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Interfaces as the locus of interdisciplinarity: from surface energy to technological function across scales

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Highlights:

- Interfaces meeting point of phenomena across disciplines through γ, φ, and $\nabla_s\gamma$.
- Interfacial structure and energy gradients connect equilibrium and transport.
- Interfaces are important in wetting, nanotechnology, formulations, energy, and water.

Abstract: Interfaces are the regions where distinct phases meet and the symmetry of bulk matter is broken, generating excess free energy that influences structure of matter, its stability, and function across scales. In this work we identify, three closely related quantities: interfacial energy γ, interfacial structure or coverage φ, and spatial gradients in interfacial energy $\nabla_s\gamma$ that can strongly influence the performance of the materials and devices in various fields, such as materials science, nanotechnology, integrated circuits, chemistry and engineering. Moreover, we show how these three quantities can help us interpret diverse phenomena, including friction and adhesion, superhydrophobicity and omniphobicity, nanoparticle self-assembly and propulsion, thin-film processing in photolithography, detergency, emulsion and foam stability, multiphase flow in enhanced oil recovery, or atmospheric water harvesting. Because these three quantities are interdependent, they establish a solid triangular base for understanding and discussing equilibrium thermodynamics, kinetic stability, non-equilibrium transport, and engineered multiphase systems. We offer this as a conceptual framework, not a complete theory, that specialists and newcomers can use to compare interfacial problems across fields and to connect them to technological applications.

Keywords: interfaces; surface energy; interfacial gradients; formulation engineering; multiphase systems; interdisciplinarity

1. Introduction

Interfaces are the regions where distinct phases meet and where the symmetry that characterizes bulk matter is inherently broken, asymmetric [1,2]. At these boundaries, liquid-gas, liquid-liquid, solid-liquid and solid-gas, molecules experience an imbalance of interactions, giving rise to excess free energy and to physicochemical properties that differ fundamentally from those of the bulk phase. This excess energy is reflected into a surface or interfacial tension (γ), which is a central determinant of structure, stability, and dynamics in condensed matter systems. Condensed matter is the matter whose cohesion energy

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between constituting molecules or atoms exceeds 9 kT at room temperature [3]. While cohesion energy defines the interaction between molecules of the same phase, the adhesion energy defines the interactions between atoms or molecules constituting different phases, defining the characteristic of the interface between phases. From the earliest thermodynamic treatments of capillarity and adsorption to modern developments in nanotechnology, the interfaces have emerged as the loci where fundamental interactions between atoms and molecules, translate into observable macroscopic behavior [4–6].

Each discipline looks at interfaces in its own way. Physicists see force imbalance, capillarity, and wetting [7,8]. Chemists see adsorption, bonding, and surface reactivity [9,10]. In materials science, interfaces are important for controlling adhesion between phases, fracture of components, and mechanical performance of composites [11,12]. In engineering, are interested in interfaces to produce good paints and coating, for separation, and control multiphase flow [13–16], whereas in biology interfaces are crucial for membranes, protein interactions, and cellular organization [9,17–20]. At first glance all these fields appear separate with their own language and methodologies, macroscopic vs. microscopic, modelled atomistic or continuous fields, but the underlying principles governing interfacial phenomena remain fundamentally the same.

At the molecular level, a phase is homogeneous and isotropic in all directions, while an interface is a region in space only a few molecules thick with sharp gradients of energy, concentration, composition, and potential varying along the normal vector of the surface area. Therefore, diffusion, convection, reactions, and mechanical deformation become coupled and directional, in ways that bulk phases do not allow [1,21]. Wetting and adhesion are directional forces resulting from the imbalance between surface and interfacial energies at the pairwise contact between solid-liquid [22–24], solid-gas and liquid-gas phases. Similarly, Marangoni directional flows originate from in-plane gradients in surface tension [25,26]. The capillary forces govern the stability of emulsions and foams [27]. At smaller length scales, these directional forces have a stronger effect on micro- , nano and molecular objects, driving self-assembly [28], controlling the stabilization of Pickering emulsions [29], controlling adsorption and interaction, and even propulsion of micro- and nanoscale objects [30,31], important tools for bottom-up control of matter.

The technological implications of interfacial phenomena and especially the tools it offers for the bottom-up control of matter are far-reaching. For example, surface energy appears as a common parameter in friction, wear and fracture of materials. Super-functional surfaces such as superhydrophobic [32], omniphobic [33], ice-repellant surfaces [23,34], and self-cleaning coatings [35] are both related to geometry of the materials surface and its surface energy. In nanotechnology, the synthesis [1], assembly [36], and dynamic behavior of nanoparticles are mainly the result of the interfacial interactions, which control nucleation pathways, aggregation, and collective organization. In integrated circuit manufacturing interfaces play a crucial role [6], especially at the current technology level with smallest features manufactured on the order of few nanometers any defect or surface contaminant may damage the delicate circuit elements, such as transistors and connections. To better understand, the processes such as photolithography [37], thin-film deposition [38], silicon wafer cleaning and photoresist pattern development [39–41] rely critically on precise control of wetting, adhesion, and level of contamination at interfaces, to ensure that the wafers chips are free of defects. In consumer products, including detergents [42], cosmetics [43], and coatings, functionality arises from the manipulation of interfacial tension and the stabilization of complex multiphase systems. In energy applications, such as enhanced oil recovery [44–46], the mobilization of trapped fluids in porous media is governed by interfacial tension and capillary forces.

