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Trapping of drops by wetting defects

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Controlling the motion of drops on solid surfaces is crucial in many natural phenomena and technological processes including the collection and removal of rain drops, cleaning technology and heat exchangers. Topographic and chemical heterogeneities on solid surfaces give rise to pinning forces that can capture and steer drops in desired directions. Here we determine general physical conditions required for capturing sliding drops on an inclined plane that is equipped with electrically tunable wetting defects. By mapping the drop dynamics on the one-dimensional motion of a point mass, we demonstrate that the trapping process is controlled by two dimensionless parameters, the trapping strength measured in units of the driving force and the ratio between a viscous and an inertial time scale. Complementary experiments involving superhydrophobic surfaces with wetting defects demonstrate the general applicability of the concept. Moreover, we show that electrically tunable defects can be used to guide sliding drops along actively switchable tracks—with potential applications in microfluidics.
Drops moving along solid surfaces are ubiquitous. We encounter them on rainy days on the windows of our houses, cars, trains and airplanes and in many technological applications including cleaning and coating technology and two-phase flow microfluidics. Wetting defects such as topographic patterns and chemical patches of variable wettability can trap drops, prevent their removal or allow for steering them in certain directions with important consequences for the efficiency of drop condensation from vapour in heat exchangers and fog harvesters. Animals and plants in arid environments make use of specific wettability patterns to collect humidity more efficiently. Conversely, insects and plants in humid environments frequently make use of anisotropic wetting structures to steer impinging rain drops off their surface. While the critical conditions governing the detachment of pinned drops from wetting defects have been addressed in considerable detail, the physical parameters controlling the inverse process, namely the capture and guidance of mobile drops by wetting defects, is largely unexplored. From a purely static perspective, one would expect that both processes are governed by the same local force balance at the contact line that has been studied extensively following the seminal work by de Gennes and coworkers on the wetting of heterogeneous surfaces in the 1980s. For moving drops, however, dynamic effects can lead to richer dynamics than those dictated by the static energy landscape due to surface heterogeneity. The most generic question that arises is whether or not a certain wetting defect is strong enough to capture a passing drop. As we will show in this work, the answer to this question involves not only the pinning forces exerted by the defect but also the balance between inertia and viscous dissipation of the drop. For aqueous drops of millimetric size and common wetting defects, all three forces turn out to be of the same order of magnitude. This results in a rather sharp transition between the extreme cases of overdamped dynamics for more viscous liquids and very weakly damped situations, such as Leidenfrost drops, that lose little energy upon passing a single defect.

In this work, we determine the critical conditions for drop trapping over a wide range of driving forces, defect strengths and drop properties (size, viscosity). To vary the driving force, we change the slope angle of an inclined plane. To vary the defect strength, we make use of recently introduced electrically tunable wetting defects based on electrowetting, as well as topographic and chemical defects on superhydrophobic surfaces. The former approach enables a continuous variation of the energy landscape experienced by the drop upon tuning the externally applied voltage while leaving the chemical and topographical homogeneity of the surface intact.

Results
Inclined plane setup. We consider a millimetre-sized drop sliding down an inclined plane. Unless stated otherwise, the substrate surface consists of a thin oil-impregnated polymer film with a Young contact angle \( \theta_y \) of \( \sim 90^\circ \) and a very small contact angle hysteresis \( \Delta \theta < 3^\circ \) resulting in a very small roll-off angle just below \( \theta_y \approx 3^\circ \). Inclination angles of \( \alpha = 3...15^\circ \) give rise to steady sliding speeds \( v_0 \) ranging from a few mm s\(^{-1}\) to several cm s\(^{-1}\). This corresponds to capillary numbers of \( Ca = \mu v_0 \gamma \approx 10^{-4}...10^{-3} \), where \( \mu \) is the viscosity and \( \gamma \) the surface tension. As viscous forces are small compared to capillary forces, the drops retain their essentially half-spherical shape during sliding. On the lower part of the surface, there is a horizontal wetting defect oriented perpendicular to the trajectory of the drop, as indicated by the dashed lines in Fig. 1a. In practice, the defect consists of two electrodes submerged below the polymer film that are separated by a small gap (see Methods for details).

Interaction between drops and electrical traps. Figure 1 shows a series of snapshots of two drops sliding down the inclined plane for two different voltages. Above the defect, both drops assume a constant steady sliding velocity \( v_0 \) that is determined by the balance of the (effective) gravitational driving force and frictional (viscous) dissipation. Upon reaching the defect, the drop gets trapped if the voltage \( U_0 \) applied between the two electrodes exceeds a critical threshold value \( U_c \) that corresponds to a critical strength of the defect. For lower voltages—that is, for weaker defects, it passes (see Fig. 1 and Supplementary movie 1).

