systems, where gravity is not relevant, with controllable micron scale systems where it is. In such systems, and for outstanding questions related to dissipation and driven dynamical systems, gravity and the frictional forces it induces can completely dominate the effects we want to study.

Gravity tends to have significant effects on soft and complex matter systems both because the basic units are large and because the interactions are often entropic/thermal. For materials of typical density the gravitational energy for raising a particle its own radius, $mgr = 4/3 \pi r^4 \rho g$, is comparable to room temperature when $r \sim 0.5 \ \mu m$. For much smaller particles thermal motion dominates, for larger particles gravity is important and causes sedimentation, stresses, and strains. When gravity is important, it can limit growth beyond a certain size and cause the system to fall out of equilibrium.
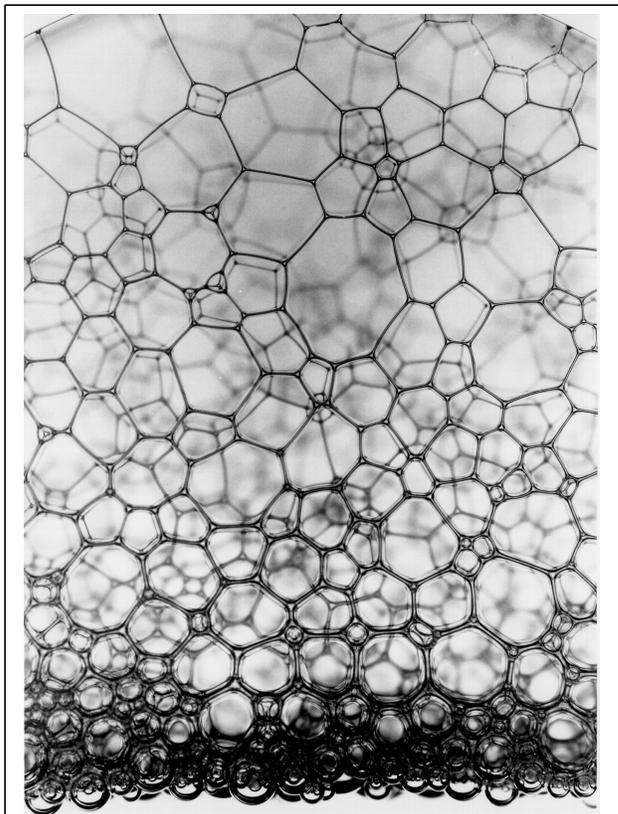
Figure 5. Foam draining, coarsening, and polygonalizing in gravity. D. J. Durian and D. A. Weitz, "Foams", in Kirk-Othmer Encyclopedia of Chemical Technology, 4th edition, J. I. Kroschwitz, ed., Vol. 11, 783-805 (1994).

There are many examples where the presence of gravity introduces qualitatively new phenomena. In some systems, the effects of gravity are dominant, often unwanted, and have been extensively studied. The drainage of foams is an interesting subject of much past and present investigation. The fluid would not drain out of a foam if gravity were not present. However, drainage can also prevent foams from being stable and uniform. Likewise, in colloidal systems, sedimentation and fluidization are important processes. Again, these processes would not occur without the presence of gravity. However, such processes limit the stability of colloids and prevent their application as model systems with nothing but excluded-volume entropic interactions. The effects of gravity thus prevents us from addressing questions relating to rigidity, glass transitions and aging. In driven and reacting systems, gravity couples to density fluctuations and can eliminate growth, limit self-assembly, destroy patterns, lead to instabilities (unwanted or wanted ones), and put systems under stress and strain gradients. Due to these influences we cannot study the fundamental processes of interest. On the other hand, for granular materials, gravity is a control parameter of crucial importance. Unfortunately, on earth it is not under control! There are no convenient ways of varying gravity especially if you want to reduce it. Although doing precision experiments in the μ-gravity range may not always be necessary for these systems, it is nevertheless important to be able to lower gravity substantially in order to observe its effects.

Thus the study of soft and complex matter in many of its manifestations can benefit from a µg environment. Big, slow, heavy, dissipative systems like µg. Further, it allows experiments with no substrates or boundary supports, and experiments on rigidity, rheology, biology, and growth without the perturbations due to stresses. The self-assembly process with large complex building blocks forming macroscopic three-dimensional dynamic ordered structures is most naturally done in µg, free from sedimentation, and stress.

µg allows a controlled gravity environment for granular materials and foams to determine whether the properties scale with gravity as predicted. It also allows a new class of experiments on the effects of friction and dissipation in granular systems where dissipation from inelastic collisions determines the structure and evolution of a particle gas. It may also provide a laboratory for studying large-scale objects that would have difficulty sustaining their own weight when significant gravitational forces exist.

