Coated Landau–Levich | CoMPhy Lab
Department of Physics, Durham University
comphy-lab.org

Pulling a Film from a Patchy Bath: Langmuir–Blodgett Meets Landau–Levich

When a flat plate is withdrawn vertically from a quiescent bath, a thin liquid film is dragged out along with it. On a homogeneously wetting plate the thickness follows the Landau–Levich scaling $h \sim \ell_c \,\mathrm{Ca}^{2/3}$, where $\mathrm{Ca} = \eta U/\gamma$ compares viscous drag to capillary smoothing at the dynamic meniscus and $\ell_c = \sqrt{\gamma/(\rho g)}$ is the capillary length (**landauLevich1942**; **quere1999fluid**; **rioBoulogne2017**). On a *partially* wetting plate the story sharpens: below a critical capillary number $\mathrm{Ca}^\star$ set by dynamic wetting failure the contact line cannot keep up, and the plate emerges dry (**bonnWettingSpreading2009**). That threshold is the throughput bottleneck of Langmuir–Blodgett deposition, the route by which lipid multilayers and membrane-protein arrays are built molecule by molecule on a substrate passing through a compressed monolayer. Pre-coat the plate with a patterned soft layer — vesicle patches, protein prints, lithographic wettability stripes — and the contact line pins on patches of characteristic size ℓ_p. Pinning injects a new length scale into the meniscus problem. A second dimensionless group $\Lambda = \ell_p/(\ell_c \,\mathrm{Ca}^{1/3})$, comparing patch size to the dynamic-meniscus length, then decides whether the meniscus averages over many patches or resolves them one at a time. This MPhys or Master's-year project offers three parallel routes into the same question, and you pick the one that fits your strengths: analytical scaling, Basilisk C simulation of the withdrawn film with spatial wettability, or the companion Langmuir–Blodgett experiment in Prof. Bromley's laboratory (Durham Physics). The three routes answer the same question from different sides; a student takes only one.

TL;DR

Three parallel routes to the same question, of which a student picks one: (i) derive the scaling theory of a coated Landau–Levich withdrawal, or (ii) build a Basilisk C simulation of the same geometry with spatially varying wettability (with Dr Vatsal Sanjay, CoMPhy Lab), or (iii) run the companion Langmuir–Blodgett experiment on a patterned glass slide with designed proteins and lipid vesicles in a compressed amphiphile monolayer (with Prof. Beth Bromley, Durham Physics). One question runs through all three: how does a pre-existing patchy coating of size ℓ_p and areal fraction ϕ reshape the critical capillary number for film entrainment (**bonnWettingSpreading2009**)? The shared target is the (Ca, Λ) regime diagram with $\Lambda = \ell_p/(\ell_c \,\mathrm{Ca}^{1/3})$; theory, simulation, and experiment each anchor it from their own side.