These examples can be discussed in terms of three closely related aspects of interfaces: (i) the magnitude of interfacial energy or tension, γ; (ii) interfacial structure, including coverage, roughness, and chemical heterogeneity; and (iii) spatial variations in interfacial energy, represented by the tangential gradient $\nabla_s\gamma$. Existing approaches typically address either ideal, clean interfaces within classical thermodynamics or highly specific models tailored to individual technologies, or applications offering limited cross-disciplinary transferability. In the first case (i), it is to be understood that the magnitude of the surface tension and energy regulates the existence of phases, Figure 1A, miscibility and adhesion between phases with manifestation in wettability, emulsion, foaming, *etc.* The evolution of γ with time, space or temperature, has tremendous impact in the very existence of biological life, in production and utilization of consumer goods, spanning most of the industrial fields. For the second case (ii), in particular, structured interfaces, Figure 1B, where adsorbed molecules, colloidal particles, or deliberately engineered architectures actively alter the local energy landscape, require extensions beyond the classical treatment of sharp, homogeneous boundaries [47]. The functional interfaces, such as the superhydrophobic, superhydrophilic, omniphobic, icephobic, *etc.* are all consequences of populated and nanostructured interfaces.

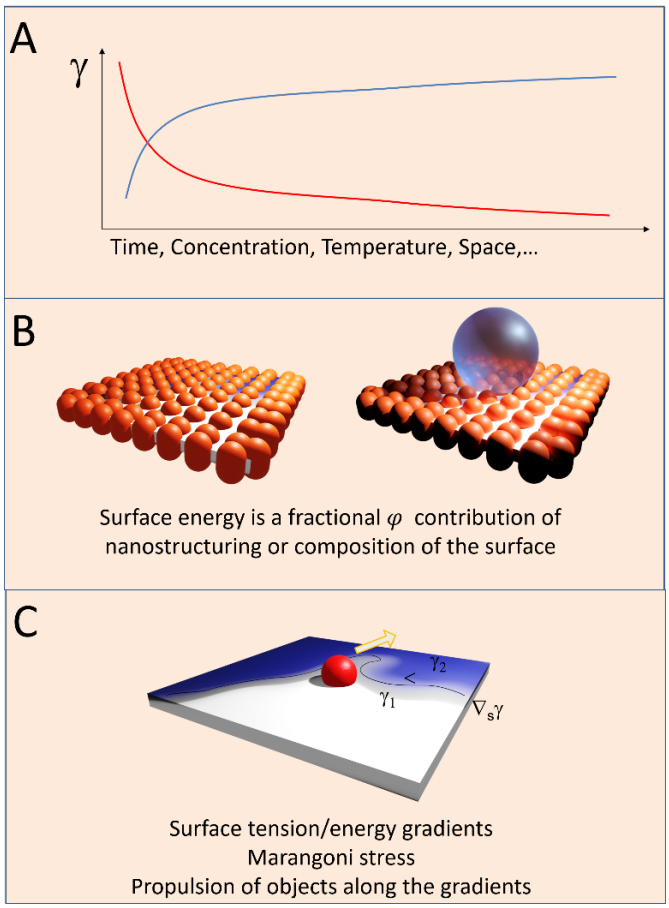


Figure 1. Schematic representation of the interfacial quantities used throughout this work. **(A)** Interfacial energy or tension, γ, is determined by the thermodynamic state and interfacial composition and may increase or decrease as these conditions change; **(B)** ϕ denotes a dimensionless descriptor of interfacial structure, such as fractional surface coverage, phase fraction, or composition, where appropriate; **(C)** Spatial non-uniformity in variables controlling γ generates a tangential interfacial-energy gradient, $\nabla_s\gamma$, which produces Marangoni stress. Created by the authors with Blender 4.1.

Finally, for the third case (iii), many interfacial phenomena of practical importance are inherently non-equilibrium in nature and are driven by spatial gradients in interfacial energy, Figure 1C. These forces that drive motion, transport, and self-organization are the results of gradients that emerge from variations in composition, temperature, surface coverage, or external fields. For example, Marangoni flows result from gradients in surface tension along a fluid interface, leading to fluid motion from regions of low to high surface tension. Similarly, the motion of particles, droplets, and liquid marbles at interfaces is a response to gradients in surface and interfacial free energy [25,31,48].

In the following sections, in the spirit of the inaugural issue of *Interdiscipline* journal, we present a few of the multifaceted aspects of interfaces and underline their fundamental interconnection across multiple domains, including materials science, nanotechnology, electronics manufacturing, consumer products, and energy systems.

2. Theoretical basis: interfacial energy, structure, and gradients

Interfaces are thermodynamic regions characterized by an excess free energy arising from the disruption of cohesive interactions present in the bulk phases. For a system containing an interface of area A, the total Gibbs free energy can be expressed as:

$$G = G_{bulk} + \gamma A \tag{1}$$

where γ is the interfacial free energy per unit area.

A distinction in terminology is necessary when different types of interfaces are considered. Surface free energy is the reversible free-energy change associated with creating unit surface area and is expressed in J m^{-2}.