Similarly in the case of conventional chemical or topographic surface patterns, the drop 'feels' the presence of the defect only when it overlaps with it. The (free) electrical energy of the system as a function of the drop position is \( E_0(x) = -cAU^2\phi(x)/2 \), where \( c \) is the capacitance per unit area between the drop and the electrode(s) on the substrate, \( A \) is the area of the drop–substrate interface and \( \phi(x) \) is a symmetric function varying smoothly between 0 for \( x > R \) and 0.25 at \( x = 0 \) (see Methods section and Manne et al.21).

Including gravity, we obtain the net energy landscape experienced by the drop

\[
E(x) = -mg \sin \alpha \cdot x - \frac{1}{2} cAU^2\phi(x).
\]

This energy landscape can be gradually tuned from a monotonically decreasing slope at zero voltage to a function with a well-defined local minimum at higher voltage, as illustrated in Fig. 1c.
When the sliding drop reaches the wetting defect, it first accelerates because it is pulled into the potential well (see Fig. 2). As expected, higher voltages lead to faster acceleration. Furthermore, the absolute velocities at the same inclination angle are higher for water drops than for more viscous water–glycerol mixtures. After passing the centre of the trap, the drops slow down again. For low voltages, they escape the trap again at a final velocity close to the initial one and continue to slide downhill. Beyond the threshold voltage, however, the drops get trapped. In the case of water–glycerol drops, the speed of trapped drops gradually decreases from its maximum value to zero as the drops come to rest. In contrast, water drops oscillate a few times around their final equilibrium position before they eventually come to rest.

Critical trapping conditions. To determine the critical conditions for the trapping of drops, we repeated our experiments for various inclination angles and drop sizes with drops of both pure water and water–glycerol mixtures. For each condition, we determined the critical voltage \( U_c \) required for trapping. As expected, \( U_c \) is found to increase both with increasing inclination angle \( \alpha \) and with increasing drop size. For the same drop size and inclination angle, we also find that water drops consistently require higher voltages—that is, stronger defects to become trapped than water–glycerol drops, despite the fact that the energy landscape is the same in both cases (up to a minor difference in density of <10%). Figure 3a, b shows a representation of all results as a function of the initial sliding velocity \( v_0 \) and the trap strength measured in units of the applied voltage \( U \) for water and for water–glycerol drops. Blue symbols denoting drops that pass the trap are grouped at high initial velocities and low voltages. The red symbols denoting drops that get trapped are grouped at low initial velocities and high voltages. Plotting the data as a function of \( v_0 \) provides a more consistent representation than using the (sine of) \( \alpha \). At first glance, this may seem surprising since one would expect that the balance of the gravitational driving force \( F_g = mg \sin \alpha \) and a viscous dissipation force \( F_d = 2R \nu v_0 \) (\( R \): base radius of the drop; \( \nu \): viscous friction coefficient) leads to \( v_0 \propto \sin \alpha \). However, calibration measurements indicate a substantial influence of the small but finite pinning forces \( F_p \) due to the intrinsic roughness and contact angle hysteresis (see Methods section). These forces oppose sliding and lead to a reduced effective gravitational force \( F_{g, e} = mg \sin \alpha - F_p \) (ref. 11). Irregularities due to random variations of \( F_p \) are automatically taken into account when representing the data as a function of the measured values of \( v_0 \) rather than \( \sin \alpha \). Next to a characterization of \( F_p \), the calibration measurements also yield quantitative values for the dissipation coefficients \( \lambda_w = (4.5 \pm 0.6) \text{ kg s}^{-1} \) and \( \lambda_{wg} = (1.2 \pm 1.3) \text{ kg s}^{-1} \) for water and water–glycerol mixtures, respectively. In agreement with earlier findings22, these values suggest that the dissipation is governed by contact line friction rather than bulk dissipation. For the present situation of a lubricated drop on a surface with finite hysteresis, the contact line friction results from a combination of steady viscous dissipation23 and microscopic unsteady motion related to contact angle hysteresis22,24 (see Methods section).

