

Project Description – SPP 2171 Dynamical Wetting of Flexible, Adaptive and Switchable Surfaces

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Dynamics of Liquid-Liquid-Elastic Three Phase Lines

Project Description

1 State of the art and preliminary work

Dynamical wetting of soft solids. — The dynamical wetting of *rigid* surfaces is governed by a balance of capillary forces and viscous dissipation inside the liquid [1, 2]. On *soft* surfaces however, spreading dynamics typically stem from quite different physics. Capillary forces at the three phase line deform the soft solid into a sharp *wetting ridge* [3]. A spreading motion of the liquid causes a dynamical change of this deformation. The associated dissipation in the solid, and not the viscous liquid flow, governs the spreading motion [4, 5]. Therefore, spreading rates can be decelerated by orders of magnitude as compared to rigid solids, an effect which is frequently called *viscoelastic braking*. Pioneering work has revealed a scaling relation between the dynamical wetting behavior and the frequency dependence of the loss modulus of the solid [5].

The amplitude of the wetting ridge is governed by the so-called elasto-capillary length

$$\ell = \frac{\gamma}{G}, \quad (1)$$

where γ is the surface tension of the liquid and G is the static shear modulus of the solid. Typical values experienced in soft wetting are $\gamma = 60 \text{ mN/m}$ and $G = 1 \text{ kPa}$, resulting in deformations in the range of tens of microns. The capillary traction of a (moving) contact line resembles a line force that is virtually infinitely sharp. Bulk elasticity cannot stably support such kind of traction, which would lead to a log singularity in linear theory. The key regularizing mechanism is solid surface tension, by which a stable balance of capillary forces, similar to the Neumann balance for liquids, is established at scales below ℓ .

Recently we have developed a first quantitative theory that goes beyond scaling relations and is thus capable of predicting spreading rates [P1]. In this model, the solid deformation and dissipation are calculated from the theory of linear viscoelasticity, taking the full rheological spectrum of the substrate material into account, as well as the capillarity of the elastic surface. This way we could also describe a regime at larger velocities in which experiments no longer obey the scaling laws but instead, the viscoelastic braking force saturates. For even larger velocities, the contact line motion becomes unsteady, resembling a stick-slip type of motion [P1][6].

While the qualitative features of experimental observations are well represented by this theory, a quantitative understanding of stick-slip motion remains unavailable. Already in the saturation regime of the viscoelastic braking force, theory and experiment deviate quantitatively. Recently it has been claimed in [7] that this deviation could be resolved by a different route of calculation, using an energy dissipation balance instead of the force-based mechanical approach from [P1]. However, it is known from Newtonian mechanics that both routes should lead to consistent results, and we could demonstrate in [P2] that the difference between both models stems from an inconsistent approximation and a mistaken substitution in [7]. In addition, the model from [7] cannot be used for quantitative predictions because its prefactor is determined from comparison

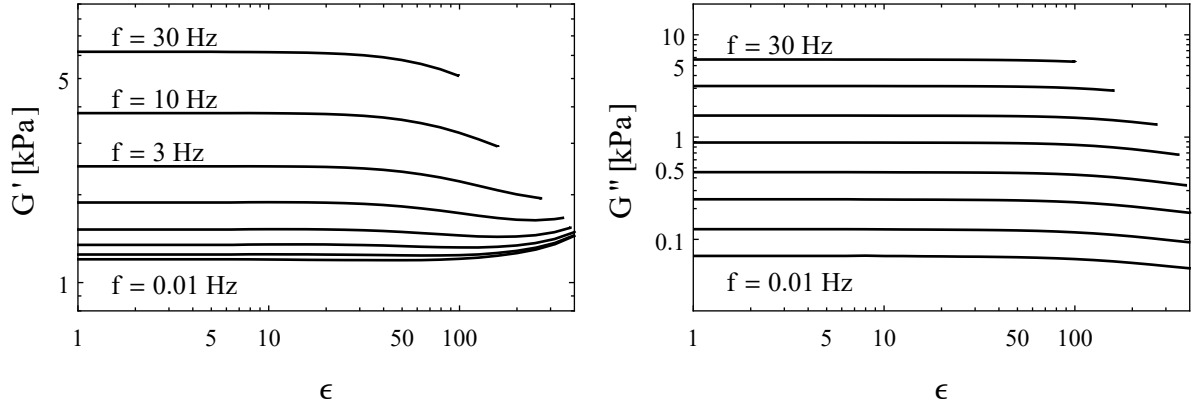


Figure 1: Preliminary measurement of the large strain rheology (Fundamentals of G' (left) and G'' (right)) of Dow Corning CY52-276. The linear viscoelastic range (LVE) is large for small frequencies and transitions directly to the strain stiffening regime. For larger frequencies, the LVE decreases and exhibits an intermediate strain-softening regime. At typical solid angles $\sim 90^\circ$, strains of 100% are easily reached in soft wetting experiments and the sharp tip of a moving wetting ridge locally excites high frequencies at significant amplitudes.

with experimental data. Thus, a quantitative understanding of the dynamics of soft wetting is still lacking in current research literature.

The current consent in the field is that the discrepancies between experiment and theory stem from the fact that experiments are conducted in a regime of large strains that, locally, reach 100% and more, while all existing models use the framework of linear viscoelasticity for which strains are assumed to be small [P2]. The large strains in the experiments could excite several sources of nonlinear behavior: (i) Due to the strong deformation of the solid, the geometry becomes nonlinear and the infinitesimal area elements in stress and strain tensor depend on the deformation. Traction can no longer be applied in the Lagrangian domain as is the case for linear elasticity [8]. This holds already for static wetting ridges, but even more so for dynamic ones because the rotation of the ridge tip causes larger and asymmetric strains [P1]. (ii) The silicone gels that are typically used in dynamical soft wetting experiments exhibit a rather large linear viscoelastic regime. In the high frequency range, however, nonlinearities can be detected already well below 100% strain (see preliminary measurements in Fig. 1). (iii) Solid surface tension may be strain dependent, which would be most important in the large-strain zone near the contact line. This could impact the elastocapillary contribution to soft wetting, and alter the microscopic boundary conditions at the three phase contact line [9].

For simple liquids, surface energy and surface tension are identical because surface molecules can freely relax back to their minimum energy configuration upon changes to the surface geometry. For solids, however, molecules define material coordinates, and they remain stationary in the Lagrangian frame (unless plastic deformations are considered). Thus, surface energy may depend on surface strains. As a consequence, surface tension is different from surface energy, and is given by the Shuttleworth relation,

$$\Upsilon = \gamma + \frac{d\gamma}{d\epsilon}, \quad (2)$$

which can be derived by variational calculus [10, 11]. Here, Υ is the surface stress, γ is the surface free energy, and ϵ is the in-plane surface strain. Previously, (2) has mostly been considered for metal surfaces, but is recently discussed very actively for soft amorphous materials, especially in the context of soft wetting and with quite controversial results and conclusions [9, 12, 13]. In [12], the local three-phase angles of liquid drops were found to strongly depend on a pre-stretch that