For fluid interfaces, surface or interfacial tension is equivalent to the interfacial free energy, and the two are numerically equivalent, with units of N m^{-1} and J m^{-2}, respectively. For solids, the corresponding mechanical quantity is termed surface stress rather than surface tension. Surface free energy and surface stress are not generally equivalent because elastic deformation can alter the surface free energy. Their relationship is described by the Shuttleworth equation:

$$\Upsilon_{ij} = \gamma\delta_{ij} + \frac{\partial\gamma}{\partial\varepsilon_{ij}} \tag{2}$$

where Υ_{ij} is the surface-stress tensor (N m^{-1} or J m^{-2}), ε_{ij} is the in-plane surface strain (dimensionless), and δ_{ij} is the Kronecker delta (dimensionless). The second term accounts for the strain dependence/ sensitivity of the surface free energy and distinguishes the mechanical surface stress of a solid from its surface free energy. In the absence of such strain dependence, the relation reduces to $\Upsilon_{ij} = \gamma\delta_{ij}$.

Equation (1) is the starting point for equilibrium interfacial science. Minimizing the total free energy gives the Young equation for the contact angle and the Young–Laplace equation for curved interfaces, and through them the shapes of drops, the rise of liquid in capillaries, and the coexistence of phases.

In real systems, however, interfaces are rarely ideal, homogeneous, or static. Instead, they are dynamically modified by the presence of adsorbed molecules, polymers, or colloidal particles, as well as by chemical heterogeneity and surface roughness. Such local factors introduce an additional level of complexity, because interfacial properties become convoluted with the local composition, morphology, and surface geometry into an effective interfacial energy. As a result, the effective interfacial free energy

should be regarded as a state variable that reflects both the intrinsic properties of the phases and the structural properties of the interface itself.

A few main interfacial quantities and the way they couple with interface geometry are summarized schematically in Figure 2, together with the physical phenomena that emerge from these relationships.

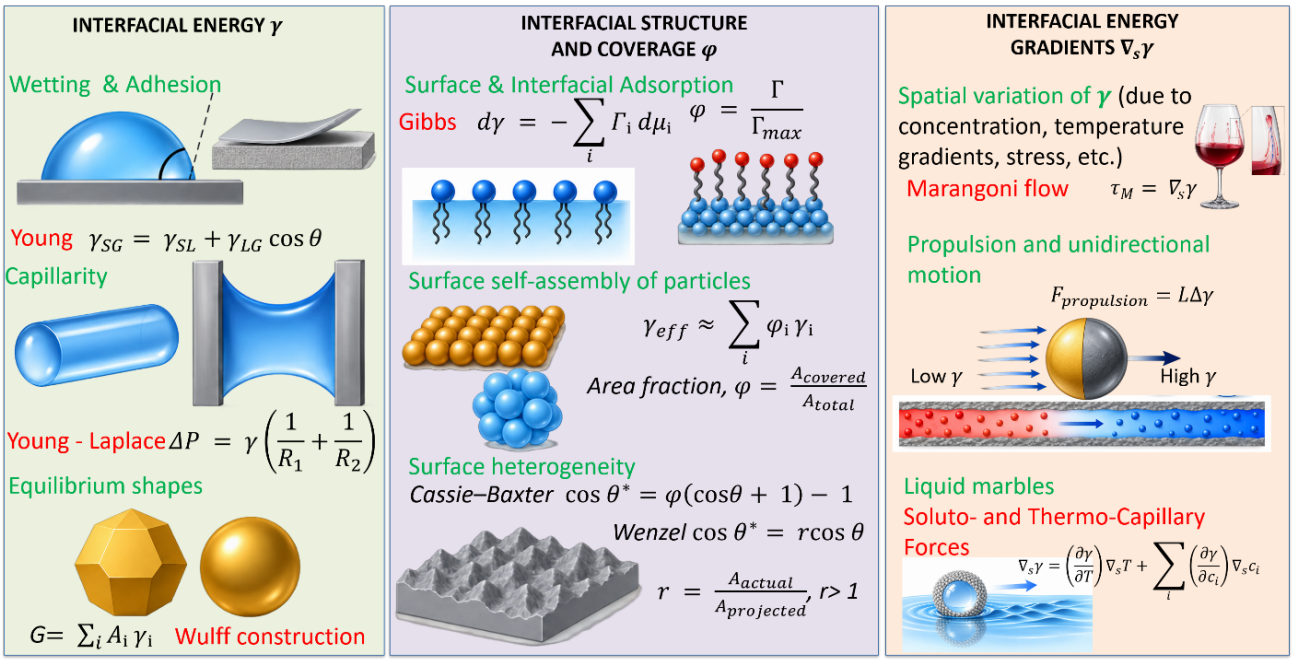


Figure 2. Principal interfacial quantities and their relationships across equilibrium and non-equilibrium phenomena. Interfacial energy, γ, governs wetting, adhesion, capillarity, and equilibrium shape. Interfacial structure and coverage, represented by ϕ, describe adsorption, self-assembly, and surface heterogeneity and their effects on interfacial energy and wetting. Spatial variations in γ generate tangential gradients, $\nabla_s\gamma$, and Marangoni stresses that drive interfacial flow and directed motion. Together, γ, ϕ, and $\nabla_s\gamma$ describe the energetic state, structural organization, and spatial non-uniformity of interfaces.

