Soft materials evolution and revolution

Soft matter has evolved considerably since it became recognized as a unified field. This has been driven by new experimental, numerical and theoretical methods to probe soft matter, and by new ways of formulating soft materials. These advances have driven a revolution in knowledge and expansion into biological and active matter.

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The study of soft matter is a relatively young discipline, with the field itself becoming recognized as a unified research field only about 40 years ago, although many materials now commonly considered as part of soft matter have a much longer history of study. The first 20 years of soft-matter research was focused mainly on the definition of the field and the development of many of its foundational principles. The past 20 years has seen an explosion of new topics with the concomitant growth and broadening of soft matter as a discipline. Advances in soft matter have been driven by both new experimental and theoretical methods to study soft materials and by development of new ways of making soft matter (Fig. 1). In addition, the study of soft matter has extended to new topics of increasing sophistication. Importantly, advances in our fundamental understanding of soft matter have been complemented by new and valuable technological applications that directly benefit society. We review this evolution of soft matter in this Comment.

An important contribution driving this growth in topics is the development of improved experimental probes of structure and dynamics of soft materials. Soft matter is intrinsically the study of properties at larger length scales. This can be understood simply from dimensional arguments: for a material to be soft its elastic modulus must be low, which corresponds to roughly 6–10 orders of magnitude less than a typical hard material. Dimensionally, an elastic modulus is an energy density. The energy reflects some sort of bond energy, which can vary by only about two orders of magnitude, from thermal energy to a covalent bond energy. Thus, the large decrease in elastic modulus must result from an increase in the characteristic length scale of the material. As a result, probes of soft matter must probe longer length scales.

Scattering methods predominated the early days of the study of soft materials, with light scattering being particularly powerful because of its larger length scale.

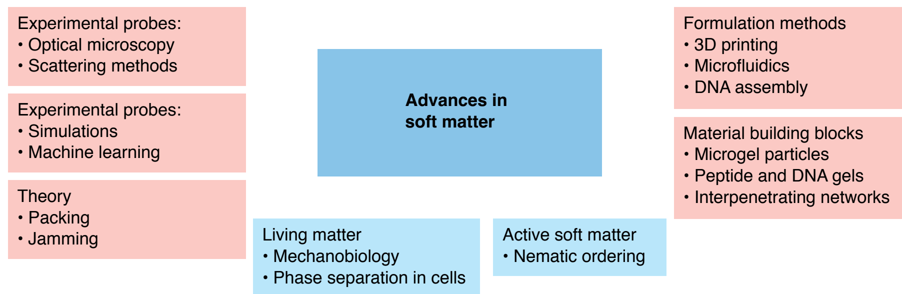

Fig. 1 | An overview of advances in soft matter. Advances in soft-matter research have been driven by new methods to study soft matter, including both experimental probes and numerical and theoretical methods; and by new methods to make soft materials, including new types of building blocks and new ways to assemble them. New topics of interest include biological systems and active soft matter.

This includes both static light scattering, which provides a probe of structure, and dynamic light scattering, which probes motion on the length scale of the wavelength of light. However, over the past 20 years, new probes have become much more widely applied. Optical microscopy, and in particular confocal microscopy, has become a powerful and widely applied probe that provides real-space imaging, rather than the Fourier-space imaging of scattering methods. It has revolutionized the study of dense colloidal suspensions as it enables individual particles to be resolved and their dynamics to be followed. This has been of great value in studying condensed phases of colloidal particles, including crystals and glasses. For example, this has enabled the study of fascinating models for ionic crystals through the addition of charge interactions[1] and the structural rearrangements in glasses as they flow[2]. Optical microscopy methods can also replace more traditional dynamic light scattering to study the dynamics of soft materials by exploiting the high sensitivity to motion following subtraction of sequential images[3]. Scattering methods have also improved, with X-ray scattering being extended to ever smaller angles and hence larger length scales, and with new probes of dynamics using both X-ray and neutron scattering methods. The use of X-ray scattering overcomes the necessity of optical index matching required for optical methods, while neutron scattering enables index matching and contrast enhancement through the use of deuterated components. Other probes of mechanical properties have also emerged to complement rheological measurements, including microrheology[4,5] and particle tracking[6]. These methods provide local measurements of the mechanical properties while not relying on any contact with the material whatsoever. Together, these experimental tools significantly broaden our ability to probe both structure and dynamics of soft materials.

Theoretical and numerical techniques have also been essential in advancing our knowledge of soft matter. Computer simulation has become increasingly sophisticated and powerful, making it indispensable in advancing our understanding of both structure and dynamics of soft matter. For example, the creation of more dilute yet solid structures by inducing interactions that are restricted to 'patches' was guided through simulations[7]. Other types of numerical method are also becoming increasingly prevalent through advances in the analysis of big datasets, making machine learning more accessible for scientific applications[8].

Just as new analysis methods have been developed, so too have new types of soft materials emerged. There are two complementary contributions to these new materials. New methods have been developed to assemble or formulate building blocks into interesting and useful structures; and the basic building blocks have been expanded in ways that enable new materials to be constructed.

