

Insights from Soft Condensed Matter*

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ABSTRACT

The distinctive behavior of polyatomic structures such as colloidal particles, surfactant micelles and polymer molecules in a liquid are reviewed. The qualitative differences between these forms of “soft matter” and small-molecule solids and liquids arise from their weak connectivity and entropic interactions. These effects produce spatial organization within one polyatomic structure co-operative organization amongst many such structures. Such self-organization may arise in thermal equilibrium, from an irreversible growth process, or from flow. Conversely, the structures alter the transmission of forces in new ways. Potential benefits from the understanding of soft matter for electronic materials, for chemistry and for biology are mentioned.

Introduction

The physicist’s method of reflection about the world has, especially in this century, opened our eyes to the world like few activities in history. Relativity has shown a profound link between space and time, unveiling a startling unity of mass and energy. Quantum mechanics has revealed that motion entails spatial and temporal periodicity, leading to phenomena of beauty, precision and utility that are inconceivable in terms of everyday experience. Perhaps this is why ours has been called the century of physics.

Though the implications of relativity and quantum mechanics have dominated physics in the twentieth century, these are still just particular examples of the physics enterprise. As these examples have developed, other insights from completely new directions have appeared. One such insight is the symmetry under magnification that many condensed-matter systems show. This symmetry dominates the behavior of matter undergoing a continuous phase

transition, for example. This magnification symmetry has arisen not from relativistic, quantum or other properties of the matter’s ultimate constituents. Rather, this domain has emerged from the workings of mundane forces and random fluctuations.

Another such domain—soft condensed matter—is the subject of this essay. Soft matter occupies a middle ground between two extremes: the fluid state and the ideal solid state. The mobile molecules of a simple fluid may freely exchange positions, so that their new positions are permutations of their old ones. By contrast the molecules of an ideal solid are fixed in position and may not readily permute in this way. Soft condensed matter is a fluid in which large groups of the elementary molecules have been constrained so that the permutation freedom within the group is lost. For example, thousands of small molecules may be fastened together to form a rigid rod or a flexible chain. The new behavior of soft matter emerges because these groups of fastened-together molecules are large. It emerges because the thermal fluctuations that dominate the fluid state coexist with the stringent constraints characteristic of the solid state.

The best-known soft-matter structures are polymers—hydrocarbon molecules in which many repeating subunits are connected to form a flexible chain. Colloids, emulsions and foams are fluids containing compact grains or droplets or bubbles of matter, each large enough to constitute a distinct phase, but small enough that thermal fluctuations are important for their properties. Surfactants are small molecules that contain within themselves two strongly immiscible parts. A surfactant molecule in a liquid such as water has one part that is strongly immiscible with the water. The immiscible parts spontaneously aggregate into spheres, flexible rods, bilayers and more elaborate structures. These structures may grow to arbitrary size. Their variety increases when a second liquid, such as oil, is added. The surfactant aggregates then become receptacles for the oil. Such a liquid, formed from an equilibrium dispersion of two immiscible fluids plus a surfactant is called a microemulsion.

The field of soft condensed matter has developed many aspects [1]. In surveying these below, I emphasize ways that these materials have brought us qualitative new notions about how matter can behave. A central theme of this field is self-organization: the spontaneous creation of regular structure that strongly constrains the spatial arrangement of the system over and above the constraints on the polyatomic constituents. I shall discuss new types of periodic structure, as well as dilation-symmetric, fractal structure. But self-organized structure is only part of the new behavior of soft condensed matter. Another part involves new kinds of organized motion. Soft matter can move in unprecedented ways and thereby confer unprecedented flow properties on fluids.

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These distinctive behaviors of soft matter offer potential impact on other fields: the world of electronic structure and optical excitation, the world of chemical transport and reactions, and the world of living organisms. I'll close by mentioning some of these potential impacts.

Principles

Pick up a cube of Jello [2] in one hand and a cube of ice in the other. The contrast between soft condensed matter and conventional matter is immediately apparent. The rigidity and strength of the ice arises from its atomic composition. The molecules lie packed adjacent to one another; compressing the ice between the fingers pushes these packed molecules into one another. The compression creates virtual atomic excitation and requires energy—an energy of the order of electron volts per atom. With only a fraction of a percent compression, the compressional energy approaches the binding energy of the atoms. Then the ice is susceptible to brittle fracture. The Jello by contrast is much more resilient: it sustains a factor-of-two compression with no apparent damage, though it is much weaker than the ice.