The interface may be treated as a composite region characterized by a spatial distribution of local environments, Figure 2. In particle-laden interfaces, chemically heterogeneous surfaces, or nanostructured coatings, distinct patches arise from adsorbates, phase-separated domains, or surface topography, thus contributing differently to the overall energetics [49]. Such a complex interface can be seen as a "marbled" if random or patterned if engineered surface, composed of multiple micro- or nanoscale surface patches. The total free energy then takes the additive form for surface patches:

$$G = G_{bulk} + \sum_i \gamma_i A_i \tag{3}$$

where the interfacial tension of each phase γ_i is weighted by its area A_i, where $A_{total} = \sum_i A_i$. Such an interfacial structure is seen in systems where surface morphology and chemistry can amplify intrinsic wetting properties, Figure 2, into superhydrophobic or superhydrophilic. Classical models such as those of Wenzel and Cassie–Baxter [50] describe how roughness and heterogeneity can modify apparent contact angles by tunning the geometry and chemistry of the surface patches leading to an overall increase or decrease in the contact areas between solid–liquid and liquid–gas [1,51]. In other words, surface energy

alone does not fix how a surface wets, because two surfaces of the same chemistry can behave very differently if their texture differs; this is how superhydrophobic, icephobic and omniphobic behavior arises. Similarly, in colloidal and nanoparticle systems, the adsorption of particles at interfaces leads to the stabilization of emulsions and foams by creating steric barriers to coalescence, reflecting the interplay between interfacial energy and structural organization.

Furthermore, when composition, temperature, or coverage varies along an interface, the surface tension varies too, and the resulting tangential stress sets the fluid in motion. This is the Marangoni effect, and the same stress can push particles and droplets along the interface [16,26], discussed in Section 2.1.

In addition to energy and gradients, interfaces act as a locus for multiple transport processes. Diffusion, convection, and chemical reactions often occur simultaneously at interfaces, leading to complex behavior. For example, in multiphase systems such as emulsions [43] or porous media [7], interfacial phenomena govern mass transfer, phase distribution, compartmentalization [52], flow resistance through porous media [7], *etc.* These effects are particularly relevant in applications such as enhanced oil recovery, where the mobilization of trapped fluids depends critically on the balance between interfacial tension and capillary forces [44,53].

At the nanoscale, interfacial effects become dominant due to the high surface-to-volume ratio of materials. In nanoparticle synthesis and self-assembly, the interfacial energy dictates nucleation pathways, aggregation behavior, and the formation of ordered structures. Similarly, in Pickering systems, the adsorption of nanoparticles at fluid interfaces stabilizes emulsions and enables the formation of structured materials with tunable properties [54]. These systems illustrate how interfacial phenomena can be employed to design materials with specific functionalities by controlling together the chemistry and the structure of the interface.

2.1. Hierarchy and interdependence of γ, φ and ∇sγ

The quantities γ, ϕ, and $\nabla_s\gamma$ do not constitute three independent axes of a parameter space, but form a hierarchy of interrelated quantities. First, γ denotes the surface/interfacial free energy or, for fluid interfaces, the corresponding surface/interfacial tension, with dimensions of energy per unit area (J m^{-2}), numerically equivalent to force per unit length (N m^{-1}) for a mobile liquid interface. Its value depends on the thermodynamic state and interfacial composition, and may therefore be expressed generally as $\gamma = \gamma(T, p, \{c_i\}, \{\Gamma_i\})$.

Second, ϕ is a structural descriptor rather than an independent energy. Here, ϕ denotes a dimensionless structural descriptor such as fractional surface coverage or phase fraction. Other structural descriptors are retained explicitly where appropriate; for example, surface roughness is described by the Wenzel roughness ratio r, rather than by ϕ, see Figure 2. Changes in these quantities modify the interfacial free-energy balance and therefore the effective macroscopic response. The Wenzel and Cassie–Baxter descriptions of wetting provide familiar examples in which surface structure modifies the observable contact angle without constituting an independent interfacial energy.

Third, $\nabla_s\gamma$ is a derived field quantity, representing spatial variation of γ along the interface. If the local interfacial tension depends on temperature, bulk composition, surface excess, and interfacial structure, application of the chain rule gives:

$$\nabla_s\gamma = \left(\frac{\partial\gamma}{\partial T}\right)\nabla_s T + \sum_i \left(\frac{\partial\gamma}{\partial c_i}\right)\nabla_s c_i + \sum_i \left(\frac{\partial\gamma}{\partial\Gamma_i}\right)\nabla_s\Gamma_i + \left(\frac{\partial\gamma}{\partial\phi}\right)\nabla_s\phi \quad (4)$$

This expression makes explicit that a surface-tension gradient is generated by spatial non-uniformity in the variables controlling γ. The relevant driving quantity for interfacial transport is the tangential surface gradient, $\nabla_s\gamma$, rather than the unrestricted spatial gradient $\nabla\gamma$. Since γ has units of N m^{-1}, $\nabla_s\gamma$ has units of N m^{-2} (Pa) and therefore represents a tangential interfacial stress underlying Marangoni flow:

$$\tau_M = \nabla_s\gamma. \quad (5)$$

This tangential stress constitutes the basis of Marangoni transport, which drives interfacial flow from regions of lower toward higher interfacial tension. The direction and magnitude of the resulting fluid flow or particle/droplet motion depend not only on $\nabla_s\gamma$, but also on interface geometry, hydrodynamic coupling, and the applicable boundary conditions.

Thus, γ, ϕ, and $\nabla_s\gamma$are not independent material parameters, but coupled descriptors of interfacial energetic state, structure, and spatial non-uniformity. This interpretation provides the basis for the organization adopted throughout this work.