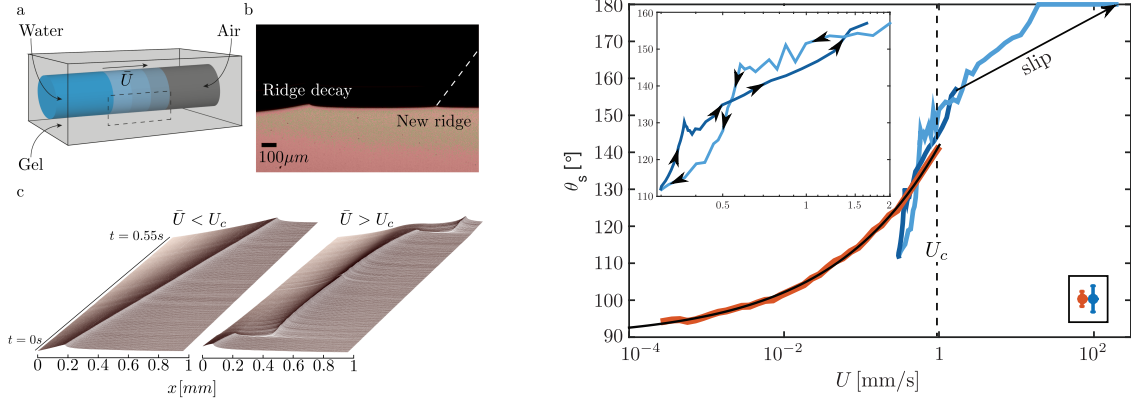


Figure 2: Measurement of the dynamic three phase angles at a liquid-vapor-soft solid three phase contact line by shadowgraphy of a cylindrical cavity (unpublished). Left: Setup (a), shadowgraph (b) and space-time representation of a wetting ridge for steady and stick-slip motion (c). Right: Dynamical solid angle θ_s versus contact line speed U for steady motion (red) and during a stick-slip cycle (blue).

has been applied to silicone gels. From this, the authors concluded $d\gamma/d\epsilon \gg \gamma|_{\epsilon=0}$. In contrast, Schulman et al. [13] find $d\gamma/d\epsilon = 0$ for incompressible elastomers, and a weak Shuttleworth effect for surfaces of glassy polymers.

A surface layer which is stiffer than the bulk elastic material (a “skin”) will be tensioned by an externally applied stretch. The leading order mechanical consequences would be indistinguishable from those of a strain dependent surface energy: a Laplace pressure that scales with (skin) tension and surface curvature [14]. This would allow for two simple explanations of the strong Shuttleworth effect measured in [12]: (i) Polydimethyl-siloxane (PDMS), the material used in [12], forms glassy surface layers in oxidative environments [15, 16, 17]. Tensioned by an externally applied pre-stretch, such layers would introduce a strain-dependent Laplace pressure. (ii) High concentrations of polystyrene (PS) particles had been embedded near the surface to track deformations in [12]. These particles are much stiffer than the bulk substrate and, at high concentration, cause an increased effective surface modulus.

In recent unpublished work, we have shown that the three phase angles of water on top of a PDMS gel are actually dynamical quantities that, in addition to a possible influence of a pre-stretch, also depend on the speed at which the wetting ridge moves. Fig. 2 (left) shows a setup that is suitable for high-speed measurements (several 1000 fps) of surface profiles with micrometric resolution. The gel is prepared inside a cuvette with plane and parallel windows, and contains a cylindrical cavity. Filling the cavity partially with a liquid creates a wetting ridge on the inside of the cavity, which can then be imaged shadowgraphically through the cuvette and gel. By measuring the solid opening angle θ_s as a function of the contact line velocity U , we found a significant increase of θ_s with U that could not be explained by bulk rheology (see Fig. 2 (right)). Rather, this indicates that the solid surface tension increases as a function of speed, which could originate from a surface strain or surface strain rate dependence. In non-stationary motion we find a hysteretic relation between θ_s and U , centered around the values from stationary motion. This supports the hypothesis of a strain rate dependence. An in-situ measurement of both, dynamic surface strain, and surface tension, is not available so far.

Moving contact lines have previously been suggested to be used as microrheometers [18]. While the scaling relation between the dynamic contact angle and the frequency dependence of the loss modulus could well be used, quantitative microrheology would require a quantitative theory that can account for all the intricate relations that have been listed above. Another work, where uncrosslinked polymer chains have purposefully been added to the gel network [19], indicates that poroelasticity and contamination of the test liquid by extractable constituents of

soft solids could impact the dynamical wetting behavior.

In contrast to the complexity of soft wetting, caused by its rather nonlinear character, there are closely related cases for which linear models are apparently sufficient to yield quantitative predictions. In *soft lubricated contacts*, for instance, two soft solids move relative to each other, separated by a liquid-filled gap. The interplay between lubrication pressure and elasticity causes a lift force [20] which is impacted by viscoelastic dissipation in the soft solid [P3]. Also closely related is the problem of a rigid body adhering to a soft elastic material, for which we could show that solid surface tension leads to a boundary condition at the three phase line that is equivalent to Young’s angle for liquids [P4]. An important consequence is that, similar as for liquid droplets on soft surfaces, small objects ($\ll \ell$) tend to sink into the elastic material if adhesion is strong.

In the regime of large deformation elastic problems, analytical progress is typically rather difficult or even impossible because of the strongly nonlinear character of the underlying equations. In some cases, self-similar solutions representing the underlying scaling behavior of the governing equations can be found. This is typically the case near singularities, for instance near the self-contacting zone of a surface crease or the deformation over a volume sink [P5]. To date, a similarity description for nonlinear wetting ridges that takes not only the Neumann-like angles, but also bulk (visco-)elasticity into account, remains unavailable.

An important and currently still open question is whether the linear viscoelastic theory would be applicable to describe soft wetting dynamics in case the strains remained small. Due to the local Neuman-like balance [3], this would require capillary tractions that are comparable or smaller than the gel-liquid surface tensions, a situation that can hardly be achieved with liquid-vapor interfaces, but most likely with liquid-liquid interfaces: close to a critical point, surface tension can become arbitrarily small [21].

Phase separation on soft solids. — When a homogeneous liquid mixture of two components becomes unstable, either by a change in temperature or by an enrichment of one of the components, phase separation is promoted by the gain of (bulk) energy. However, the surface tension between the two distinct phases poses an energetic barrier to the formation (nucleation) of a new phase. Only in the spinodal regime, phase separation occurs in the form of a long-wave instability without such a barrier [22]. Normally, however, phase separation occurs through nucleation, growth, and coarsening of small droplets of a new phase. If r is the characteristic length scale of the newly nucleated phase (i.e., the droplet radius), the gain of bulk energy and the expense of surface energy scale as r^3 and r^2 , respectively. This yields a critical r below which nuclei of the new phase are unstable [22]. Heterogeneous nucleation on top of solid surfaces is typically preferred over nucleation in bulk solution [23] if the contact angle of the newly created phase with the solid is small. This effect can be further enhanced by surface topography which may substantially alter the relation between volume and surface energy of the nucleus.

The static and dynamic wetting properties of soft solids have so far predominantly been investigated for stable macroscopic two-phase scenarios, i.e. by dispensing liquid droplets [P1] or in dip-coating configurations [6]. Much less attention has been paid to the nucleation of a separate phase on top of a soft surface. Nonetheless, the apparent wetting properties of soft surfaces depend on the size of the droplet, which is especially important on small scales. If droplets are smaller than the elastocapillary length ℓ , they tend to sink into the substrate [24]. This does not only lower the apparent contact angle, but also the overall surface energy, at an only mild expense of bulk elastic energy. Thus it can be expected that droplet nucleation on soft surfaces proceeds differently from rigid ones.