The resiliency of Jello arises from its weak connectivity. Its atoms are not packed together. Most of them are in the form of liquid water. The restoring force of the compressed Jello cube arises from the long, randomly coiling gelatin polymers that have been dispersed in the water and have then intertwined to form a network as the water cooled. Compressing the cube distorts the network and pulls on the ends of the gelatin molecules. Because it is contorted, each molecule can elongate easily, just as a spring or a loose wad of wire can. Its molecular bonds can rotate and allow elongation with virtually none of the atomic distortion seen in the ice. A second important feature of the gelatin molecules is their low density. There is plenty of room for the polymer coils to distort without crowding one another the way ice atoms do. Surfactant rods and sheets, aggregated colloidal particles and the droplet interfaces of emulsions have this same low density. It is this low density and weak connectivity that make soft matter soft.

A second feature of Jello is needed in order to account for its easy deformability. The gelatin molecules are not frozen into a single configuration but are constantly fluctuating from one random configuration to another. The resulting random-walk shape has a preferred size and end-to-end distance. If this distance is distorted by an imposed compression, there are necessarily fewer configurations accessible. Thus the distortion reduces the entropy of the molecule and requires work. This work is the origin of the tension in a gelatin molecule. A loose string buffeted by a random barrage of ping-pong balls would feel an analogous tension. The work is far smaller than the electron-volt-per-atom scale of

an ordinary solid. It is of the order of a thermal energy kT per crosslinked section of the gelatin. The thermal energy itself is only 1/40 of an electron volt; moreover, the number of crosslinked segments in the Jello is far fewer than the number of atoms.

Self-organization

Soft matter's most striking property is its ability to self-organize— to create a coherent order throughout spatial regions indefinitely larger than the soft matter constituents. The most familiar type of order is the breaking of rotational or translational symmetry to form spatially oriented or periodic states. Soft matter like ordinary matter shows a wealth of such states: the liquid crystals [3]. Soft matter has revealed another form of organization that involves another symmetry: spatial dilation.

dilational order When a flexible polymer such as a gelatin molecule is put in solution, each successive segment extends in a random direction relative to its predecessor: the molecule has the form of a random walk. This in itself is a primitive form of organization. Though the correlations of steps of a random walk are structureless, the distribution of steps in space is not. The density of steps near an arbitrary segment falls off inversely with distance instead of being uniform. This length-scale dependent density reflects a type of spatial order that is not connected to rotations or translations but to dilation. Dilation is the transformation to a magnified co-ordinate system. A structureless, uniform material looks the same when magnified, provided the magnification is too weak to see its molecular constituents.

A section of a very long random walk also looks the same when magnified. A set of configurations viewed at one magnification is indistinguishable from a set viewed at another, provided the two magnifications are not too strong or too weak. The dilation symmetry may be characterized quantitatively in terms of the falloff of density of steps with distance. In d dimensional space the density falls off as the $2 - d$ power of the distance. This scaling exponent (and related ones) characterize the dilation symmetry in the same way that linear momentum characterizes translational symmetry and angular momentum characterizes rotation symmetry.

In the last three decades, dilation symmetry has emerged as a powerful form of self organization in soft matter. This era has brought the means of conceiving of this symmetry, of framing it in mathematical terms and even of predicting the power laws that define it. It has also brought a wealth of new realizations, that have expanded the range of dilation-symmetric phenomena to a startling degree. The first inkling of this breadth came with the realization

that real polymers do not have the size in solution expected for random walks: they are too big. Empirically, their size grows as the .6 power of their length, not the .5 power expected for random walks. Somehow the polymer expands because its subunits prefer the solvent to one another. In effect, the subunits repel one another. Though ad-hoc ways of accounting for this swelling date from the '50s [4], it was not until 1971 [5] that the meaning of this swelling emerged. The solvent effect produces not just a global swelling but an expansion at all length scales. As such, it destroys the dilation symmetry of the random walk and replaces it with a new representation of dilation symmetry, characterized by a new set of scaling exponents.