3. Interfaces in fundamental science and advanced technologies

Interfaces play a central role in modern fundamental science across multiple length scales. In fundamental science and advanced technologies surfaces and interfaces represent the primary loci where various interactions meet and important physical phenomena arise. This section examines the interfaces from the perspective of some key domains including physics, chemistry, nanotechnology, and even in biology, and medicine.

3.1. Interfaces in physics: capillarity, wetting, and interfacial transport

In physics, interfaces are associated with force imbalances, capillary and wetting phenomena. For example, a curved interface supports a pressure difference, given by the Young–Laplace equation:

$$\Delta P = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad (6)$$

which describes the pressure drop across gas bubbles, and liquid droplets, capillary rise, and the stability of multiphase systems. It plays a significant role in flotation, oil recovery, emulsification, Ostwald ripening, *etc.*

Further, wetting behavior of sessile droplet on a flat surface can be gauges by the balance of interfacial energies at the three-phase contact line, as described by the Young equation:

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG}\cos\theta \quad (7)$$

where the γ_{SG} is the surface energy of the solid (solid-gas interface), the γ_{SL} is the interfacial tension between the solid-liquid interface, γ_{LG} is the surface tension of the liquid and θ is the contact angle of the sessile liquid droplet with the solid surface. This is important in paintings, coatings, textiles, non-stick surfaces, *etc*.

Extensions to rough and chemically heterogeneous surfaces, through the Wenzel and Cassie–Baxter models [22,50], can amplify wetting behavior, leading to the extreme situations mentioned earlier, such as superhydrophobicity, superoleophobicity, or superhydrophilicity [1,55].

Non-equilibrium interfacial phenomena are dominated by gradients in surface tension, which generate tangential stresses and induce fluid motion, Marangoni flows, which has been extensively studied in systems ranging from thin films to biological fluids [56]. It has significant importance in integrated circuit manufacturing especially in silicon waver drying, a droplet of isopropyl alcohol applied in the middle of the spinning waver moves the water away from the center causing rapid drying. More recent work has extended these concepts to active droplets and self-propelled systems driven by interfacial energy gradients [25,26,57].

3.2. Interfaces in chemistry: adsorption, catalysis, and surface reactivity

In chemistry, interfaces are the sites where molecular interactions, adsorption, and surface reactions take place. The Gibbs adsorption isotherm connects the interfacial tension to surface adsorbate species and concentration:

$$d\gamma = -\Sigma_i \Gamma_i d\mu_i \quad (8)$$

where μ_i is the chemical potential of species i, and $\Gamma_i = N_i/A$ is the surface excess concentration of species i. Any changes in the chemical potential directly influence interfacial energy through adsorption processes.

Surface reactivity is another aspect, as reactions often proceed via adsorbed intermediates whose stability and orientation are directly dependent on the surface energetics. This is evident in heterogeneous catalysis, where different regions on the catalyst surface can have different activities [58], or in complex catalysts consisting of Pt nanoparticles (the acting catalyst) on ceramic support (the reservoir of adsorbate reactants).

At liquid-liquid interfaces, chemical reactions can also be affected by the specifics of the interfacial environment, for example by confinement, orientation effects, and enhanced local concentrations, for example in phase transfer catalyzed reactions. Interfacial catalysis and reaction acceleration have been reported in emulsions and microdroplets, where the interface acts as a reactive environment distinct from the bulk phase [52].

Comprehensive works have been written on surface chemistry, from self-assembly monolayer formation, to surface passivation and surface modifications by employing rational chemical functionalization [1].

3.3. Interfaces in nanotechnology: nanoparticle synthesis, self-assembly, and active systems

At the nanoscale the surface-to-volume ratio is so high that interfaces often dominate behavior, for example in nucleation, a nucleus forms only when the bulk free-energy gain outweighs the interfacial energy cost, which makes stability size-dependent and controls the formation of nanoparticles [59].

Self-assembly processes are driven by the minimization of interfacial free energy, resulting in the formation of ordered structures from simple building blocks [21], as it is the case for the amphiphilic molecules, polymers, or nanoparticles that can organize into micelles, vesicles, and complex hierarchical

structures. In colloidal systems, particle adsorption at interfaces leads to the formation and stabilization of Pickering emulsions [36,60].

Interfaces also power motion, as it is the case for catalytic nanomotors and self-propelled particles that exploit local gradients in chemical concentration, interfacial energy or gas formation, which push the particles into directional motion [61].

Interfaces are crucial for the further development and innovation in nanotechnology.

3.4. Interfaces in electronics and micro/nanosystems

In electronic materials and microfabrication, interfaces determine structural integrity and device performance. Thin films, multilayer structures, and heterojunctions all rely on controlled and reliable interfacial interactions between different materials.

In photolithography, the deposition of photoresist layers involves complex interfacial processes during spin coating, where film thickness and uniformity depend on the interplay between viscous forces and interfacial tension [6]. Further subsequent manufacturing steps, for example pattern transfer, require precise control of adhesion and interfacial stability to avoid defects, such as pattern collapse [40].

At small length scales, capillary forces become increasingly significant. In micro- and nanoelectromechanical systems (MEMS and NEMS), interfacial forces can dominate over inertial forces, leading to phenomena such as stiction, the fabricated components can stick together due to capillary or van der Waals interactions [62].