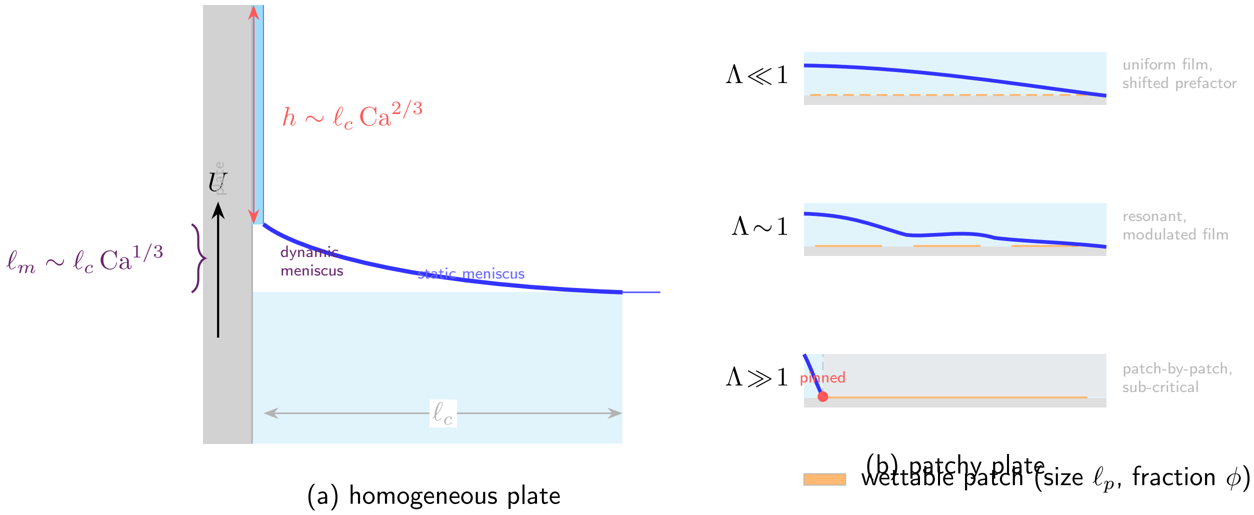
Description

The classical derivation sits on a two-region matched asymptotic balance (**landauLevich1942**; **quere1999fluid**; **rioBoulogne2017**). Far from the plate the meniscus is static, curved on the capillary length ℓ_c. Close to the plate, a dynamic meniscus of length $\ell_m \sim \ell_c \,\mathrm{Ca}^{1/3}$ matches the static meniscus to the flat entrained film. Balancing viscous drag $\eta U/h^2$ against capillary smoothing $\gamma \partial_x^3 h$ in the dynamic meniscus fixes the thickness, $h \sim \ell_c \,\mathrm{Ca}^{2/3}$. On a completely wetting plate the contact line carries no additional stress and the derivation is closed. On a partially wetting plate the static contact angle θ_e sets an upper bound on how fast the three-phase line can advance before dynamic wetting failure forces transition to a Landau–Levich film, yielding a critical $\mathrm{Ca}^\star$ that depends sharply on θ_e (**eggers2004**; **snoeijerWetting2006**; **snoeijer2008**; **bonnWettingSpreading2009**). It is this partial-wetting threshold, not the pure Landau–Levich law, that caps the pull-out speed of Langmuir–Blodgett deposition.

In Prof. Bromley's laboratory, a Langmuir trough holds a compressed amphiphile monolayer at the water surface, through which a substrate is withdrawn; proteins and lipid vesicles in the subphase adsorb onto the plate. The compression is held at a target surface pressure during deposition, and the transfer ratio fixes the deposited mass per dip. Four patterning routes give complementary handles on patch geometry: vesicle splatting leaves membrane patches of $\mathcal{O}(50\text{–}100)$ nm; protein prints via dip-pen nanolithography leave engineered patches of $\mathcal{O}(10^2\text{–}10^3)$ nm; micro-contact printing of mixed self-assembled monolayers (**wilbur1994**; **mrksich1995**) gives wettability-contrasted patches at $\mathcal{O}(1\text{–}10)$ µm; and photolithographic wettability contrast (**darhuber2000**) gives stripes up to $\mathcal{O}(10\text{–}10^2)$ µm. For Langmuir–Blodgett-relevant capillary numbers ($\mathrm{Ca} \sim 10^{-7}\text{–}10^{-4}$, so $\ell_m = \ell_c\,\mathrm{Ca}^{1/3}$ spans $\mathcal{O}(10\text{–}10^2)$ µm), vesicle and dip-pen patches sit deep in the homogenised $\Lambda \ll 1$ regime; micro-contact-printed SAMs approach the $\Lambda \sim 1$ shoulder; photolithographic stripes push into $\Lambda \gtrsim 1$. The four routes together place ℓ_p across three decades and straddle the crossover in Λ.