Nucleation processes are relevant in various phase change phenomena. An important case that had previously been investigated also in contact with soft surfaces is the condensation of (water) vapor [25, 26]. Vapor condensation is relevant in many industrial processes, notably cooling applications e.g., in power generation. It was discovered in [25] that condensation on

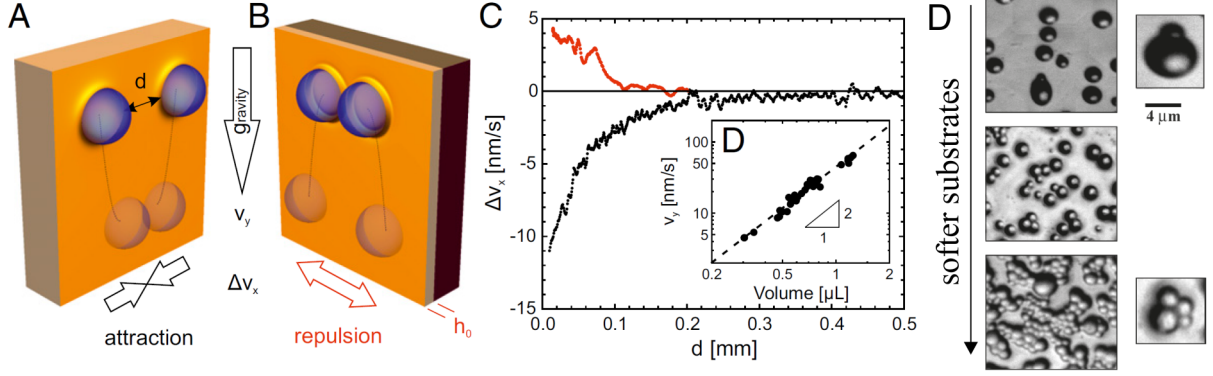


Figure 3: A-C: interaction of droplets on soft surfaces (images taken from [P6]). The droplets move down a vertical soft wall, driven by gravity. Their horizontal motion stems from an elastocapillary interaction. A: On thick soft layers, droplets always attract, and they were found to merge upon contact. B: On thin soft layers, droplets repel in the far field. C: relative horizontal velocity as a function of drop-drop distance on thick (black curve) and thin (red curve) layers. D: Water vapor condensation on increasingly soft surfaces (image taken from [25]). Soft surfaces facilitate nucleation and condensation. Droplet clusters were found in all cases, but droplets did not merge.

soft surfaces can greatly be accelerated as compared to rigid surfaces. The nucleation density of condensate droplets increased with substrate softness (see Fig. 3 D). This was attributed to the beneficial ratio of volume to liquid-vapor surface area and the correspondingly reduced nucleation threshold on soft surfaces. Further, [25] reports that droplets on soft surfaces grew faster than on rigid surfaces, leading to an overall faster condensation rate. It was also found that the condensed droplets would not merge on softer substrates, despite a certain tendency of forming clusters of multiple close-by droplets. This non-coalescence was attributed to elastic lamellae in between the droplets, formed by the capillary tractions at their three-phase lines [25]. Such non-coalescence is in contrast to [P6], where droplets would always merge, even on softer surfaces than in [25] (cf. Fig. 3 A-C). This distinct behavior is likely caused by the different substrate materials since the non-stoichiometrically cross-linked PDMS used in [25] is known for its high fraction of uncrosslinked chains [19] that lead to poroelasticity or even plastic deformations.

The case of liquid-liquid phase separation, which is relevant in the scope of this proposal, has not yet been investigated on soft surfaces. Nonetheless, a similar facilitation of droplet nucleation as in the vapor condensation case can be expected. Phase separation can be induced by changing temperature or composition. The miscibility gap of a binary mixture depends on temperature and can thus be tuned to reach into the composition of the previously homogeneous phase [22]. A local enrichment of one component can also lead to phase separation. The latter strategy has recently gained significant attention in sessile drop evaporation [27]. For sessile droplets, the evaporation rate has a sharp peak near the contact line. This leads to an evaporative enrichment of the residual component near the contact line, with a number of consequences ranging from solute redistribution [28] to shape changes [P7]. In the case of liquid combinations that exhibit miscibility gaps, evaporative enrichment leads to liquid-liquid phase separation [27, 29].

After the initial nucleation process, phase separation proceeds through coarsening of the newly formed compartments. In a quiescent liquid, coarsening typically proceeds through Ostwald ripening and the coalescence of droplets that undergo Brownian motion [22]. In presence of convective motion, coalescence can also be induced by inertial or viscous collisions between droplets. In case of heterogeneous nucleation on top of a solid surface, these coarsening processes are normally not possible. Limited by diffusion or surface attachment, droplets grow until they touch and merge, giving rise to so-called breath figures [30, 31]. On elastic substrates, however, another type of coarsening process could be possible (see Fig. 3 A-C). In recent work we have

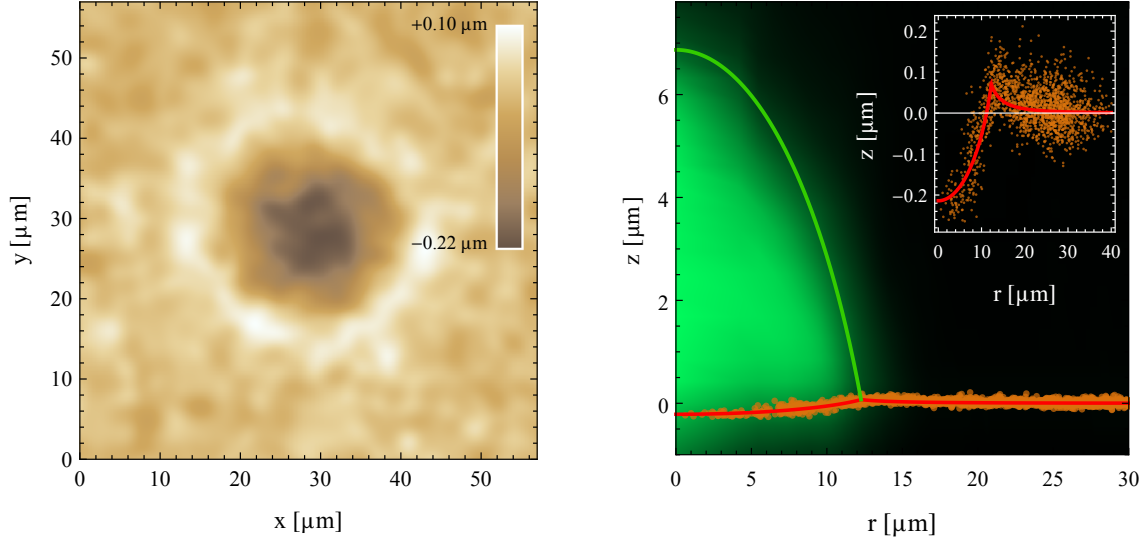


Figure 4: Preliminary measurement of a fluorescently labeled protein condensate on a silicone gel, immersed in aqueous medium. Left: height map determined from sub-pixel particle localizations, linear interpolation, and Gaussian smoothing with radius $1\ \mu\text{m}$. Right: azimuthally averaged protein signal and estimated drop surface (green), together with the localizations of the particles at the gel surface (orange) and the analytical model for the substrate shape (red). The inset shows a zoom to the length scale of the substrate deformation.

demonstrated that droplets on soft surfaces interact through an elasto-capillary mechanism [P6]. The lengthscale of the interaction force and the timescale of the consequential droplet motion depend on the geometry of the substrate, the elastocapillary length, and the rheology of the substrate material [P6, P8]. Importantly, the direction of the interaction (attractive/repulsive) depends on the ratio between droplet size and substrate thickness [P6]. The influence of such interactions on the coarsening dynamics have not yet been investigated.

Phase separation recently became a highly active research topic in cell biology [32, 33], triggered by the discovery of the liquid-like nature of so-called p-granules, and their condensation/dissolution dynamics in 2009 [34]. In contrast to ‘regular’ cell organelles, such condensates of proteins do not possess a lipid membrane, which allows for faster dynamics [32]. Various types of such ‘droplet organelles’ are known to date, providing various functionalities that range from protein assembly to stimuli responses [32], and some are associated with neurodegenerative diseases [35]. The physico-chemical properties of such droplet organelles remain largely unexplored.