5. Enabling Technologies

In order to make substantial progress in answering the "big" questions in soft and complex matter, we need to have detailed measurements of the time dependence of both average and local properties and their correlations. While ultra-low angle scattering needs to be further developed to give us the average properties, there is an increasing consensus that nothing beats the information from real-space, real-time imaging of the individual particles or fields. Since the individual units of interest in soft and complex matter are large, it is reasonable to expect that improvements and modifications of present technologies will allow local internal probes of the chemical, elastic and thermal fields. Extension of present techniques for 3D imaging (e.g. confocal and two-photon microscopy) and manipulation (laser tweezers) should allow faster and smaller micro/nano resolution. An excellent tool for many of these studies would be magnetic resonance imaging, MRI. At present it has proven useful for the larger systems, e.g. granular materials, since the highest resolution MRI machines are in the many-micron range. However, there is tremendous potential in this area considering the ability of MRI to distinguish different chemical species and environments, temperature and fluid motion. X-ray tomography is a complementary technique to MRI that can give spatial imaging of

particles. It excels at determining average densities in flowing materials where MRI has problems. Resolutions down to the 1 μm limit are currently being attempted.

On either side (upstream, downstream) of the improved measurement instrumentation, progress is needed in the synthesis and characterization of the materials. Of course, there is nothing that beats a creative chemist, and more must be brought into the field. With the mesoscopic scale of our building blocks, new materials can be fabricated either chemically or physically. It possible to create micron-size particles of almost arbitrary shape using soft and hard stamping techniques as well as more conventional optical lithographies. While these can presently produce only billions of particles (cubic millimeters), that is sufficient for most scientific investigations.

Of particular importance is the science of coating surfaces generally and particles in particular. For example, coating the surfaces of particles can dramatically change how they interact with their environment and allow control of the properties of the system. Coatings can be fabricated either using chemical means (that is, by growing the coats directly onto the surfaces) or by more physical means (essentially by shrink-wrapping the particles in another material using fluid processing). Much of this research requires a better understanding of wetting phenomena. Examples of questions that are currently of interest include: How does wetting occur at nanoscales, how is wetting impacted by disorder (surface heterogeneities), and how does one understand wetting with colloidal and surfactant solutions?

Another important area for progress is in the analysis of the experiments and development of theory and simulations. Theoretically, there is a need for multi-scale computation codes and a method for code sharing throughout the community.

6. Needed μg research tools

It is clear that experiments in μg are important and enabling particularly for the outstanding questions in soft and complex condensed matter science. But this will require modified and new tools for use in the μg environment. The instruments recommended by this workshop include:

An MRI facility with 1-100 μm resolution for studying the structure, dynamics and flow of colloids, foams, emulsions and granular materials. Almost any such facility

would find wide use with increasing interest as the resolution and rate of acquisition improved. It is probably worthwhile setting up a ground-based effort to determine the best nuclei and materials for optimizing this instrument.

An X-ray tomographic facility to allow studies of microstructure and densities in flowing materials.

Improved low angle light scattering instruments. These are needed to bridge the gap from microscope observations to macroscopic photos and to follow dynamical processes. Previous and present μg experiments have shown unprecedented ranges of growth and coarsening undisturbed by sedimentation or separation and present techniques allow only qualitative measurements.

More advanced microscopes: confocal, two photon, deconvolution, with 3D tweezers, and better time and spatial resolution. Coupled with new fluorescent (quantum dot), temperature, stress and chemical probes. An atomic force microscope would give additional information about biological matter.

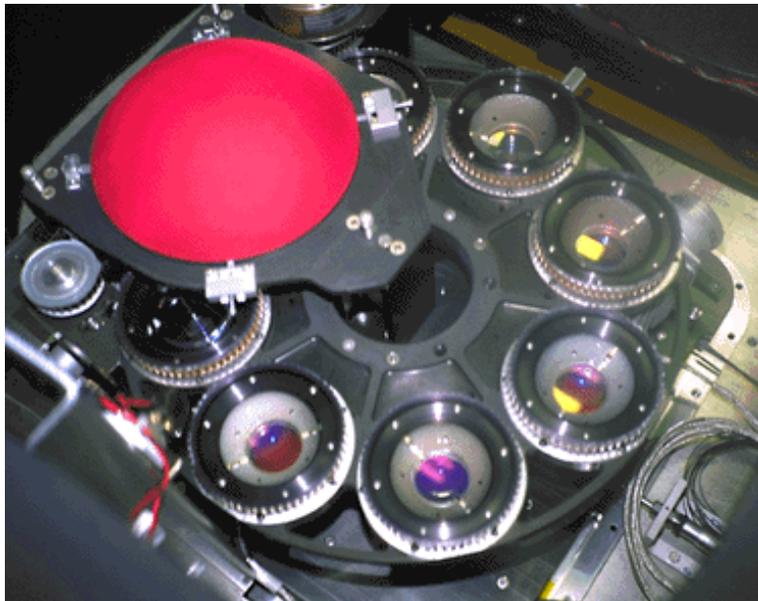An "infra" centrifuge. A way to control effective gravity from ambient μg to