The patchy plate introduces four substrate-side dimensionless controls beyond Ca: the patch areal fraction ϕ; the geometric ratio $\Lambda = \ell_p/\ell_m = \ell_p/(\ell_c\,\mathrm{Ca}^{1/3})$; the equilibrium contact-angle contrast $\Delta\theta = \theta_e^{\mathrm{wet}} - \theta_e^{\mathrm{dry}}$ between wettable and less-wettable patches; and the substrate hysteresis $\Delta\theta_{\mathrm{hyst}} = \theta_A - \theta_R$ between advancing and receding limits on a single patch. Where the patterning is anisotropic (stripes rather than spots), a fifth geometric control enters, $\chi = \ell_\parallel/\ell_\perp$, comparing patch lengths parallel and perpendicular to the pull-out direction. Two asymptotic limits follow. For $\Lambda \ll 1$ the dynamic meniscus integrates over many patches; the substrate acts homogenised with an effective contact angle $\theta_{\mathrm{eff}}(\phi, \Delta\theta)$ set by Cassie averaging, and the Landau–Levich prefactor shifts but the functional form is preserved (**bonnWettingSpreading2009**). For $\Lambda \gtrsim 1$ the meniscus resolves individual patches and the contact line advances patch-by-patch; the defensible prediction is *selective* deposition, with liquid preferentially transferred onto wettable regions rather than entrained as a uniform film (**darhuber2000**; **maleki2007**). Whether a *sub-critical* entrainment window (entrainment at $\mathrm{Ca} < \mathrm{Ca}^\star$) opens on the patchy substrate, and which of ϕ, $\Delta\theta$, $\Delta\theta_{\mathrm{hyst}}$, χ governs any such threshold shift, is an open question this project is designed to settle.

Two further controls enter from the liquid side and the coating itself. If the pre-existing coating is an elastic film of thickness t on a rigid substrate (a hydrated protein layer, a soft polymer stripe), substrate deformation at the contact line adds the thin-layer elastocapillary length $\ell_{ec} = \sqrt{t\gamma/E^*}$, with E^* the reduced modulus of the layer (**bertin2022**); the ratio ℓ_{ec}/ℓ_p decides whether capillary forces deform individual patches. On the liquid side, the compressed amphiphile monolayer carries a surface elasticity $E_s = -A\,\partial\Pi/\partial A$, giving a Marangoni number $M_s = E_s/\gamma$ that modulates the dynamic meniscus independent of substrate physics; at typical deposition pressures ($\Pi \sim 30$ mN/m for DPPC), M_s reaches $\mathcal{O}(1)$ and must be carried explicitly in any scaling derivation. Mapping the full $(\mathrm{Ca}, \Lambda, \phi, \Delta\theta, \Delta\theta_{\mathrm{hyst}}, \chi, \ell_{ec}/\ell_p, M_s)$ response surface is out of reach for a single Master's-year project; locating the $\Lambda \sim 1$ crossover at fixed $(\phi, \Delta\theta)$ along one patterning route is the scientific target.



(a) homogeneous plate

(b) patchy plate

Figure 1: Clean-plate Landau–Levich vs the coated-plate hook. (a) Homogeneous plate: the dynamic meniscus of length $\ell_m \sim \ell_c \, \mathrm{Ca}^{1/3}$ matches the static meniscus to a flat film of thickness $h \sim \ell_c \, \mathrm{Ca}^{2/3}$; on partially wetting substrates, $\mathrm{Ca} < \mathrm{Ca}^\star$ leaves the plate dry. (b) Patchy plate: the contact line pins on patches of size ℓ_p and areal fraction ϕ. The dimensionless group $\Lambda = \ell_p/\ell_m$ decides whether the dynamic meniscus averages over many patches ($\Lambda \ll 1$), resolves individual patches ($\Lambda \sim 1$), or advances fully patch-by-patch ($\Lambda \gg 1$).

The project offers three parallel routes onto that response surface, and a student picks one. The analytical route fixes the two asymptotic limits of the patchy Landau–Levich scaling, the dependence of the effective threshold on ϕ and the patch contact-angle contrast $\Delta\theta$, and the location of the $\Lambda \sim 1$ crossover. The computational route builds a two-dimensional Cartesian Basilisk C simulation of the withdrawn film for transverse-stripe patterning, with spatial wettability imposed through the `contact.h` infrastructure (**popinet2015quadtree**; **basiliskVatsal**; **basiliskVatsalDropFilm**); because `contact.h` sets only the geometric contact angle, the effective dynamic contact-angle response is calibrated against a partial-wetting benchmark in the spirit of **afkhami2009**; **afkhami2018** before any sweep, and the imposed $\theta_e(x)$ is smoothed over the three-to-five finest cells at patch edges to avoid mesh-locked spurious pinning. (Ca, Λ) is then swept at fixed $(\phi, \Delta\theta)$ to resolve the regime diagram; a disjoining-pressure closure for an elastic pre-coat (**bertin2022**) is a natural extension, not required for the Master's deliverable. The experimental route runs the companion Langmuir–Blodgett sweep in Prof. Bromley's laboratory: compressed monolayer at fixed surface pressure, patterned substrate (vesicle splatting, dip-pen nanolithography of proteins, micro-contact-printed mixed self-assembled monolayers (**wilbur1994**; **mrksich1995**), or photolithographic wettability contrast (**darhuber2000**)), and entrained-film thickness measured against pull-out speed across patch densities. Each route answers the same question from its own side.