To understand this shift of symmetry required a major reframing of our description of many-body matter. There is no simple explanation of the exponents as there is for a random walk. Here, the -1 power law arose straightforwardly from the two spatial derivatives in the diffusion equation describing random walks. If the power is to shift to a fractional power, must this second derivative somehow change to a fractional derivative? Clearly, a major generalization of the mathematical description is required. In 1971, DeGennes recognized that the generalization needed for the self-repelling polymer was the same as that needed to describe continuous phase transitions such as a critically opalescent fluid or a magnet at its Curie temperature [5]. He realized that the .6 power was in essence a critical exponent. Meanwhile Wilson showed that the needed mathematical language for all such systems was that of renormalized field theory [6].

self-organization within a molecule Some forms of self organization occur at the level of a single polyatomic constituent, such as a polymer molecule. Others are collective phenomena involving many polyatomic constituents. I turn first to organization within a molecule.

The classical examples above show the power of self organization that soft matter can generate. The forms of self-organization can also show a dazzling variety, as the following examples illustrate. Some forms occur within a single molecule, such as DNA, that resists twisting and bending. If such a molecule's ends are joined to form a loop, the preferred shape is circular. But if the loop is twisted, the preferred shape is no longer planar. Instead the molecule twists around itself in a shape called a supercoil [7]. A mechanical twisting at one point in the molecule can thus cause a global change in the molecule's conformation. Organisms may well use this phenomenon as a means of coiling and uncoiling DNA and otherwise manipulating it in the process of cell replication or gene expression.

A more subtle level of single-molecule self structuring occurs when the "molecule" is in the form of a two-dimensional membrane, such as graphite

oxide [8] or a red blood cell membrane [9] or a sheet of paper. Such membranes resist bending or stretching. When confined into a small space, they develop the familiar but mysterious structure of the crumpled state [10,11]. Alternatively, they may be made sufficiently flexible that thermal fluctuations bend them strongly on a local scale. These thermal fluctuations might be expected to leave the membrane in a strongly contorted state, as they do for the polymers discussed above. Remarkably, the reverse happens: the local undulations lead to a global flattening. This surprising reversal happens because of the two-dimensional connectivity of the membrane. Such a membrane may bend easily in one direction. But it cannot bend in both directions at once (producing Gaussian curvature) without also stretching: corrugating a sheet in one direction makes it stiffer in the perpendicular direction. The membrane's resistance to stretching thus makes the sheet bend less than it would otherwise.

Two possibilities are open to the membrane. On the one hand, it might break its directional symmetry and choose to contort in one direction while remaining flat in the perpendicular direction. A moderate amount of local bending anisotropy can tip the balance in this direction, according to recent calculations [12,13]. On the other hand, the membrane might retain its directional isotropy and simply moderate its bending so as to avoid excessive stretching. This possibility implies a progressive flattening at large length scales. The local bending means that the membrane has an effective thickness, like the corrugated wall of a cardboard box. This thickness makes the membrane stiff, and limits similar corrugations at larger scales. The result is that both the bending and stretching stiffness change progressively when measured on larger and larger length scales. According to recent simulations, the bending modulus grows roughly as the .6 power of the linear size, while the stretching modulus decreases roughly as the -.5 power [14]. This dependence is consistent with analytical estimates [15] and experiments [8]. This subtle form of scaling is a startling consequence of the interplay of elasticity with thermal fluctuations.

self-organization from entropic interactions The thermal fluctuations of chain molecules or molecular sheets give rise to mutual self-organizing effects on the ensemble of constituents in the fluid. One of the most dramatic forms of spatial organization results from these fluctuations in a molten polymer liquid. Two immiscible polymer chains, A and B, can be joined together at the ends to form a "diblock copolymer". In a liquid of such copolymers the A species must segregate from the B species. But this phase separation cannot proceed normally since the A and B chains are connected. The result is a microscopic phase separation into small regions containing A or B chains. The size of these domains is limited, since the A-B junctions are necessarily at the boundaries of a domain, and the chains extend-

ing from the boundary must fill the interior. Increasing the domain size reduces the interfacial area between A and B regions and thus reduces the energetic cost, as in any phase-separating fluid. But this increased size ultimately forces the chains to stretch, reducing their entropy.