Figure 4 shows a preliminary experiment with a protein solution. In this example, protein condensation was triggered by adding a crowding agent. The protein droplet deforms the PDMS-based substrate into a stationary wetting geometry that reveals information about the interaction with the environment and the substrate. The droplet and substrate shapes were simultaneously imaged by confocal microscopy. The protein was labeled with a green fluorescent dye, while the surface deformation was tracked with fluorescent beads embedded immediately below the gel surface. The fits of theoretical surface profiles, shown in Fig. 4, reveal a surface tension of the protein against the aqueous medium of $(0.94 \pm 0.08)\text{ mN/m}$ and an apparent contact angle of $58^\circ \pm 2^\circ$, indicating a somewhat stronger interaction between PDMS and the protein as compared to the surrounding aqueous medium.

The experiment from Fig. 4 demonstrates the capability of soft wetting phenomena to reveal physico-chemical properties of materials in cases where classical methods would fail, e.g. due to small sample volumes or minute surface tensions. It also demonstrates that a profound knowledge about the statics and dynamics of liquid-liquid soft wetting could prove highly valuable to

other domains of scientific research. Yet, the dynamical case requires better fundamental understanding that becomes accessible through simple liquids with properties that can be calibrated independently.

1.1 Project-related publications

1.1.1 Articles published by outlets with scientific quality assurance

- [P1] Karpitschka S, Das S, van Gorcum M, Perrin H, Andreotti B, Snoeijer J (2015) Droplets move over viscoelastic substrates by surfing a ridge. *Nat. Commun.* 6:7891.
- [P2] Karpitschka S, Das S, van Gorcum M, Perrin H, Andreotti B, Snoeijer J (2018) Soft wetting: Models based on energy dissipation or on force balance are equivalent. *Proc. Natl. Acad. Sci. U.S.A.* 115(31):E7233–E7233.
- [P3] Pandey A, Karpitschka S, Venner C, Snoeijer J (2016) Lubrication of soft viscoelastic solids. *J. Fluid Mech.* 799:433–447.
- [P4] Karpitschka S, van Wijngaarden L, Snoeijer J (2016) Surface tension regularizes the crack singularity of adhesion. *Soft Matter* 12:4463–4471.
- [P5] Karpitschka S, Eggers J, Pandey A, Snoeijer J (2017) Cusp-shaped elastic creases and furrows. *Phys. Rev. Lett.* 119:198001.
- [P6] Karpitschka S, Pandey A, Lubbers L, Weijs J, Botto L, Das S, Andreotti B, Snoeijer J (2016) Liquid drops attract or repel by the inverted cheerios effect. *Proc. Natl. Acad. Sci. U.S.A.* 113(27):7403–7407.
- [P7] Karpitschka S, Liebig F, Riegler H (2017) Marangoni contraction of evaporating sessile droplets of binary mixtures. *Langmuir* 33:4682–4687.
- [P8] Pandey A, Karpitschka S, Lubbers L, Weijs J, Botto L, Das S, and J.H. Snoeijer BA (2017) Dynamical theory of the inverted cheerios effect. *Soft Matter* 13:6000–6010.

2 Objectives and work programme

2.1 Anticipated total duration of the project

The anticipated total duration of the project is 36 months, starting 1 October 2019.

2.2 Objectives

Aims. — With the proposed project we wish to (i) improve our fundamental understanding of the dynamics of wetting of soft surfaces and, especially, extend it to the case of liquid-liquid-soft solid three phase lines. With that prerequisite, we want to (ii) establish the principles of liquid-liquid phase separation in contact with soft surfaces.

(i) A quantitative understanding of the wetting dynamics on soft surfaces remains elusive, because available theories are limited to the regime of linear viscoelasticity, but experiments with liquid-vapor-soft solid contact lines show strong nonlinear behavior. Several origins for nonlinearities have been discussed, for instance the *geometry* of the wetting ridge (surface slopes of $\mathcal{O}(1)$), the large-strain bulk *rheology* of the substrate, or strain (or strain-history) dependent solid surface energies (the *Shuttleworth* effect [10]). In the proposed research we want to use liquid-liquid-soft solid contact lines to reduce and thereby disentangle these nonlinearities to yield a better understanding of dynamical soft wetting. In addition, the viscosity of the ‘outer phase’ might have an influence on the large velocity regime and the frequently observed stick-slip motion, leading, for instance, to entrainment of the receding phase. Quantitative understanding of soft wetting could enable contact lines to be used as near-ideal micro-rheometers, since liquid interface exert one of the sharpest known line forces.

(ii) Intimately related to the dynamics of liquid-liquid-soft solid three phase lines is the case of liquid phase separation on soft surfaces: How does a second liquid phase nucleate and coarsen on top of a soft solid that is initially covered with a homogeneous liquid phase? Rigid surfaces typically facilitate nucleation because they lower the surface-energetic expense of forming a new phase (heterogeneous nucleation). Such processes have not yet been investigated on soft surfaces. There, however, one can expect even lower barriers because small droplets tend to sink into the substrate, reducing their surface energy at an only mild expense of elastic energy. We want to elucidate the physics behind phase separation in contact with soft solids. Recently, “droplet organelles” that are formed by liquid-liquid phase separation became a highly active research topic in cell biology [32]. Many components of cells that contribute in phase separation have elastic properties (i.e., cortex, nucleus or membrane). With the proposed research we want to provide a reference case for such processes that is reduced to the simplest possible liquids and soft solids.

Objectives. — We will investigate the dynamics of the ‘liquid-immersed’ case of soft wetting. This allows for combinations of surface tensions that have remained unexplored so far and, especially, much smaller capillary tractions at the three phase line. This will give access to the linear viscoelastic regime also in experiments, and admit controlled excitation of nonlinearities. To achieve a quantitative understanding of the substrate dynamics, and to reveal how liquid phase separation proceeds in contact with soft surfaces, we will

- (O1) determine a set of suitable test materials (liquids and polymer gels),
- (O2) reveal the traction-dependence of dynamic wetting ridge shapes,
- (O3) control various nonlinearities independently and determine their nature,
- (O4) establish the relation between the nucleation/growth/coarsening dynamics of liquid-liquid phase separation and the substrate rheology.

2.3 Work programme incl. proposed research methods

Objectives (O1) - (O4) will be elaborated in the following work packages:

- (WP1) Implementation of the experimental setup and exploration and characterization of different material systems.
- (WP2) Shadowgraphic determination of dynamic solid surface shapes and liquid interface angles with the material systems from (WP1).
- (WP3) Measurements of dynamic strain fields of the surface and the bulk with particle tracking methods, complementing (WP2).
- (WP4) Time-lapse microscopy of nucleation, growth and coarsening dynamics in liquid-liquid phase separation on soft substrates.

Each of these modules will be described in detail below. The time planning is outlined in Fig. 5.

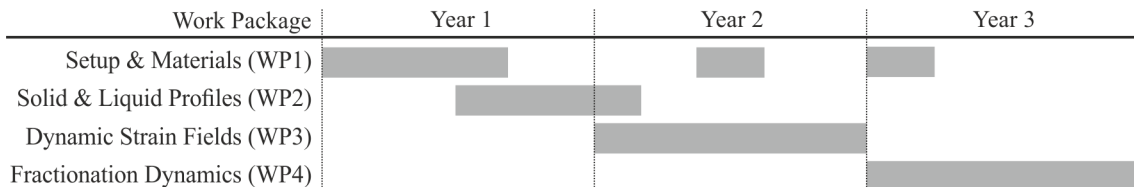


Figure 5: Timeline for the proposed work packages.