Figure 6. Apparatus for static and dynamic light scattering studies in μg, used for the PHaSE and PCS flight experiments. From the front-cover of Applied Optics, published as a companion to the paper by C. T. Lant, A. E. Smart, D. S. Cannell, W. V. Meyer, and M. P. Doherty, "Physics of hard spheres experiment - a general purpose light scattering instrument," Appl. Opt. **36**, 7501-7507 (1997).

several g. This is particularly attractive for granular materials and foams, where gravity is important and this regime is otherwise inaccessible.

A rheometer coupled with a microscope. It has always been important to understand the relation between structure and rheology. Presently, microrheology is done by observing correlated fluctuations of probe particles in a microscope. However, in cases when the system is driven far from equilibrium, there are many questions related to the macroscopic rheology and how it relates to the driven structure.

A high-speed camera. High-speed photography is the appropriate research tool for collisional granular materials, where the time evolution and the energy dissipation can directly be tracked from real-space trajectories. It is also very useful for studying fluid dynamics, microfluidics, and self-assembly among other systems.

Materials are the lifeblood of this field. A new and exciting aspect lies in the fabrication of new materials via μg chemistry. The complexity and size of the elementary building blocks could be extended by performing the chemistry on the space station. At the lowest level, polydispersity can be better controlled in μg. At a more interesting level, it may be possible to make complex, micron scale organized chemical units in μg that are impossible to realize in a 1-g environment.

7. Conclusions

Soft and complex condensed matter science is one of the forefront areas of interdisciplinary research. There is a push in this direction by major universities and laboratories. New groups are taking shape in science and engineering departments throughout the world. In this workshop we have tried to capture some of the excitement of the field which is flowering in many different directions. We are poised to answer some of the basic questions which are central to understanding the simplicity and complexity of nature: self-assembly, rigidity, the dynamics of systems driven far from equilibrium, dissipation, evolving networks. We are optimistic: progress has been made in using soft and complex matter systems to isolate fundamental problems and attack them with newly developed tools and techniques; progress has been made in taking what we have learned in simple systems and using it to understand more complex ones; progress has been made in discovering new materials and in proposing new research directions. The impact of this research is considerable; from direct relevance to 1/3 of the

manufacturing GDP, to discoveries in the physical sciences, to new materials and processes, to increasing intermix with biological sciences and to applications in nano- and biotechnologies.

The fact that soft and complex condensed matter systems involve larger, more diverse and interesting building blocks than atomic or molecular based systems, combined with their relative fragility, makes them particularly susceptible to the effects of gravity. This has not escaped the notice of NASA. Such systems are logical candidates for study in a microgravity environment. In this workshop we have identified many opportunities for microgravity research for tackling some of the outstanding problems in soft and complex matter. To take advantage of these opportunities, we have advocated the development of an expanded set of micro-gravity tools.

Having recognized from the start the importance of soft and complex matter science and the role that gravity might play, NASA has long been an advocate and supporter of both ground- and spaced-based research in this area. In doing so, it has become the lead agency for soft and complex matter research in the United States and it is natural that it should continue to do so.

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13. ABSTRACT (Maximum 200 words)

During the past decade, NASA has been a leading U.S. supporter of soft and complex condensed matter research. Experiments in space shuttles, MIR, the International Space Station (ISS), as well as ground-based research have provided new insights into several areas including hard sphere colloids, crystal growth, phase ordering, and transport of complex fluids at the critical point. To help define the next generation of flight experiments needed to answer remaining important questions in the field of soft and complex condensed matter, NASA's Office of Biological and Physical Science sponsored a workshop on Soft and Complex Condensed Matter, March 6, 2003. This workshop asked leading members in the field of Soft and Complex Condensed Matter (at the APS March Meeting) to help identify exciting unanswered questions in the field, along with specific research topics for which the absence of gravity would enable significant results unobtainable by other means. The workshop was attended by 24 participants from universities across the U.S. and from five different countries (in addition to NASA GRC participants).

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