

Soft Matter science is reaching towards maturity

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Soft matter science is a rich research field at the intersection of physics, chemistry, and biology, with deep roots in thermodynamics. The term “soft matter”, originally coined in French with the less distinguished term *matière molle* during the 1970s, encompasses many materials characterized by their softness—such as sealant, hair gel, chocolate mousse, skincare cream, mud, foam, gum, liquid crystals, rubber, and many biomaterials.

But what does it mean for a material to be *soft*? Fundamentally, it relates to the *thermal energy*, or thermal noise, denoted as $k_B T$, where k_B is the Boltzmann constant and T the absolute temperature in Kelvin. At room temperature, this thermal energy is about 4.2×10^{-21} Joules or 0.026 eV. Soft materials share a key feature: they exhibit supramolecular structures—organized forms at a scale between molecular/monomeric (nanometer) and macroscopic (millimeter). These structures arise from intermolecular interactions whose energies are comparable to the thermal noise $k_B T$, such as Van der Waals or electrostatic interactions. Some assemble spontaneously, like soap molecules forming micelles in water, or polymers forming gels when crosslinked via nanoparticles. Others require energy input—for example, vigorously mixing oil and vinegar to produce the metastable emulsion we call mayonnaise.

In soft matter systems at non-zero temperature, thermal fluctuations drive various motions—molecular translations, rotations, vibrations, and larger-scale movements such as membrane undulations, Brownian motion of colloids, and changes in polymer conformation. Each of these fluctuation modes carries energy on the order of $k_B T$ per degree of freedom, matching the cohesion energy of the structure. As a result, soft matter is characterized by large structural fluctuations, remarkable responsiveness and large resilience: these systems are easily distorted by external fields but easily healed and recovered.

Soft matter science is still relatively young as a formal discipline. Although Albert Einstein described theoretically the Brownian motion in 1905 and

Georges Friedel elucidated the mesomorphic nature of liquid crystals in 1922, the field only coalesced in the later decades of the 20th century. Through combined experimental and theoretical approaches, scientists have developed a profound understanding of the equilibrium structures and dynamics of core soft matter components such as polymer chains, colloidal particles, surfactant bilayers, and liquid crystal mesophases. Many of these advances were fueled by strong academia/industry collaborations, driven by their relevance for everyday products.

In the recent decades, research has been tackling more complex and non-equilibrium systems. Microfluidics has developed both as a tool providing novel soft matter systems and as a fertile ground for new physical questions—such as the interplay between flow, internal structure and deformable boundaries (see Joshua McGraw’s article). A unified understanding of coacervation, a liquid-liquid phase separation in ternary systems, opens both fundamental and practical perspectives (see Evan Spruijt’s article). Among many topics, a growing focus lies in the study of living matter, which is inherently soft, complex, and far from equilibrium. Active matter encompasses systems that consume energy to generate motion and organization, similarly to live matter (see the dedicated mini-theme in EPN 55/3). Artificial cells are engineered assemblies that mimic core properties of life such as metabolism, replication, and evolution. Meanwhile, researchers continue to explore and improve soft materials of direct relevance to daily life, *e.g.* edible soft matter in food science, which also presents significant complexity and variety (see the article of Peter Fischer and collaborators).

Finally, while the softness of these systems is linked to energies on the order of thermal noise $k_B T$, soft matter also shares common ground with non-thermal systems, like granular matter, which appears intermediary between liquid and solid states. The last article of this mini-theme (by Tamás Börzsönyi) gives a flavor of this topic. ■