To trap a drop, the potential well created by the defect needs to be sufficiently deep to generate a local minimum in the energy landscape rather than just a small depression (cf. Fig. 1c). In other words, the maximum of the trapping force \( F_t \) must be at least as strong as \( F_p \). In Fig. 3c, where the data of Fig. 3a,b are replotted as full and open small symbols, respectively, this means that all drops falling below the line \( F_t / F_p = 1 \) (grey thick line in Fig. 3c) should become trapped and all drops above the line should pass. While this criterion is fulfilled (up to minor experimental uncertainties) for the water–glycerol drops, it dramatically overestimates the trapping capability of the same defect for pure water drops.

To understand the origin of this discrepancy, we describe the sliding drop as a point mass moving in the potential landscape generated by gravity and the wetting defect. Neglecting the internal degrees of freedom related to shape deformation of the drop may lead to inaccuracies regarding the details of the transient motion as the drop is being captured, yet, as we will see, the approach nevertheless captures the essence of the transition between weakly and highly viscous liquids.

To simplify our analysis, we approximate the electrostatic energy given in equation (1) by a generic harmonic potential \( E_{el}(x) \propto k(x) \chi^2/2 \) (truncated at \( |x| = R \)) with a voltage-dependent stiffness \( k(U) = 4 \varepsilon U^2 / \pi \) (ref. 21). The maximum trapping force is then \( F_t = kR \propto U^2 R \). For \( |x| \gg R \), the drop does not feel the presence of the defect and hence the trapping force vanishes. With this approximation, Newton’s equation of motion for the centre of mass of the drop reads \( m \ddot{x} + \lambda \dot{x} + k x = F_{g, e} \) for \( |x| \ll R \). \( m \) is the mass of the drop. This problem contains two characteristic
time scales. First, the elasto-inertial time $T_0 = 2\pi/\omega_0$ that is related to the eigen frequency $\omega_0 = \sqrt{k/m}$ of the drop in the trap. The viscous relaxation time $\tau = 2m/\lambda$. (At first glance, one might suspect that there should be a third time scale given by the passage time $t_0 = 2R/\nu_0$ of an undisturbed drop past the defect. However, the specific initial conditions of a steadily sliding drop links $\nu_0$ to $\tau$. Hence, $t_0$ is not independent.) Using $\tau$ as the unit of time and $R$ as the characteristic length, we can rewrite Newton’s equation of motion in nondimensional form as

$$\ddot{\xi} + 2\xi + 4Q^2\xi = 4Q^2\tilde{F}_g.$$  

(2)

Here $Q = \omega_0\tau/2 = \pi\tau/T_0$ is the quality factor of our effective harmonic oscillator, and $\tilde{F}_g = F_g/F_0$ is the normalized effective driving force. (Obviously, this quantity can also be regarded as an inverse normalized trapping strength $1/\tilde{F}_g$.) The ratio between trapping strength and driving force and the ratio between the viscous and the elasto-inertial time scale are thus the two dimensionless quantities that govern the trapping of sliding drops by wetting defects. Hence, $Q$ is the second natural parameter next to $\tilde{F}_g$ that we can use to represent all trapping measurements in a single graph (Fig. 3c).

The relevant criteria and different regimes of drop trapping are easily extracted from equation 2. First of all, for the drop to become trapped, there must be a stationary solution with vanishing drop speed and acceleration. The result is $\xi_\infty = \tilde{F}_g$. Since $\xi$ is constrained to values less than unity, $\tilde{F}_g < 1$ immediately emerges as a necessary criterion for drops to become trapped, as expected. Indeed, all trapped drops in Fig. 3c fulfill this condition. Secondly, there are two different dynamic regimes, overdamped motion for $Q < 1$ and underdamped motion for $Q > 1$. In our experiments, the water/glycerol and the water drops represent these two different regimes: $T_0$ ranges from about 0.1 s to 0.5 s for both types of drops, depending on the defect strength. From the values of $\lambda$, we find $\tau_{\text{eq}} \approx 0.1 s \ll T_0$ and $\tau_{\text{eq}} \approx 0.2 s = O(T_0)$ for water–glycerol and water drops, respectively.

In the overdamped regime, visco-inertial relaxation takes place on much shorter times than the motion of the drop across the defect. Hence, inertia is irrelevant and the drop always moves with its momentary steady sliding velocity corresponding to the local slope of the energy landscape. As soon as the drop reaches the local energy minimum of the defect, it stops. This is illustrated by the calculated drop trajectories and the energy diagrams in the bottom panels of Fig. 2b,c. Note also that the total energy curve closely follows the potential energy, implying that the kinetic energy remains small at all times.