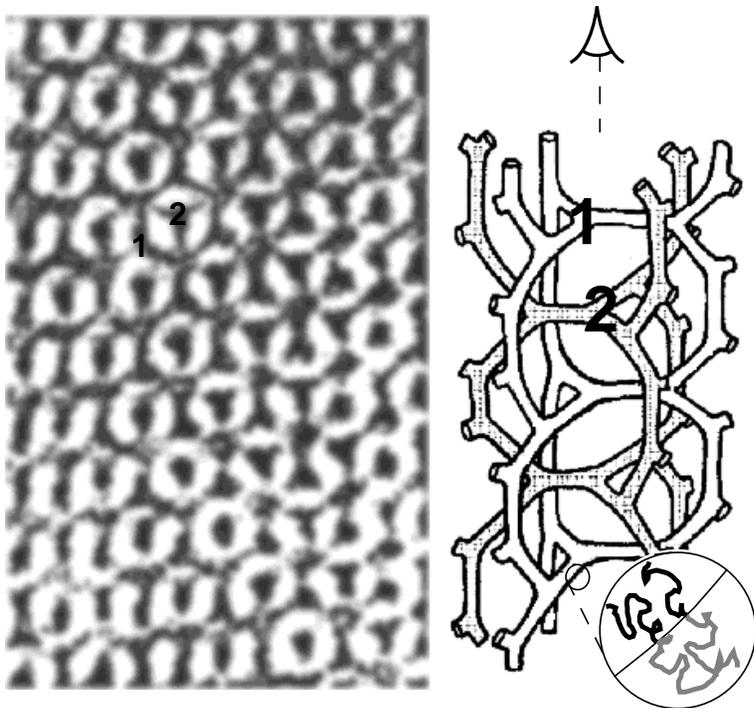


Figure 1 Transmission electron micrograph of the bi-continuous copolymer domain structure, reproduced from Ref. 16. Repeat distance is about 100 nm. The minority species in black forms two disjoint domains, labeled 1 and 2. The sketch at right, after Ref. 17, shows the three-dimensional structure inferred from such micrographs and from x-ray diffraction studies; the vertical dashed line gives the line of sight for the micrograph. The thickness of the two minority domains is reduced to make the illustration clearer. Domains 1 and 2 are shown with different shadings to distinguish them. The magnified sketch at bottom shows the orientation of individual polymers in the domains.

The domains must find the most favorable balance between these opposing tendencies. The domains typically contain hundreds of kT of interfacial energy. Thus there is a large energetic incentive to attain an optimal domain structure. The result is a strongly periodic pattern, whose shape depends on the relative length of the A and B chains used. The intricate bi-continuous structure of Figure 1 is one example. Since the domain energy depends only on the random-walk nature of the chains and their interfacial energy, the optimal structure is independent of chemical details. Thus the structures should be accurately predictable using generic numerical methods [18,19,20]. The variety of known patterns is increasing rapidly, as copolymers of different block sequences and varying degrees of elastic entropy are used [21]. These microdomains provide a means of arranging material in space whose power is only beginning to be exploited.

These copolymers are only one example of how polymer entropy may create spatial organization. Polymers grafted to colloidal particles can create large enough forces to separate these particles and induce periodic order in solution [22]. Polymers can create strong forces to separate macroscopic surfaces [23] or surfactant bilayers [24].

Two-dimensional structures can also create order via their entropic interactions. The simplest example occurs when certain lipid surfactants are dissolved in oil. These surfactants spontaneously form bilayers, with the oil-loving ends facing outward. These bilayers are not elastic membranes; they have no shear modulus. Thus thermal fluctuations make them undulate readily and give the bilayers entropy. If anything confines such a bilayer to a gap of fixed width, this entropy is reduced and a repulsive force varying as the inverse cube of the thickness results [25]. The same repulsion acts between a bilayer and its neighbors. The result of the bilayer repulsion is a long-range smectic order in the bilayers, even when the proportion of surfactant in the fluid is small. As with polymers, the addition of further features leads to a barely-explored wealth of strongly selected structures. Polymers that live in the oil, that graft to the bilayers, or that bridge between bilayers create some of these variations [24].