Interfacial phenomena also influence charge transport and electronic properties in devices, particularly at semiconductor interfaces and grain boundaries, in dye sensitized solar cells, in organic mixed ionic electronic conductors (OMIECS), where local structure and chemistry affect carrier mobility and recombination.

3.5. Interfaces in biology and medicine

Biological systems are constituted from delicate elements, assembled together and tightly interacting through large areas of interfaces. The most representative biological interface is the cell membrane, composed of lipid bilayers, define compartments and regulate molecular and ionic transport, signaling and energy transduction.

Protein adsorption at interfaces plays a critical role in biological function and biomedical applications. The interaction of proteins with surfaces determines biocompatibility, immune response of implants, osteointegration, and the performance of medical devices. Surface properties such as charge, hydrophobicity, and roughness influence protein orientation and conformation, thereby affecting biological activity [63]. Some proteins are amphiphilic and cells use these to control the surface tension of tiny protein droplets inside them, which determines how big those droplets get and how well they do their job.

In medicine, drug delivery systems make use of interfacial phenomena for targeted delivery. The adsorption and penetration of these carriers are governed by interfacial interactions with cell membranes and biological fluids [64,65].

At a larger scale, interfacial processes are also involved in physiological phenomena such as pulmonary function, where pulmonary surfactants regulate surface tension in the alveoli, preventing collapse and enabling efficient gas exchange [66].

4. Interfaces in engineering, industrial systems, and consumer applications

In engineering, interfaces are considered work benches for further constructions. Coatings, cleaning agents, and formulations are all built to alter interfacial behavior, often under non-equilibrium conditions and with a good deal of empirical tuning. The subsections below cover coatings, detergency, formulations, multiphase flow, and water management.

4.1. Coatings and surface engineering: adhesion, repellency, and durability

A coating is the simplest way to change how a material interacts with its surroundings. Modifying only the outermost layer can tune wettability, adhesion, friction, and chemical resistance without touching the bulk.

The performance of coatings is fundamentally linked to the work of adhesion, which can be expressed by the following equation named after the French scientist Athanase M. Dupré [1]:

$$W_{12} = \gamma_1 + \gamma_2 - \gamma_{12} \tag{9}$$

where γ_1 and γ_2 are the surface free energies of the individual phases and γ_{12} is their interfacial free energy. The latter is not determined by the Dupré relation itself and may be estimated using appropriate combining rules. For interfaces dominated by similar dispersive interactions, the Girifalco–Good geometric-mean approximation may be written as

$$\gamma_{12} = \gamma_1 + \gamma_2 - 2\Phi(\gamma_1\gamma_2)^{1/2} \tag{10}$$

where Φ is an interaction parameter accounting for deviations from ideal geometric-mean behavior. In the idealized case $\Phi = 1$, this reduces to

$$\gamma_{12} = \gamma_1 + \gamma_2 - 2(\gamma_1\gamma_2)^{1/2} \tag{11}$$

and substitution into the Dupré relation gives

$$W_{12} = 2(\gamma_1\gamma_2)^{1/2} \tag{12}$$

Thus, the geometric-mean expression should be regarded as a model for estimating γ_{12}, rather than as a general thermodynamic identity. Accordingly, thermodynamically favorable adhesion corresponds to a high work of adhesion and, for given surface energies of the contacting phases, is promoted by a low interfacial energy γ_{12}. Conversely, non-stick and antifouling surfaces are designed to minimize favorable interactions and adhesion with the contacting medium.

The contact between the fluid and solid interfaces are best described by the Young's Equation (5). By combining the above equations, we obtain an important result for the work of adhesion between two phases that depend on the contact angle, known as Young–Dupré equation:

$$W_{adh} = \gamma_{LG}\,(1 + \cos\theta) \tag{13}$$

from which we understand that the work of adhesion is maximized when the angle θ is small and *vice versa*.

Superhydrophobic and omniphobic surfaces exemplify the coupling between interfacial energy and structure. By combining low surface energy materials with roughness, these surfaces can achieve extremely large contact angles ($\theta > 150°$) and low contact angle hysteresis, resulting in high droplet

mobility and self-cleaning behavior [35,67]. These find use in anti-icing, corrosion protection, and contamination-resistant coatings [1].

4.2. Detergency and cleaning technologies

Cleaning is an interfacial process: (i) oily and other hydrophobic soils stick to a surface because contact with water is energetically unfavorable for them, so they stay put in a low-energy configuration; (ii) surfactants decrease the interfacial tension γ between the immiscible phases, making it easier for soil to detach; (iii) surfactant micelles can take up dirt inside them and can keep it away from the surface, so it does not redeposit [68,69].

In addition to reducing interfacial tension, cleaning processes often involve mechanical and hydrodynamic effects, such as shear forces and flow-induced detachment. In precision cleaning applications, including semiconductor manufacturing, removal of nanoscale particles requires overcoming adhesion forces dominated by van der Waals and capillary interactions. Techniques such as megasonic cleaning exploit acoustic cavitation and fluid motion to enhance interfacial detachment [70,71], evidencing that cleaning efficiency is not solely determined by chemical composition, but by the interplay between interfacial energy reduction, transport processes, and mechanical forces.

4.3. Emulsions, foams and formulation engineering

Many industrial and consumer products are based on multiphase systems, including emulsions and foams, which are thermodynamically unstable because of the high interfacial energy associated with the dispersed phase. Stabilization of these systems requires controlling interfacial properties to prevent coalescence and phase separation, *i.e.* kinetic stabilization.