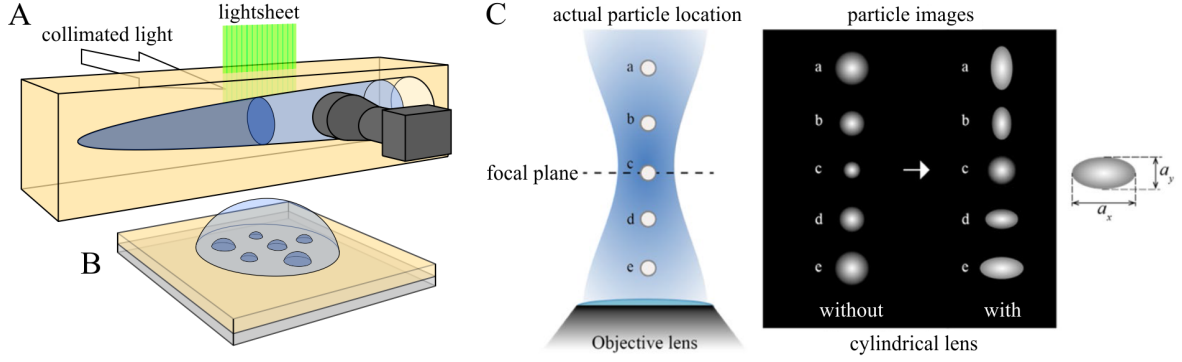


Figure 6: A. Setup for shadowgraphic profilometry of dynamic wetting ridges, combined with lightsheet fluorescence excitation for particle tracking. Wetting ridges are formed on the surface of a parabolic cavity filled with two immiscible liquids. B. Planar substrate geometry which can be imaged with an inverted microscope in various modes (brightfield, phase contrast, epifluorescence, confocal, astigmatic 3D tracking). C. Principle of astigmatic 3D PTV. The orthogonal dimensions of the particle image a_x and a_y reveal the z position of the particle (image adapted from [38]).

(WP1) Setup and Materials. — In the first work package we will implement the experimental setups required to study dynamical wetting of liquid-liquid-soft solid three phase contact lines. Two strategies for the observation of three phase contact lines are pursued: Shadowgraphy and particle-based tracking and/or correlation methods (cf. Fig. 6). In addition to these setups, we will elaborate a set of suitable materials to perform the experiments. The work described here will be continued according to the evolving requirements of the ongoing project.

Shadowgraphy is one of the simplest techniques to determine the shape of a deformed soft solid and of the liquid interface moving over it. Typically, the micron-scale deformation of the solid is hardly accessible in a sessile drop configuration. Thus we will instead use the cavity setup depicted in Fig. 6 A (for a preliminary result see Fig. 2). Here, the wetting ridge is directly visible through the (transparent) substrate material. The meniscus between the two liquids can be observed with minimal distortion only through the center of the cavity unless the refractive indices of the liquid and the gel are similar. The liquid typically relaxes orders of magnitude faster than the solid, for which the liquid meniscus can be considered spherical, and its center and wall coordinates describe it sufficiently. Optical resolution is enhanced by using smaller cavity diameters, while effects due to the non-planar geometry may become relevant if the cavity radius R becomes comparable to the elastocapillary length ℓ . We will test a number of ratios R/ℓ to find suitable conditions.

In-plane (surface parallel) deformations are not visible in shadowgraphy but might play an important role in soft wetting. Therefore, we will use also various particle-based tracking and/or correlation methods. Here, the soft substrate is typically in a planar geometry, held by a transparent, rigid support (cf. Fig. 6 B). Particles (and possibly the liquid phase) at the soft surface will be observed by an inverted epifluorescence or confocal laser scanning microscope. The latter gives 3D localization information for the particles with the simple handling and data processing available for such standard techniques, but at relatively small frame rates. To access high speed processes, we will use astigmatic 3D Particle tracking through an epifluorescence microscope. In this technique, astigmatism is purposefully introduced to the observation optics. The shape of particle images then contains the required information about its location relative to the two orthogonal focal planes [36, 37].

As substrate materials we intend to use stoichiometrically cross-linked Polydimethylsiloxane (PDMS) of relatively low molecular mass (below the entanglement threshold). Especially materials with low volatility, where contaminations of low molecular weight have been removed,

are suitable for our experiments. Such materials are readily available e.g. through Gelest inc. The rheological properties of PDMS can be tuned without having to deviate from stoichiometric cross-linking by tuning the molecular weight of the base material and the density of pendent functional groups of the crosslinker. In this WP, we will systematically test various combinations of base and crosslinking polymer to yield a wide range of substrate stiffnesses and relaxation timescales. We will also consider alternatives to PDMS based materials. One option are polyvinylsiloxanes which are frequently used as impression material in dental technology. Also, polyurethane rubbers could be considered. The surface chemical composition of the substrate material also plays an important role. We intend to artificially introduce glassy layers by plasma or ozone treatment of the surfaces, or chemical modifications, for instance through C-H insertion reactions. A reliable chemical surface modification requires low volatility materials to avoid reactions with the volatile components that could be removed by the interaction with the test liquids, destroying the functionalization.

We also intend to use and test in this WP the substrate materials that other groups in the SPP will synthesize. We intend to collaborate with the group of Rainer Jordan (TU Dresden), who will prepare polymer carpets. These essentially two-dimensional materials can be transferred to the surface of almost any bulk material. We also foresee a collaboration with the group of Leonid Ionov (U Bayreuth) who intends to work on shape changing polymers in the scope of this SPP.

We will select test liquids that do not significantly swell the substrate material. It is known that small amounts of water, for instance, diffuse through PDMS. But the total uptake remains small, and water will be an important test liquid. It has been shown in the soft wetting literature that fluorinated silicone oils also do not tend to swell PDMS gels [3]. This combination of immiscible liquids would serve as a starting point to search for other materials. Another promising category are glycol ethers that are partially miscible with water [39]. Glycol ethers are rather polar and swelling of PDMS is not expected. Various types with different properties (surface tensions, viscosities and miscibility gaps) will be tested. For WPs 2 and 3, the liquids will be used in their two-phase regime in mutual saturation. Phase separation experiments from WP4 will be performed close to the binodal [39]. Some glycol ethers possess lower critical solution temperatures with water that are within 10° C of room temperature, which will be useful for WP4. In addition to the liquid-liquid case we will test air as the outer phase to establish a connection to previous liquid-vapor soft wetting experiments.

All liquids and substrate materials will be tested for their macroscopic rheology and their surface tensions. We're aiming to start from cases where dissipation dominates in the substrate, and liquid dissipation will only become relevant during fast events like the slip-phases in stick-slip motion. We will also test explicitly the swelling of the various substrate materials by these test liquids.

(WP2) Solid & Liquid Profiles. — With the materials and the shadowgraphy setup from WP1 we will next investigate systematically the dynamical wetting ridge shapes for liquid-liquid menisci. We will tune the liquid-liquid surface tension by using various combinations of liquids. We aim to first work in a regime where the liquid-liquid surface tension is smaller than the gel-liquid surface tensions, which is required to access the regime that should be adequately described in the framework of linear viscoelasticity: the *local* angles of the wetting ridge are solely determined by the surface tensions, not the substrate elasticity [3]. The substrate elasticity is currently believed to only impact the global shape (amplitude) of the wetting ridge. We will measure the velocity dependent wetting ridge shapes along with the liquid meniscus shape (liquid angle) and compare our results to the available analytical models. We will also tune the substrate rheological properties, most importantly, its long-time storage modulus and its dissipation timescale. This will reveal whether the assumptions that underlie these models hold in the linear regime, which we expect to be the case. We also intend to collaborate on this

aspect with Sebastian Aland (HTW Dresden) who plans to model such three phase lines with a phase field approach that does not require any assumptions on a local Neumann balance.