A further form of entropic interaction appears when electrically charged species are introduced. It is entropy that causes oppositely charged pairs of ions to dissociate in the liquid. Strong structure formation arises when macroions are introduced. Macroions are colloids, polymers or surfactant interfaces with many dissociating charges. For typical charged colloids the number of charges is in the hundreds. The dissociation creates an electrostatic energy which is comparable to the entropic free energy kT times the entropy of the dissociated ions. This energy amounts to several hundred times the thermal energy kT . Thus the expected interaction energy between macroions is large. Not surpris-

ingly, the macroions take on a strong crystalline order even when separated by many volumes of solvent. This order is readily disrupted by flow, but immediately reasserts itself. Charged lipid bilayers show similar interaction; it enhances the repulsions between bilayers and thus enhances their smectic order. The expected interaction between like-charged macroions is repulsive. But there is increasing evidence [26,27] that significant attraction can occur. Our understanding of such attractions has not reached the point of consensus. Still, this puzzle shows that there is more to the interaction of macroions than their obvious Coulomb repulsion.

When the macroion is a polymer with its own internal entropy, the interplay with counterion entropy leads to strong elongation of the polymer coils. It also leads to strong short-range order in solutions of charged polymers and to anomalous flow properties that are far from being well understood [28]. The interaction between oppositely charged macroions such as a polymer and a colloidal sphere are likely to lead to further new forms of self organization. These should be strong effects because of the large energies at stake [29].

kinetically driven self-organization The self-organized structures discussed above all lie within the compass of equilibrium statistical mechanics. Further undreamed-of structures arise during irreversible, kinetic processes. A striking example is the remarkable structure of colloidal aggregates. Colloidal particles have a mutual interaction energy that grows with their size. Thus particles much larger than the solvent molecules have a nominal interaction strength that may be many times the thermal energy kT . Since the basic energy scale is large, a modest change in the fluid composition can change the mutual interaction energy from being repulsive to being strongly attractive. Now instead of forming a stable dispersion, the particles flocculate irreversibly. The attraction can easily be so strong that the particles stick together on contact without being able to migrate over each other's surfaces.

This extreme aggregation leads to irregular shapes as particles form small clusters, and these aggregate into progressively larger clusters [30,31]. Each pair of clusters that collides is frozen in the configuration it had at collision. Each collision causes a growth of the cluster mass to the sum of the constituent masses. Each also causes a growth of the radius by a finite factor that has no fixed relation to the mass factor. The result is a fractional power law relating the radius to the mass. Naturally, the same power governs each subcluster of a large cluster, as well as its own subclusters, and so forth. Thus the cluster has the same structure at many length scales; it is dilation symmetric. Like polymers, these clusters have an average density near an arbitrary particle which falls off as a power of the distance. The overall average density decreases as a power of

their mass. They (like polymers) are “fractal objects” [32]. The main geometric, elastic and hydrodynamic properties of these colloidal aggregates have now been well characterized and shown to be independent of materials and conditions over wide ranges [33]. These aggregates are a distinctive organization of matter that have emerged through the study of soft matter.

flow The kinetic effects of flow exert a major restructuring influence on structured fluids. The conventional shear flow of two surfaces sliding past each other can align smectic layers [34], elongate polymers [35] and induce melting or ordering in a colloidal dispersion [36]. But beyond these effects, flow can create qualitative new structures whose origin remains a mystery. A striking example occurs when a smectically ordered solution of bilayers is subjected to shear flow of the right magnitude. The lamellae reorganize to form a closely packed, regular array of onion-like structures, each with dozens of concentric bilayer vesicles [37]. The size and number of layers may be varied by changing the shear rate, even after the onions have initially been formed. Yet when the shear flow is stopped, the onions are stable over many months, even if solvent is added. To understand how shear induces the transition among the smectic and the various onion states is a great challenge.

Other challenging flow effects occur when a solution of suspended particles [38] or DNA [39] is subjected to an oscillating electric field. Field of the proper amplitude and frequency leads to islands of many circulating molecules and to a herringbone arrangement of these islands (Figure 2). These are just two of a variety of unstable, pattern-forming flows involving vesicles, surfaces or fluid-fluid interfaces [40,41]. Since kinetic effects can lead to such startling and inexplicable reorganization, we must look forward to even further surprises.

Rheology

The last section showed how flow can have strong effects on structure. The effects of structure on flow are just as dramatic. In soft matter the sharp distinction between solids and liquids blurs. We may characterize a simple liquid by its viscosity, the proportionality between the stress and the rate of strain. We characterize the mechanics of an ordinary solid by the modulus, the proportionality between stress and strain. In a soft material like Jello, we must speak of a modulus that depends on the strain amplitude and frequency. Often it depends on history of the strain, since this history may have organized and altered the structure within the sample.