Soft materials are often formed through self-assembly, where thermal energy drives formation of larger structures. For example, self-assembled surfactant-based[9] and block-copolymer-based[10] materials were widely studied as the field emerged. However, more recently, other assembly methods have produced a plethora of new and interesting soft materials. For example, the highly controlled and programmable assembly of DNA has made it into an important building block. New structures can be formed directly from DNA[11]; alternatively, it can also be used as a controlled linker for the assembly of other materials such as colloidal particles[12], which has resulted in a wide range of new structures[13]. Directed self-assembly, as well as chemical assembly of colloidal particle building blocks, has led to many new structures such as colloidal crystalline diamond[14]. Similarly, the manipulation of fluids using flow at the scale of the object being produced, using microfluidics, has produced many new soft materials[15–17]. Finally, additive assembly, or three-dimensional printing, is beginning to yield even more classes of new soft materials[18]. Even though both of these methods build structures from the bottom up, scale-up methods are being developed that will enable much larger-scale production of materials. Together, these formulation methods are broadening the range of soft materials that can be made and are having an important impact not only on enhancing our understanding of the nature of materials, but also on expanding the potential technological utility of these materials.

In addition to the development of new methods to assemble soft matter, the fundamental building blocks used for this assembly have also been greatly expanded. For example, gels made of many different materials have been created, such as peptide[19] and DNA[20] gels, or gels made with interpenetrating networks where each network contributes differently to the properties of the combined structure yielding new and interesting properties[21–23]. Gels and elastomers have become essential building blocks, and by structuring them into small particles or microgels, they can be further assembled with ease to create more complex soft materials.

The study of soft matter has also broadened significantly in the fundamental concepts that are used to investigate soft materials. Packing has been a longstanding problem of great importance to the field, starting from the fundamental question of the random close packing of spheres, where the maximum volume fraction that spherical objects can be packed is a constant that is well known[24] but has never been analytically calculated. However, the packing of spheres is actually a singular example and changing the particles to ellipsoidal shapes results in much packing to significantly higher volume fractions[25]. More recently, different classes of ordering during packing have been discovered, with hyperuniformity being an important example[26]. The dynamics of packed objects has also emerged as a broad area of interest. Highly packed, frictional objects or granular materials[27] can flow, almost like a liquid, yet can also become jammed, resulting in solid structure. This jamming transition was recognized to have many similarities to the glass transition, and jamming has become a longstanding topic of investigation[28]. Many of these materials exhibit a slow relaxation of their dynamics, resulting from complex aging processes and reflecting similarity to the physical phenomena that contribute to aging[29].

A more recent direction of research in soft matter is that of active systems. These are systems where there is some internal means of converting chemical energy into mechanical energy, thereby providing a driving force within the system itself[30]. Active matter is intrinsically non-equilibrium, and a common theme in its study is the investigation of non-equilibrium physics. So far, little generic understanding of non-equilibrium physics has been achieved. Instead, most progress has been on the patterns formed by the active materials. For example, concentrated rod-like structures form patterns when they move collectively on surfaces[30,31], and collective motion of active objects can even produce new classes of phase separation[32]. This topic remains one of very active effort.

One generic and important class of active material is living matter, and soft-matter studies have increasingly crossed into the study and understanding of living systems. Biology is, by nature, soft matter, and the understanding of the mechanical and rheological properties of cells and tissues is a soft-matter problem of direct importance. Early measurements demonstrated that the elastic behaviour of cells is similar to many soft materials and can be modelled as a 'soft glassy material'[33,34]. A new field has also emerged in biology, known as mechanobiology, which is the study of the effects of mechanics and forces on biological function[35]. The experimental, numerical and theoretical tools of soft matter are essential in mechanobiology and have helped advance the field considerably.

Another elegant merging of soft matter and biology is the discovery of a liquid–liquid phase separation in cells that leads to the formation of concentrated droplets of proteins that are not surrounded by a membrane[36]. This phase separation can be a near-equilibrium phenomenon that leads to liquid droplets, or it can be a more kinetically driven phenomenon that leads to solid gel-like condensates. These condensates can sequester RNA or other proteins and thus may play an important role in the cell[37]. The formation of these condensates entails concepts that have been widely investigated in soft matter, including, for example, the depletion interaction[38] and kinetic[39] and equilibrium[40] gelation. More generally, soft-matter science has been applied increasingly successfully to understand fundamental aspects of biology, from structure formation in cells to pattern formation in developmental biology. This reflects the contrast between the molecular viewpoint that typifies the biological approach and the collective, statistical viewpoint that typifies the soft-matter approach, and highlights the importance of soft matter in biology.

Finally, soft-matter science in increasingly important to technology and has a big impact on the health and well-being of society. An important timely example of this is in the development of the messenger RNA vaccines that have been so successful in bringing the world out of the great pandemic. These vaccines depend on self-assembled lipid nanoparticles for delivery, and the vaccines would not be viable without the lipid nanoparticles[41,42]. These particles are derived from the structure of liposomes, which was one of the early topics of research in soft matter. They are made using techniques derived from a method that was first used to produce nanoparticles at commercial scale for fish food[43]. Soft materials are also now used in many other biotechnological applications. For example, modern sequencing technologies use hydrogel microparticles[44] that have been studied for years by soft-matter scientists. Other concepts widely studied in soft matter affect materials in our daily lives. For example, the highly nonlinear properties of soft materials, such as yield stress[45] or shear-thickening[46] fluids, are essential in providing aesthetic properties of home, personal care and cosmetic goods and in controlling the taste, texture and mouthfeel of modern foods, such as alternative meats[47]. The technological contributions of soft matter are rapidly increasing. These are ultimately the topics that will ensure the health, interest and importance of the field of soft matter, and its continued growth. ❐

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