We will continue with liquid combinations for which the liquid-liquid surface tension is larger and, in collaboration with Uwe Thiele (U Münster) and Jacco Snoeijer (U Twente), finally compare the results to liquid-vapor interfaces for largest surface tensions. This way we will tune the different interfacial tensions and monitor their impact on the wetting ridge shapes and the dynamics of the meniscus. The deviations from the case of smallest surface tensions and from existing models can then be used to amend models by the required nonlinear terms. Due to the successive increase of the nonlinear nature, a perturbation approach could be possible. Tuning surface tensions and substrate stiffness independently allows us to tune horizontal and vertical length scales independently, focusing the ‘nonlinear zone’ to the vicinity of the contact line.

These experiments also specifically point to the threshold and the properties of stick-slip motion and its comparison to the liquid-vapor case of soft wetting. Importantly, the large velocities in the ‘slip’-phase could lead to entrainment of the receding phase. The entrainment of a receding phase into the advancing phase is, in general, an important aspect of dynamical wetting problems. A receding meniscus suffers from a threshold velocity after which a so-called Landau-Levich film is created [40]. This effect depends on the viscosity ratio of the two phases. An elastocapillary version of such a problem has been investigated for Helfrich-type surface elasticity [41], but not yet for the case of liquid-liquid contact lines on bulk viscoelastic surfaces. Here we intend to use test liquids with different viscosity ratios and substrates with different rheological properties to systematically investigate the entrainment threshold.

As optional extension to this WP we consider studying the dependence of soft wetting dynamics on the geometry of the soft layer, notably its thickness. These experiments would be performed in a planar substrate configuration. Since dissipation and wetting dynamics are known to depend on the substrate thickness, one could also think about modulating the support topography, similar to [42]. This could lead to a synchronization of stick-slip cycles to the periodicity of the layer thickness, which could give additional insights to the depinning mechanism that remains debated in literature [6][P1].

These measurements could also be used as input parameters for the modeling work of the group of Sebastian Aland (HTW Dresden), with whom we intend to collaborate throughout the course of this project. We also plan a collaboration with Uwe Thiele (U Münster) and Jacco Snoeijer (U Twente), who could apply the theoretical part of their project also to the case of liquid-immersed soft wetting.

(WP3) Dynamic Strain Fields. — The shadowgraphy experiments will only reveal the vertical deformation and the overall shape of the wetting ridges. However, tangential displacements could equally well be important in soft wetting dynamics because they add to the elastic energy and to the dissipation in the solid. These contributions become relevant especially where the ridge slopes reach or overcome $\mathcal{O}(1)$. The most important consequence of surface tangential strains is their potential impact on the surface tension of the solid, the so-called Shuttleworth effect. Here we intend to resolve the strain fields explicitly, predominantly at the surface, but also to some extent in the bulk of the elastic material.

To measure the strain fields, we plan to embed particles at the surface of the gel (see Fig. 4) and analyze their displacements as a three-phase line moves along the surface. This type of measurement will be done (i) with a planar substrate geometry, observing the fluorescence signal of the particles with an inverted epifluorescence or confocal microscope through the rigid support of the soft layer, and, (ii) in the cavity geometry described above using a laser light sheet for fluorescence excitation [P5]. In the planar substrate geometry, small droplets of the ‘inner’ liquid will be placed with a syringe through the surface of a large droplet of the ‘outer’ liquid. Fluorescent dyes that specifically dissolve in only one of the liquids could in addition be used to image the shapes of the ‘inner’ droplet.

The image data are then analyzed by tracking individual particles, correlation-based methods similar to particle imaging velocimetry (PIV), or optical flow. The latter technique optimizes a continuous deformation field to represent the distortion of the particle image with respect to a reference image under a regularizing assumption which, especially useful in our case, can be the elastic energy associated with the deformation [43, 44]. Three-dimensional particle localizations can be obtained either by confocal microscopy, which is readily available and easy to handle, but relatively slow. High speed 3D localizations of up to several thousand frames per second can be achieved by another technique called astigmatic 3D tracking [36, 37]. In this technique, astigmatism is purposefully introduced to the observation light path of the microscope. The shape of the particle images then depend on the location of the particle relative to the two orthogonal focal planes (cf. Fig. 6). In the scope of the particle-based techniques, an exchange of know-how between our project and that of Kirsten Harth (U Magdeburg) is envisioned.

Certainly, the particles at the surface could have an influence on the wetting dynamics. Thus we will compare our particle-based measurements to the shadowgraphy experiments. Instead of embedding the particles at the gel surface, they could also be included in the bulk of the gel, or in distinct layers at specific distances to the free surface of the gel. This way, also the bulk strain field can be resolved, excluding an influence of surface-near beads on the soft wetting dynamics.

We will also test the impact of surface modifications on the soft wetting dynamics and the underlying strain fields, with their implications on the Shuttleworth effect. Besides plasma or ozone oxidized PDMS (see also WP1), we also intend to transfer polymer carpets provided by Rainer Jordan (TU Dresden) to PDMS surfaces. Another possibility would be the transfer of nanometrically thin PS films, as has recently been done to study the relaxation of these PS films on soft solids [45]. This way, different coefficients in the Shuttleworth relation Eq. 2 can be realized and, due to the explicit resolution of in-plane surface strains, probably also be calibrated. Together with the measurement of the soft wetting dynamics, this will provide invaluable data to develop a theoretical understanding and description. On the latter aspect, we intend to collaborate with Sebastian Aland (HTW Dresden) and compare our results to the liquid-vapor case studied jointly by Uwe Thiele (U Münster) and Jacco Snoeijer (U Twente).

The polymer carpets studied by Rainer Jordan (TU Dresden) can also respond to the local fluid composition. In this aspect we intend to host the PhD student from Rainer Jordan's group within the scope of a PhD student exchange. These experiments will be complementary to those suggested by Hans Riegler (MPIKG Potsdam).

(WP4) Phase Separation Dynamics. — In this work package, we plan to investigate the dynamics of liquid-liquid phase separation on soft solids. These experiments will be performed in the planar-substrate geometry in order to access the distribution of small droplets with high spatio-temporal resolution. We consider three methods of inducing phase separation: (i) By changing temperature, placing substrates on a transparent heat stage mounted on our microscope. This process will be limited by heat transfer and critical conditions should first be reached at the liquid-substrate contact. (ii) By changing the liquid composition, e.g. by selective evaporation or by flushing the sample liquid at controlled rates with a syringe pump. Due to an unavoidable boundary layer at the substrate, critical conditions will first be reached in the bulk liquid. Whether nucleation starts first in bulk, or at the soft surface, depends on the nucleation facilitating properties of the soft surface. (iii) By using a liquid combination where the substrate has significantly distinct permeabilities for the individual components. A pre-loaded substrate would then cause critical conditions initially at the surface.

All methods are limited by the diffusion of heat or molecules, either in the liquid or in the gel. For case (ii), enrichment gradients can in-situ be established by using sessile droplet evaporation [27, 29]. Another option are microfluidic channels in which compositions and their gradients can precisely be controlled. We do not primarily aim at quench-like situations in which the spinodal decomposition regime is accessed by rapid and strong changes of a parameter, which

will be difficult to realize on top of a soft polymeric layer. We rather intend to cross the binodal at a realizable and controlled rate in order to monitor the onset of nucleation and the successive coarsening in dependence of the substrate elasticity and geometry.