In Jello the rheological properties follow readily from the known properties of its polymeric subunits and their hydrodynamic interaction with the solvent. In other polymer fluids (and fluids of wormlike micelles), flow is strongly inhibited by the mutual *entanglement* of the molecules. To understand the flow

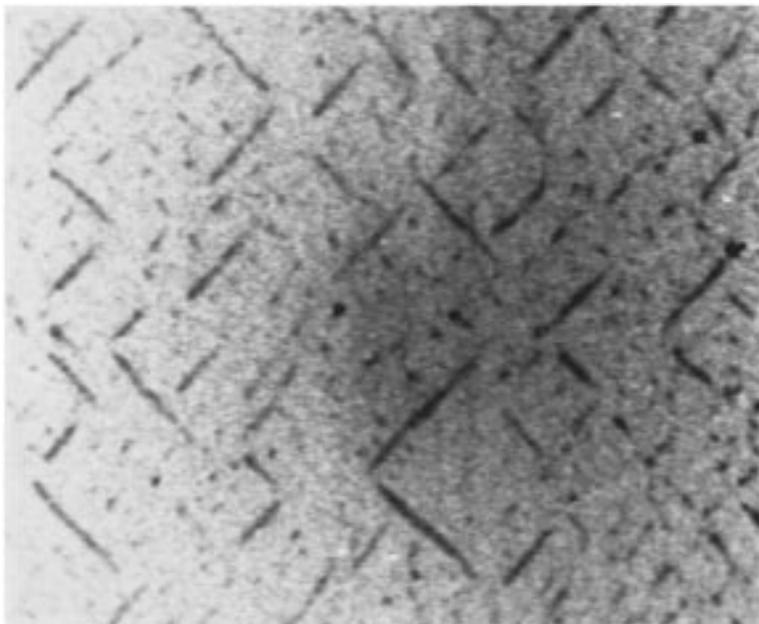


Figure 2 Precipitation patterns in a DNA solution induced by an oscillating field, reproduced from Ref. 39 by permission. Horizontal electric field had an amplitude of 300 V/cm, a frequency of 2 Hz and was applied for two minutes. Sample volume is a horizontal slab 10 microns deep. Black streaks are regions of concentrated DNA about 10 microns wide.

requires an additional fundamental insight about the molecular motions that can lead to disentanglement. Such an insight came in the 1970s with the work of DeGennes, Edwards and Doi [42]. The theory supposes that the important motion for disentanglement is the brownian motion of each molecule along its own contour, a motion known as “reptation”. The reptation hypothesis has grown into a powerful and successful kinetic theory of disentanglement rheology—a “standard model” to which experiments and other theories are compared. By addressing the phenomenon of polymer flow, the murky notion of disentanglement has been brought to a level approaching conceptual mastery and confident prediction.

Many other aspects of soft-matter rheology still baffle us. The most per-

plexing is the phenomenon of turbulent drag reduction [43]. A very few large polymers in a liquid are able to alter significantly the way the liquid flows through a pipe. A few parts per million of polymer can reduce the drag during turbulent flow by nearly a factor of two. The polymers seem to forstall the large dissipation that occurs near the pipe walls during turbulent flow. The polymers appear to affect the flow by undergoing a “coil-stretch transition”, in which elongational flow stretches the chain from a contorted random walk to nearly full elongation. But beyond these elements, little is understood or confirmed.

An even more fundamental phenomenon occurs when a few large suspended particles are suspended in a flowing fluid. The flow can easily be made fast enough so that convective motion of the particles completely dominates any diffusive Brownian motion. At the same time the flow can be slow enough that the inertial effects leading to turbulence are completely negligible. And yet, when one observes the particles through a microscope, their motion, except for its glacial pace, resembles a turbulent flow [44]. Instead of moving in a coherent fashion, the particles collide, swirl and move at greatly different speeds. The basic effect responsible is the hydrodynamic interaction, the alteration of one particle’s motion owing to the perturbed flow near another particle. This chaotic flow appears to be a motion as fundamental as turbulence, though conceptually simpler. But our understanding of it is much more primitive than even our meager understanding of turbulence. No analog of the Reynolds number has been proposed to quantify the passage from coherent motion to this chaotic state. Nor has any asymptotic scaling hypothesis been convincingly formulated.

soft glasses Other strange flow phenomena occur in dense emulsions like mayonnaise. Mayonnaise holds its shape because its many micron-sized drops of oil are packed together, with only a small amount of water between the drops. Any external deformation distorts the drops further and increases their interfacial area; this increase costs energy and thus creates a stress opposing the deformation. In this way a collection of liquid droplets becomes a disordered elastic solid—a glass.