Surfactants reduce interfacial tension and create kinetic barriers to coalescence, while particles can provide steric and mechanical stabilization leading to Pickering emulsions and foams, see Figure 3. In particle-stabilized systems, the adsorption of solid particles at interfaces creates a robust barrier against droplet coalescence, leading to enhanced stability compared to molecular surfactants [29,43], Figure 3C.

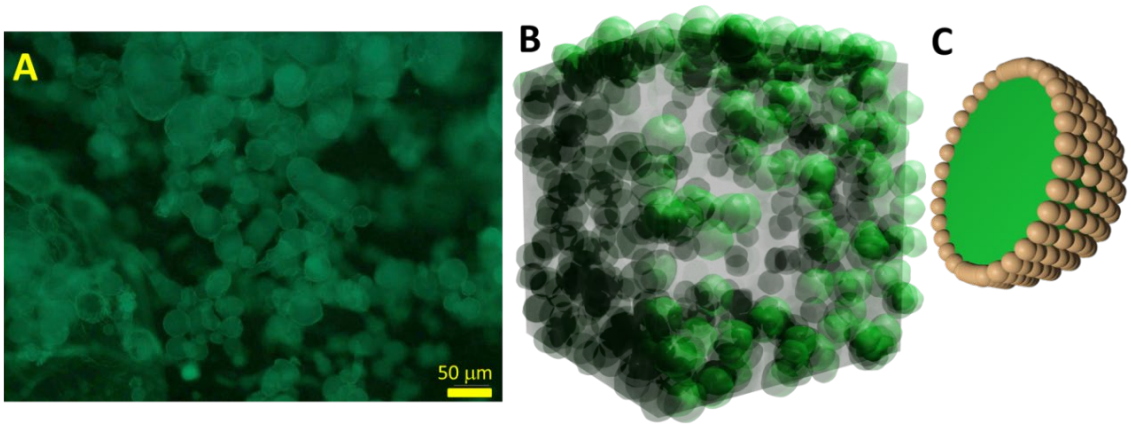


Figure 3. Schematic illustration of Pickering-emulsion stabilization. **(A)** Optical microscopy image of an oil-in-water (o/w) Pickering emulsion obtained by the authors; **(B)** 3D graphical representation of the Pickering emulsion; **(C)** schematic representation of an oil droplet kinetically stabilized by the steric barrier formed through nanoparticle self-assembly at the oil–water interface. Panels **(B)** and **(C)** were prepared by the authors using Blender v. 4.1.

The microstructure of emulsions, including droplet size distribution and interfacial rheology, determines macroscopic properties such as viscosity, texture, and optical appearance. In food, cosmetic, and pharmaceutical formulations, these properties are critical for product performance and consumer perception [43].

Why does formulation matter for interfaces? Synthetic chemistry can deliver an excellent single-molecule active, but that molecule seldom works alone. Whether it is a drug, a cosmetic bioactive, or a functional additive, its efficacy, stability, safety, and feel are set by the multicomponent, often multiphase system it is delivered in. A drug, for example, is accompanied by excipients that encapsulate it, protect it from degradation, set its release rate, and direct it to its target. In cosmetics, hydrophobic or labile actives are routinely encapsulated within emulsion droplets or foam lamellae to achieve optimal spreading, skin penetration, and prolonged efficacy on the skin surface. Similar principles apply to many industries, such as paints and coatings, oil and gas extraction, mineral extraction in flotation processes, food industry, rheological modifiers, detergents, *etc.* The same applies to nanomaterials, which they also must be incorporated into formulations, thus becoming useful active ingredients. In many sectors, the formulation itself, rather than the isolated active, emerges as the true intellectual and technical innovation of the company producing it.

4.4. Multiphase flow and enhanced oil recovery

In energy and process engineering, interfacial phenomena govern the behavior of multiphase flows in porous and confined systems. Enhanced oil recovery (EOR) is a clear case of interfacial control. Whether oil moves through a porous reservoir depends on the capillary pressure needed to push it through the pores:

$$\Delta P = 2\,\gamma\,cos(\theta)\,/\,r \qquad (14)$$

where r is the pore radius and θ is the contact angle. High interfacial tension and unfavorable wettability lead to strong capillary trapping, limiting recovery efficiency. The remedy is to lower γ or to change which fluid the rock surface prefers. Surfactant flooding, or supercritical CO_2 lowers interfacial tension, and change the wettability of the porous rock, see Figure 4.

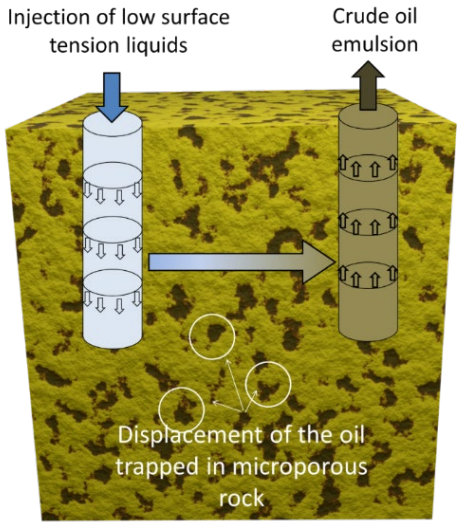


Figure 4. Schematic representation of EOR, illustrating oil displacement within a porous medium promoted by modification of the oil–water interfacial tension. The 3D graphical representation was prepared by the authors using Blender v. 4.1.