These processes will be observed by phase contrast microscopy, fluorescence microscopy (epi- or confocal) and potentially a quantitative schlieren approach [7]. By these methods, nuclei can typically be detected even if their size is much smaller than the optical resolution. A quantitative analysis may still yield an integral measure of the nucleus size but its spatial dimensions can, of course, not be determined independently. Highly sensitive in that context would also be a total internal reflection based approach, for which we would collaborate with Kirsten Harth (U Magdeburg). The selective solubility of dyes, which has successfully been used in [29], could be used to distinguish liquid phases in fluorescence microscopy. Characteristic for phase separation processes, however, is a certain sensitivity to the presence of trace impurities like dyes, so these experiments require careful cross-checks.

We also intend to repeat the particle based measurements to determine the response of the soft solid to the nuclei. However, it could well be possible that particles promote nucleation, which will be tested by comparison to measurements without particles, or by varying particle densities and measuring the corresponding nucleation densities and growth rates. But even without particles, nucleation processes are frequently governed by microscopic surface defects that can hardly be excluded in general. Working in cleanroom conditions available at the MPI-DS will provide conditions that are controlled to some extent. Repeated dissolution and nucleation experiments and a statistical analysis on nucleation sites will reveal details on the nucleation pathway. On the nucleation aspects we intend to collaborate closely with Sebastian Aland (HTW Dresden) to model such processes. Phase field models are very well suited because topology changes (like the formation of a new droplet) are implicitly accounted for.

Of special interest is also the coarsening process after the initial nucleation phase. In addition to well-known coarsening processes, soft surfaces mediate elastocapillary interactions between sessile droplets [P6] that could lead to new coarsening dynamics. We will track large ensembles of droplets over time to derive the evolution of their statistics. Importantly, the geometry of the soft substrate influences these interactions: while for thick layers, the interaction is always attractive, for thin layers, the interaction in the far field changes sign and becomes repulsive, which could lead to stable droplet patterns in which additionally the droplet sizes might play a role. In this context we foresee an intense collaboration with the joint project by Uwe Thiele (U Münster) and Jacco Snoeijer (U Twente) who plan to study experimentally and theoretically the condensation and coarsening of droplets in supersaturated vapor environments.

2.4 Data handling

Experimentally and numerically generated raw data will be stored locally and made available to other researchers upon request. Descriptions of the raw data including all methods used in their generation will be stored together with the data in the form of digitized lab journals. All data will be stored in long-term maintained formats like TIFF images or ANSI encoded text files on a redundant fileservers architecture available at the MPI-DS. Analyzed and compiled data will be published in peer-reviewed scientific journals, preferentially in open-access format, as is standard in the field. We intend, together with the central project of the SPP, to compile our methods and experimental procedures into tutorials, to enhance their accessibility for young researchers or researchers from other disciplines.

2.5 Other information

Role within the Priority Programme SPP2171. — The priority programme has been established to improve our fundamental knowledge on dynamical wetting of flexible, adaptive,

and switchable surfaces. Fundamental understanding of dynamical wetting of flexible surfaces is the central aspect of this project proposal. The planned work in the liquid immersed case could bridge the current gap between experimental and theoretical work, and shed new light on the controversially discussed Shuttleworth effect. We plan close collaborations with many other researchers that are applying for funding in the scope of this SPP. The fundamental aspects of dynamical wetting on flexible surfaces will be investigated mostly in collaboration with Sebastian Aland (HTW Dresden) and the joint project between Uwe Thiele (U Münster) and Jacco Snoeijer (U Twente). An extension to adaptive and/or switchable surfaces is planned in collaboration with Leonid Ionov (U Bayreuth) and Rainer Jordan (TU Dresden). We also intend to exchange technical know how with Kirsten Harth (U Magdeburg), and the other groups mentioned before. We envision several possibilities for fruitful PhD student exchanges with our collaboration partners, giving this project a central and well-embedded role within the priority programme.

2.6 Descriptions of proposed investigations involving experiments on humans, human materials or animals

No experiments with humans, human materials, or animals are planned.

2.7 Information on scientific and financial involvement of international co-operation partners

No international cooperation partners are required for the proposed research.

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4 Requested modules/funds

4.1 Basic Module

4.1.1 Funding for Staff 171.0k€

Position	Year basis k€ p.p.	Year 1 k€	Year 2 k€	Year 3 k€	Total k€
PhD student 75%	48.4	48.4	48.4	48.4	145.2
Student assistant	8.6	8.6	8.6	8.6	25.8
Total	57.0	57.0	57.0	57.0	171.0

The PhD student will be supervised by the PI in setting up the experiments, evaluating suitable material combinations, and on performing and analyzing the experiments described in WPs 2-4.

We are convinced that students should be involved in laboratory research early on in their career to gain invaluable hands-on experience. Therefore we apply for funding of a student assistant for the entire duration of the project. The student assistant supports the PhD student in conducting and analyzing experiments. This will be highly helpful for the PhD student in obtaining comprehensive datasets for different experimental parameters. It will also strengthen the profile of the PhD student due to the gained experience in supervision. The salary of the student assistant is based on 40 hrs per month and the cost estimate provided by the University of Göttingen to comply with local standards.

4.1.2 Direct Project Costs

4.1.2.1 Equipment up to 10,000, Software and Consumables 16.5k€

Running costs for consumables:

Position	Year 1 k€	Year 2 k€	Year 3 k€	Total k€
Solvents & test liquids ¹	2.0	1.0	1.0	4.0
Substrate materials ¹	2.0	1.0	1.0	4.0
Tracer particles ²	1.0	1.5	1.5	4.0
Cuvettes & glass substrates ³	1.0	1.0	1.0	3.0
Others lab consumables ⁴	0.5	0.5	0.5	1.5
Total	6.5	5.0	5.0	16.5

¹Typical solvents and test liquids are glycol ethers, fluorinated silicone oils, ethylene glycol or similar. High purity water is available through the resources of the host institution. Typical substrate materials are PDMS gels and PVS or PU rubbers. In the first year during WP1, a larger quantity of substances will be tested. During the remaining years, mostly consumption or replacements due to limited shelf life have to be considered.

²We intend to use bright and non-bleaching particles (FluoSpheres by Invitrogen). These tracer particles are required for high-speed tracking which requires high intensity fluorescence excitation. They amount to about 500€ per 5 – 10 ml of dispersion with 1% solid fraction. More particles will be required in the later stages of the project.

³The shadowgraphy and lightsheet experiments require high quality cuvettes with four plane and transparent side windows. For precise particle localizations in confocal microscopy, and reproducible astigmatic particle images, we will use type 1 precision coverslips.

⁴ Typical other lab consumables are materials required for liquid handling and gel preparation. Personal protective equipment (gloves etc.) is not included here and will be covered by the host institution.

4.1.2.2 Travel Expenses 14.4k€

- SPP-Events.....3.92k€
The PhD student and the PI should attend the meetings coordinated by the SPP. The PI is supposed to visit 2 internal meetings of 4 days and one 1 Conference of 5 days, for which we request 1.46k€ (60€ boarding costs per night, 20€ catering per day, 200€ travel per round trip, assuming same-day travel for national events). The PhD student will visit the same events, and, in addition, one advanced school (5 days) and one PhD workshop (4 days), so we request 2.46k€ for the SPP-related travel of the PhD student.
- Conferences.....3.27k€
In addition, the PhD student should attend one national conference per year (3x5 days), and one international conference (typically APS DFD in the US) toward the end of the project (4 days, 100€ boarding costs per night, 30€ catering per day, 1000€ travel costs, one additional travel day, total 1.65k€).
- Short-time visits to cooperation partners.....7.20k€
In addition to the coordinated events in the SPP, we plan one to two short (2 day) visits per year to our collaboration partners for both PI and PhD student. (12 visits, 2 persons, 1 night per trip).
- Long-term PhD student exchange.....0k€
The expenses for this exchange will be covered by the central funds of the SPP.