The deliverable is a predictive rule. Given a target entrained-film thickness at a given pull-out speed, the regime diagram says which patch size, areal fraction, and contact-angle contrast deliver it — and, where $\Lambda \gtrsim 1$, which patch geometry drives *selective* deposition onto wettable regions rather than uniform entrainment. That rule matters because the Langmuir–Blodgett throughput bottleneck is the rate-limiting step for scaled manufacture of lipid-multilayer biosensors, membrane-protein arrays, and the functionalised surfaces of soft-electronic and soft-biomedical stacks. All simulation code, analysis scripts, and experimental data are released under the CoMPhy Lab open-source workflow on GitHub.

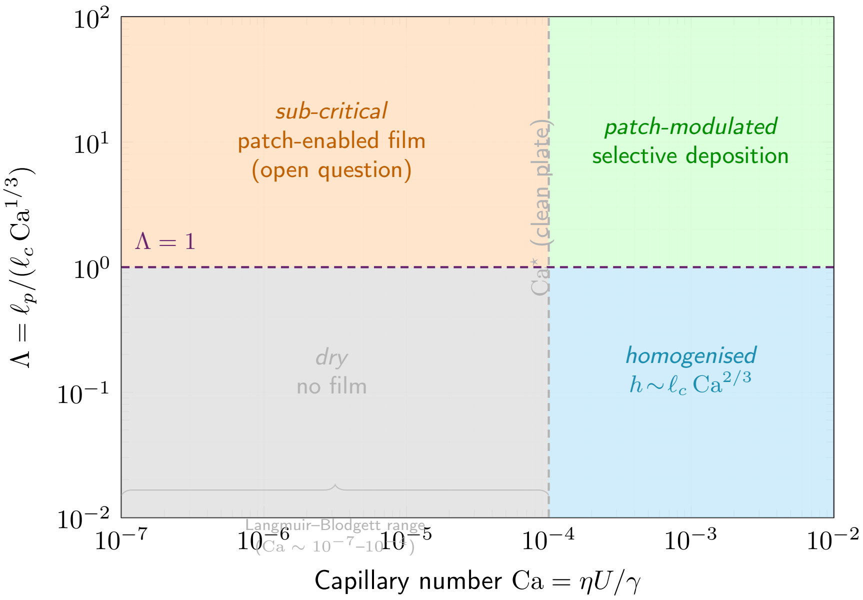


Figure 2: Target regime diagram on the (Ca, Λ) plane, with the clean-plate Landau–Levich threshold $\mathrm{Ca}^\star$ as the $\Lambda \to 0$ reference. Three regimes: homogenised ($\Lambda \ll 1$), resonant ($\Lambda \sim 1$), and isolated-patch entrainment ($\Lambda \gg 1$). Markers from Langmuir–Blodgett experiment (Bromley lab) and Basilisk C axisymmetric simulation (CoMPhy Lab).

What you will do and what you will learn?

The project has a shared foundation, three parallel routes (pick the one that fits your strengths), and a shared closure:

