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Editorial

Capillarity in soft matter: Droplets, bubbles and particles

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Abstract:
Capillarity, the study of interfaces between immiscible media, was founded in the early 19th century, yet it continues to drive discovery at the frontier of soft matter research. Interfacial tension governs an extraordinary range of phenomena across length and time scales—from the wetting of droplets, to the nucleation of bubbles, to the self-assembly of particles at fluid interfaces. This editorial briefly addresses various capillarity-relevant phenomena in representative soft matter systems—droplets, bubbles, and particles—and calls for closer interdisciplinary collaboration in theory, experimentation, and numerical methods to unravel the rich underlying physics and harness interfacial phenomena for next-generation technologies.

Capillarity is one of the oldest subjects in fluid mechanics. Wetting and meniscus formation have been studied for centuries, and many of their governing principles are now well established. Yet capillarity remains a vibrant and rapidly evolving field. New experimental, theoretical, and computational advances continue to uncover rich interfacial phenomena across soft matter with broad implications for materials science, chemical engineering, biology, and medicine.

One of the most familiar manifestations of capillarity is the behavior of droplets. Although seemingly simple, droplet dynamics are governed by a subtle interplay between surface tension, viscosity, inertia, and gravity. As a result, droplets exhibit a wide range of fascinating phenomena, including impact, wetting, coalescence, drying, dissolution, freezing, and fragmentation.

Young's law, which describes the equilibrium contact angle of a droplet on a solid surface, forms the foundation of wetting theory. Building upon this classical concept, electrowetting enables active control of droplet wettability through applied electric fields, opening new possibilities for the manipulation of droplets in microfluidics. When a droplet rests on a soft substrate, capillary forces deform the solid, giving rise to elastocapillary phenomena that are highly relevant to biological systems and flexible devices. Furthermore, when a solid surface moves relative to a droplet, dynamic wetting becomes essential. The advancing and receding contact angles characterize the response of the moving contact line, with the well-known Cox–Voinov law linking the dynamic contact angle to contact-line velocity and viscous effects.

Droplet coalescence has a long and rich history in capillarity research (Eggers et al., 2025). Extensive theoretical, experimental, and numerical studies have established scaling laws for the growth of the liquid bridge connecting coalescing droplets, elucidated the subsequent relaxation dynamics, and revealed remarkable phenomena such as coalescence-induced droplet jumping on superhydrophobic surfaces. The opposite process, droplet breakup, is equally fundamental. The pinch-off of a liquid neck represents a classic singularity problem in fluid mechanics, where the neck radius continuously decreases until rupture, giving rise to universal self-similar dynamics near the point of breakup. An even more violent manifestation of droplet breakup is fragmentation, which continues to attract considerable interest (Villermaux, 2007). Fragmentation occurs in a wide range of settings, from the classical problem of

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droplet splashing upon impact to extreme conditions involving high-speed collisions, shock waves, or intense laser irradiation, where droplets can undergo explosive disintegration or even plasma formation.

Evaporation of droplets is another fundamental capillary phenomenon. The coupled effects of evaporation, wetting, and contact-line dynamics govern the deposition patterns formed during droplet drying, playing a crucial role in printing and coating technologies (Wilson and D'Ambrosio, 2023). Beyond simple single-component droplets, the drying of multicomponent droplets reveals a wealth of complex phenomena, including enhanced Marangoni flows, phase segregation, and spontaneous emulsification. Likewise, the freezing and melting of droplets have received increasing attention because of their importance in aerospace, power, and climate-related processes. More broadly, capillary-driven liquid transport provides the physical basis for many microfluidic technologies, enabling precise fluid manipulation and the development of novel functional devices.

Bubbles represent another important class of systems in which capillarity plays a defining role. Bubble nucleation, growth, coalescence, detachment, and collapse are central to a wide range of natural and technological processes, including fermentation, boiling, and catalysis. Starting from the formation of the vapor or gas nucleus, classical nucleation theory has provided a fundamental framework for understanding phase transitions over the past century. However, nucleation remains an active research area, particularly for heterogeneous nucleation on complex surfaces, nanoscale systems, and nonequilibrium environments, where deviations from classical predictions continue to inspire new theoretical developments.

The stability of surface nanobubbles remains one of the most intriguing problems in interfacial science. Despite their expected dissolution based on classical diffusion theories, nanobubbles can persist for surprisingly long periods. Various mechanisms, including surface contamination, dynamic equilibrium, contact-line pinning, and interfacial charge effects, have been proposed to explain their unusual stability, highlighting the complexity of nanoscale gas–liquid interfaces (Lohse and Zhang, 2015).

Bubble dynamics are also critically important in electrochemical systems, particularly in water electrolysis and gas-evolving reactions. Bubble nucleation, growth, and detachment from electrode surfaces directly affect device performance by blocking active reaction sites, increasing transport resistance, and altering local flow and concentration fields. Understanding and controlling bubble behavior is therefore essential for improving the efficiency and durability of emerging energy technologies.

Particles at fluid interfaces represent another fascinating class of capillary systems, where interfacial deformation gives rise to capillary interactions and collective behaviors. Built upon the superposition approximation, fundamental theoretical frameworks were established for understanding capillary interactions between particles, revealing how interface deformations generated by individual particles can mediate long-range interactions (Kralchevsky and Nagayama, 2000). These interactions have been utilized for particle migration and self-assembly into ordered or dynamically evolving structures.

In recent years, the study on particles at interfaces has expanded far beyond spherical colloids to encompass a wide range of particle geometries and complexities, including ellipsoids, rods, fibers, plates, deformable particles, magnetic colloids, and active matter. The interplay between particle shape, wettability, interface curvature, and external fields gives rise to diverse collective behaviors, from anisotropic assembly and interfacial phase transitions to dynamically reconfigurable structures. Such capillary-driven processes have enabled new strategies for designing functional materials, including responsive interfaces, photonic crystals, and soft robotic systems.

Despite these remarkable advances, many fundamental questions remain unanswered. How can we predict capillary phenomena in complex fluids containing multiple interacting components, such as mixtures of droplets, bubbles, and particles? How can interfaces be engineered to guide the self-organization of particles into desired three-dimensional architectures? Addressing these challenges will require closer collaboration across disciplines and the development of new theoretical frameworks, advanced experimental imaging techniques, and state-of-the-art numerical methods. The future of capillarity is therefore not only about understanding interfaces—it is about harnessing them. The ability to manipulate droplets, bubbles, and particles through interface engineering offers unprecedented opportunities for sustainable manufacturing, energy technologies, and advanced functional materials.

Conflicts of interest

The author declares no competing interest.

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