Similar principles apply in other multiphase systems, including carbon capture, groundwater remediation, and chemical reactors, where phase distribution and transport are governed by interfacial interactions.

4.5. Water management and environmental interfaces

Water harvesting is a sequential process between adsorption of water, nucleation of a droplet and detachment and collection. Nature offers a well-known example in the Namib Desert beetle *Stenocara*. Its back carries hydrophilic bumps surrounded by hydrophobic regions. Fog droplets nucleate and grow on the bumps until gravity overcomes pinning at the boundary, and then they roll toward the beetle's mouth [1]. Thus, bio-inspired surfaces can be made by patterning, alternating areas with different wettabilities such that on the hydrophilic areas for nucleation of water droplets and hydrophobic domains to ensure the droplet mobility [72]. Bioinspired interfaces like these may lead to better atmospheric water generators, next generation of fog-harvesting materials, as well as functional building facades for cities of the future.

5. Machine learning in interfacial science and engineering

Machine learning (ML) offers a data-driven complement to traditional theoretical and experimental methods in interfacial science. Rather than relying on predefined physical equations and assumptions, ML algorithms identify patterns directly from experimental or simulation data and construct predictive models starting from a set of experimental or modelled parameters. In the context of the description adopted here, ML approaches can establish relationships between interfacial structure and state variables and the resulting interfacial properties. Structural descriptors associated with ϕ, together with temperature, composition, surface coverage, and other state variables, can serve as model inputs for predicting γ. When these quantities vary spatially, the predicted local values of γ can further define $\nabla_s\gamma$, linking data-driven descriptions of interfaces to non-equilibrium transport and Marangoni phenomena. Conversely, experimentally measured γ, wetting, adhesion, or transport behavior can be used as target properties for identifying structural or compositional conditions associated with a desired interfacial response. Butler *et al.* [73] reviewed how the ML techniques accelerate discovery across molecular and materials science, highlighting their utility for property prediction. In surface chemistry and catalysis, Malone *et al.* [74] applied a hierarchically interacting particle neural network to predict adsorption energies, for H, N, and O atoms on single-metal and bimetallic transition-metal surfaces, achieving mean absolute errors (MAE) above the computational tools such as density functional theory DFT but it dramatically reduces computational cost. Sena *et al.* [75] developed an XGBoost model that predicts water contact angles on a range of solid polymer surfaces from combined experimental and computational descriptors, with MAE less than 5°, offering a practical tool for designing various surface coatings. For multiphase systems, Saddiqi *et al.* [76] employed Long-Short Term Memory (LSTM) machine learning model, to model oil-water emulsion stability over time, function of droplet characteristics and surfactants, demonstrating predictive performance for systems relevant to food, pharmaceutical, and industrial products. Yousefmarzi *et al.* [77] and others have shown that ML algorithms can reliably estimate interfacial tension in oil-water and gas-water systems, important for the optimization of emulsions and foams.

Machine learning is a fast-growing part of artificial intelligence [73]. These tools help scientists build, test, and improve models for complex problems that traditional methods either cannot solve or would take too much computing power.

In surface and interfacial science, ML can make it easier for the scientist to connect different scales of description, by learning useful relationships or simplified parameters that link detailed atom-by-atom simulations (which are accurate but very slow) to larger-scale continuum models (which are fast but less detailed) [78–83]. Admittedly, though challenges remain, such as the lack of standardized datasets for complex interfaces [78,84], but the outlook appears optimistic as these datasets are being slowly built and becoming widely available.

6. Conclusion

In this work we treat interfaces in a unified way, as the place where atomic- and molecular-scale processes determine meso- and macroscale behavior. We covered a variety of processes and phenomena, from capillarity and wetting in physics, adsorption and catalysis in chemistry, nanoparticle self-assembly in nanotechnology, precision cleaning and pattern collapse in electronics, biological membranes and drug delivery in medicine, to coatings, detergency, emulsions, foams, enhanced oil recovery, and water harvesting in engineering. In our attempt, we made use of three parameters, interfacial energy γ, structural coverage or heterogeneity φ, and tangential interfacial-energy gradients $\nabla_s\gamma$ [85–87]. The three quantities are coupled, not independent [85–87]. Our perspective reframes interfacial science as a central, interdisciplinary locus for condensed matter and engineering.

Data availability statement

No new data were generated or analyzed in this study.

Declaration of generative AI and AI-assisted technologies

The authors used generative AI tools only to improve language and readability. The intellectual content of the manuscript (including ideas, analysis, and conclusions) is our original work. The manuscript complies with academic integrity and publication ethics standards. Specifically, the authors used ChatGPT, for language polishing in limited sections of manuscript. The Graphical Abstract Image was generated with ChatGPT. The authors take full responsibility for the content of the manuscript.

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Authors' contribution

Conceptualization, M.H., O.I.N. and A.H.; methodology, M.H., O.I.N. and A.H.; validation, M.H., O.I.N. and A.H.; formal analysis, M.H., O.I.N. and A.H.; writing—original draft preparation, M.H., O.I.N. and A.H.; writing—review and editing, M.H. and A.H.; visualization, A.H.; supervision, A.H.; All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Andrei Honciuc holds the position of Associate Editor for *Interdiscipline* and has not peer reviewed or made any editorial decisions for this paper. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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