4.1.2.3 Visiting Researchers — none

4.1.2.4 Expenses for Laboratory Animals — none

4.1.2.5 Other Costs — none

4.1.2.6 Project-related Publication expenses 2.25k€

Open access publication will be aimed for wherever possible. Typical open access publication in high quality journals amounts to 2k€ (PNAS) to 5k€ (Nature Communications). Therefore we request the maximum possible supporting funds of 0.75k€ per year.

4.1.3 Instrumentation

4.1.3.1 Equipment exceeding Euro 10,000 — none

4.1.3.2 Major Instrumentation exceeding Euro 50,000 — none

5 Project requirements

5.1 Employment status information

Karpitschka, Stefan: currently employed as research group leader at the Max Planck Institute for Dynamics and Self-Organization, Department Dynamics of Complex Fluids, funded by department resources and the Max Planck - University of Twente Center “Complex Fluid Dynamics – Fluid Dynamics of Complexity”. Fixed term contract until April 30, 2022.

5.2 First-time proposal data

Not applicable.

5.3 Composition of the project group

Besides the applicant (Karpitschka, Stefan) and the requested PhD student, a postdoc, Michiel van Limbeek, has agreed on joining the group of Stefan Karpitschka at the MPI-DS for soft wetting related research. Michiel van Limbeek will be supported by funds of the Department of complex fluids at the MPI-DS (led by Stephan Herminghaus) and perform part of the experiments listed in WPs 2&3.

5.4 Cooperation with other researchers

5.4.1 Researchers with whom I have agreed to cooperate on this project

- Sebastian Aland (HTW Dresden) — is applying for a project in the SPP to develop numerical methods to describe soft wetting phenomena (phase field and finite elements approaches). We have agreed to collaborate on many aspects of the research proposed here. The methods proposed by Sebastian Aland are outstanding because of the way in which multi-physics problems are monolithically represented and solved. This yields convergent methods for problems that are typically prone to stability issues. The combination of our experimental results and his simulations will give unprecedented insights to the physics of soft wetting phenomena.
- Kirsten Harth (U Magdeburg) — With Kirsten Harth we intend to share know-how and expertise on particle-based measurements on strain fields in soft solids. The total internal reflection based technique that Kirsten Harth intends to implement in the scope of this SPP could also be useful for our phase separation experiments.
- Leonid Ionov (U Bayreuth) — is applying for an SPP project on shape changing polymers in soft wetting problems. These materials could also be interesting in the scope of liquid-liquid-soft solid wetting experiments. We will share our expertise on soft wetting dynamics and profit from the material sciences know how in the group of Leonid Ionov.
- Rainer Jordan (TU Dresden) — intends to study the wetting properties of polymer carpets in the scope of this SPP. These quasi-two-dimensional polymer networks respond by buckling or creasing transitions to changes in their environment, like temperature, pH, or solvent composition. This could be interesting for many aspects of the research proposed here, i.e. for substrates that respond to phase transitions in the liquid on top of them, but also to investigate surface layers with distinct mechanical properties as compared to a bulk phase.
- Hans Riegler (MPIKG Potsdam) — intends to study polymer carpets prepared by Rainer Jordan in terms of their responsiveness to global (laterally homogeneous) enrichment by using the well-controlled enrichment evolution during spin cast processes. This approach is

complementary to our soft wetting experiments where enrichment is laterally highly inhomogeneous, and we plan to share our results on both aspects.

- Uwe Thiele (U Münster) & Jacco Snoeijer (U Twente) — will study soft wetting dynamics, condensation of vapor droplets, and coarsening dynamics in the scope of this SPP. We foresee a strong collaboration on several aspects of our work, including the different nonlinearities that we intend to study (WPs 2&3), as well as for the phase separation experiments (WP4). The liquid-vapor case of Thiele & Snoeijer will be much more influenced by nonlinearities than the liquid-liquid case we intend to study. The combination of our work could prove very helpful in determining the underlying principles. Similar holds for the coarsening dynamics of droplet ensembles on soft surfaces; length scales of interactions could be tunable independently by controlling the outer phase in the liquid-immersed situation, but the magnitude of the interaction will most likely be larger in a gaseous environment.

We intend to apply for two ‘outgoing’ long-term PhD student exchanges, as are encouraged by the coordination board: (i) During the first or second year with an experimental group, potentially with Leonid Ionov (to work on shape changing polymers), or Rainer Jordan (to work on polymer carpets) (ii) During the second or third year with the group of Sebastian Aland, in order to achieve a coherent experiment/theory comparison. We also offer to host students from other groups that seek know-how on dynamical soft wetting. Such incoming exchanges have been envisioned with all our collaborators and will be planned according to the dynamical needs of each of our projects. The expenses for these exchanges will be covered by the central funds of the SPP.

5.4.2 Researchers with whom I have collaborated scientifically within the past three years

Bruno Andreotti (ESPCI Paris), Lorenzo Botto (Queen Mary U London), Hans-Jürgen Butt (MPIP Mainz), Jens Eggers (U Bristol), Christian Kähler (U BW München), Detlef Lohse (U Twente), Alvaro Marin (U Twente), Manu Prakash (Stanford U), Hans Riegler (MPIKG Potsdam), Jacco Snoeijer (U Twente), Miguel A. Rodriguez Valverde (U Granada), Leen van Wijngaarden (U Twente), Herman Wijshoff (Océ technologies and TU Eindhoven).

5.5 Scientific equipment

The following scientific equipment relevant for this proposal is available at the MPI-DS:

- Motorized inverted research microscope Nikon Ti2-E (double layer epifluorescence, PIV laser coupling, brightfield, Plan APO & water immersion objectives)
- Motorized inverted research microscope Nikon Ti2-E (epifluorescence, brightfield, phase contrast, polarization, PerfectFocus system, Plan APO & water immersion objectives)
- Olympus FV1000 inverted confocal research microscope with dual scanner
- Manual upright research Microscope Leica (brightfield, darkfield, epifluorescence)
- Double Cavity PIV Laser (532nm, 100 Hz repetition rate per cavity, 50mJ per Pulse)
- 2 High speed cameras PhantomVision VEO4k 990 (938fps @ 4096x2304)
- High speed camera PhantomVision VEO 410 (5200fps @ 1280x800)
- Various long working distance microscopes and macro lenses
- Various CMOS and CCD cameras
- 2 Lumencor Sola SE Light Engines
- Anton Paar MCR502 Rheometer (Peltier plate & hood, RheoOptics microscopy access, UV curing unit, PP and CP geometries)

- DataPhysics optical contact angle goniometer
- Various syringe pumps
- Fully equipped cleanroom for photo-lithography
- NanoScribe 3D printer Photonic Professional GT

5.6 Project-relevant cooperation with commercial enterprises — none

5.7 Project-relevant participation in commercial enterprises — none

6 Additional information

The research proposed here does not overlap with other projects that have been applied for or granted. Currently, third party funding is received from the “Max Planck – University of Twente Center for Complex Fluid Dynamics – Fluid Dynamics of Complexity”, in which evaporation-related wetting phenomena of multi-component liquids on (structured) rigid surfaces are investigated. The applicant has also applied for funding from the DFG within the scope of CRC937. The biofilm-related research within that project has, besides fundamental aspects of viscoelastic material properties, no overlap with the research proposed here.