Under strong enough stress an emulsion or foam flows. This flow is unlike the yielding of ordinary solids made of stiff atomic particles. There strain becomes concentrated in fracture cracks or plastic flow zones. In a typical emulsion the stress relaxes instead by means of discrete, localized yield events, each involving a handful of droplets [45]. The yielding events do not seem to persist at preferred places, but occur throughout the material. Thus a yielding event at one point seems to shift the nearby droplets enough that all regions are equivalent after sufficient time. The overall stress in such materials shows

suggestive dependence on frequency and strain rate; often this dependence resembles a power law [46]. The basic nature of all simple emulsions is the same; one differs from another only in volume fraction and droplet size distribution. Thus it should be possible to come to a common understanding of how their yielding differs from that of conventional solids and how the apparent power-law responses arise. These questions are being actively pursued [47,48].

Bridges to other fields

electronic condensed matter In the sections above, we have seen a wealth of behavior emerge from simply-defined systems. It is only natural that soft-matter phenomena should prove useful for understanding and manipulating phenomena in other domains. The domain of electronic motion is a prime example. Progress in our control of electron motion and ordering in recent decades has hinged in large part on our ability to create interfaces between metals and insulators, or between one semiconductor and another. The self-organizing abilities of soft matter provide a natural avenue to make such interfaces. For example, the copolymers discussed above can be readily designed so as to make domains of desired shapes and sizes. Since the domains arise from a small number of polymer properties, there is great flexibility to make them with a range of polymer types having a range of desired electronic properties. Such structures are being developed to study magnetic incommensurability effects [49].

The organized “self-assembled surfactant monolayers” that form at a metal or semiconductor surface offer further potential for electronic control. The charged surfactant heads can create a controllable electron depletion in the substrate. Such a system can be operated as a field-effect transistor [50] whose conductance is controlled by the state of the monolayer, with its sensitivity to solvent or flow effects.

chemistry Soft-matter structures also allow one to manipulate chemical reactions. Often molecule-sized pores are used as the site of organic reactions, in order to limit the transport of reactants and products selectively according to their size and shape. Up to now the claylike zeolite minerals have been the porous materials used. Their range of pore structures is limited by their bonding configurations. Recently it has proved possible to use the microdomain structures of surfactant-water mixtures to create inert, mineralized pore structures. The soft-matter microdomains were “transcribed” into hard, mineral form [51]. In the domain of materials science, colloidal structures have long been used to create materials. Composite materials of polymers with colloidal aggregates make tough rubber compounds [52]. Likewise, particulate

minerals form the green bodies which are heat-treated to make strong, precisely shaped ceramic parts. The emerging knowledge of soft matter must increase the control and understanding of these strong materials.

biology Living cells are full of polymer chains, lipid vesicles, macroions and self-assembled rods and tubes. Still, it is not clear whether the distinctive behavior of these entities is of the essence in understanding the machinery of life. On the one hand physical effects like microphase separation, entropic interaction and membrane stress propagation may be crucial. Such effects are attractive candidates to explain such important processes as protein folding, the formation of ordered complexes in the cell, or organized motility in cells. On the other hand, the important process may be better thought of via the enzyme paradigm of explicit molecular reactions being catalyzed in an inter-related sequence. In either case, understanding how these physical processes influence the cell must be helpful.

Conclusion

Physics may be viewed as a space of concepts. By combining these concepts we may understand a broad range of phenomena. But some phenomena cannot be understood in this way; they lie beyond the compass of established concepts. These phenomena, if they are simple and broad, expand our space of concepts into new dimensions. The physics of soft condensed matter is valuable, in large part because it has been a source of such new dimensions. The field has shown us how to conceive nature in ways formerly beyond our imagining. Soft matter physics has brought much understanding, but is continually uncovering basic mysteries. There is no sign that this creative process is abating.

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