1. **Foundation.** Re-derive the classical Landau–Levich scaling $h \sim \ell_c\,\mathrm{Ca}^{2/3}$ from the matched-asymptotic balance at the dynamic meniscus (**landauLevich1942**; **quere1999fluid**), and derive the partial-wetting critical capillary number $\mathrm{Ca}^\star(\theta_e)$ set by dynamic wetting failure (**bonnWettingSpreading**
2. **Analytical route.** Extend the derivation to a patchy substrate in two asymptotic limits: the homogenised limit $\Lambda = \ell_p/\ell_m \ll 1$ with a Cassie-averaged effective contact angle, and the patch-resolved limit $\Lambda \gtrsim 1$ with contact-line pinning patch-by-patch; locate the crossover analytically and fix the dependence on patch areal fraction ϕ and contact-angle contrast $\Delta\theta$.
3. **Computational route.** Build a two-dimensional Cartesian Basilisk C simulation of the withdrawn film under transverse-stripe wettability via `contact.h` (**popinet2015quadtree**; **basiliskVatsal**; **basiliskVatsalDropFilm**), calibrated against a partial-wetting benchmark in the spirit of **afkhami2009**; **afkhami2018** with $\theta_e(x)$ smoothed over the three-to-five finest cells at patch edges; sweep (Ca, Λ) at fixed $(\phi, \Delta\theta)$ to resolve the regime diagram. A disjoining-pressure closure for an elastic pre-coat (**bertin2022**) is a natural extension, not required for the Master's deliverable.
4. **Experimental route.** Run the companion Langmuir–Blodgett experiment in Prof. Bromley's laboratory: compressed amphiphile monolayer on a Langmuir trough held at fixed surface pressure, patterned substrate (vesicle splatting, dip-pen nanolithography of proteins, micro-contact-printed mixed self-assembled monolayers (**wilbur1994**; **mrksich1995**), or photolithographic wettability contrast (**darhuber2000**)), and entrained-film thickness measured against pull-out speed across patch densities.
5. **Closure.** Place your route's contribution on the (Ca, Λ) regime diagram, identify whether the $(\phi, \Lambda, \Delta\theta)$ window admits sub-critical entrainment or selective deposition onto wettable

patches, and release all code, analysis scripts, and data under the CoMPhy Lab open-source workflow.

Industrial and scientific context

Langmuir–Blodgett deposition is the workhorse technique for assembling sub-monolayer to multilayer films one molecule thick at a time (**bonnWettingSpreading2009**); its canonical target in the Bromley laboratory is the functional supported membrane — lipid bilayers and engineered membrane-protein arrays on glass or silicon. Throughput is capped by the partial-wetting critical capillary number $\mathrm{Ca}^\star$: too fast, and the contact line breaks down into dynamic wetting failure; too slow, and the per-dip rate collapses below what is useful for scaled manufacture. The clean-plate scaling is well understood (**landauLevich1942**; **quere1999fluid**; **rioBoulogne2017**), but the substrate in a Langmuir–Blodgett transfer is *never* clean: it carries the pre-existing patch structure deposited on the previous dip, and for biologically functional surfaces that structure is both heterogeneous and soft. No predictive continuum description covers the pre-coated regime, and no systematic experimental map of entrained-film thickness against patch geometry has been placed alongside one. Closing that gap — analytically, numerically, and experimentally — gives a design rule for sub-critical entrainment: given the patch areal fraction and contact-angle contrast produced by a chosen biological or lithographic patterning route, predict the pull-out speed that delivers a target multilayer thickness. The project sits squarely in the soft-matter / condensed-matter-physics interface: dynamic wetting of heterogeneous substrates (**bonnWettingSpreading2009**), elastocapillary deformation of thin soft pre-coats (**bertin2022**), and open-source multiphase CFD (**popinet2015quadtree**; **basiliskVatsal**). For a Durham MPhys or Master's student, the project offers three complementary outputs, any one of which is a full Master's-year deliverable: the matched-asymptotic theory of the patchy threshold, the Basilisk C simulation framework for heterogeneous-wettability dip-coating, or the first Langmuir–Blodgett dataset on heterogeneous substrates. Each anchors the (Ca, Λ) regime diagram from its own side.

If you have any questions, feel free to contact us vatsal.sanjay@comphy-lab.org/ vatsal.sanjay@durham.ac.uk or drop by Ph255 (Rochester building) at the Department of Physics at Durham University.

Collaborators	E-mail	Based at
Dr. Vatsal Sanjay	vatsal.sanjay@comphy-lab.org vatsal.sanjay@durham.ac.uk	Ph255 (Rochester building)
Prof. Beth Bromley	beth.bromley@durham.ac.uk	Dept. of Physics, Durham

Last updated: April 23, 2026