In the case of weak damping, on the other hand, $\tau$ becomes larger than $T_0$. As a consequence, the drop dissipates little energy during a single passage of the defect: the kinetic energy becomes substantial. Even in the presence of a well-defined energy, minimum the drop can escape the defect with the help of inertia if the trap is too shallow. Only if the trap is deep enough, the

Figure 3 | Trapping diagram at wetting defect. Red and blue symbols and coloured regions indicate trapped and passing drops, respectively. (a,b) Electrical trapping for drops of variable size (diamond: 20 µl; circle: 40 µl; square: 60 µl) as a function of initial velocity $v_0$ and applied voltage $U$. (a) Pure water; (b) water–glycerol mixture. (c) Trapping diagram as a function of normalized driving force $F_g/F_0$ and quality factor $Q$ of the trap (cf. equation 2). Green-shaded region: no potential minimum; yellow: potential minimum but escape by inertial overshoot; red: trapping. Horizontal grey line: quasistatic trapping limit in the absence of inertia. Solid black line: trapping limit in the presence of inertia. Small symbols: same data as in (a,b). Large symbols: superhydrophobic surfaces with mechanical defect. Data for electrical trapping are corrected for contact angle hysteresis reduction due to electrowetting33. See also Supplementary movie 3.
Whenever electrical defects, very viscous drops with droplets of various water–glycerol mixing ratios. Similarly, for the released. The large symbols in Fig. 3c show the results for a series critical inclination angle at which an already pinned drop is force of these defects is determined experimentally from the resulting in a combined topographic and chemical defect due to were scratched with a sharp needle under controlled load, geometry. The electrical defect is located between trapping (red) and passing (blue) reflects the force balance for sessile water–glycerol drops of variable size (square: 20 μl; cross: 80 μl) driven by an air jet with volumetric flow rate \( J \). Transition between trapping (red) and passing (blue) reflects the force balance driving air drag and electrical trapping forces. Inset: experimental viscous dissipation becomes strong enough to prevent drop escape. In this case, the drop oscillates a few times before coming to rest, as shown in the top panels of Fig. 2. The trapping criterion for \( Q > 1 \) is given by the requirement that the drop actually stops and reverses direction before leaving the trap—that is, that \( \bar{\zeta} = 0 \) is reached while \( \bar{\zeta} = \bar{x}/\bar{R} < 1 \). Solving the corresponding analytical expressions numerically, we obtain the solid black line in Fig. 3c as a critical trapping condition. For \( Q \ll 1 \), this criterion approaches \( F_t \sim 1 \), as required. For \( Q > 1 \), the critical value of \( F_t \) decreases and increasingly deeper defects are required to trap the drops, in agreement with our experimental observations.

**Discussion**

The analysis presented above is rather generic. For any small wetting defect, the lateral extent of the drop–defect interaction is determined by the width of the drop. For a hydrophilic stripe of width \( w \ll R \), for instance, the depth of the potential well is given by \( \Delta E = \gamma 2w \Delta \cos \theta_y \), where \( \Delta \cos \theta_y \) describes the difference in wettability between the wetting defect and the homogeneous part of the surface. Knowing both depth and width of the wetting defect, we can approximate the trapping potential by a generic harmonic potential \( E_{\text{trap}}(x) \propto k x^2/2 \), where \( k \approx 4 \gamma w \Delta \cos \theta_y / R \) for a chemical stripe defect. Like in the case of electrical defects, details of the potential shape should not affect the generic scenario as long as contact angle hysteresis and sliding speeds are not too high, such that macroscopic drop deformations during sliding are prevented. Many novel functional surfaces such as superhydrophobic, superoleophobic and oil-impregnated nanotextured\(^{25-27} \) surfaces fulfill these criteria. To test the general applicability of our approach, we fabricated nanotextured polymeric superhydrophobic surfaces with \( \theta_1 = 160^\circ \)and \( \Delta \theta \approx 3^\circ \). These surfaces were scratched with a sharp needle under controlled load, resulting in a combined topographic and chemical defect due to local removal of the hydrophobic polymer layer. The trapping force of these defects is determined experimentally from the critical inclination angle at which an already pinned drop is released. The large symbols in Fig. 3c show the results for a series of drops of various water–glycerol mixing ratios. Similarly for the electrical defects, very viscous drops with \( Q \ll 1 \) get trapped whenever \( F_g \sim F_t / F_I < 1 \). Less viscous drops can also escape for smaller values of \( F_g \). The transition between trapping and non-trapping follows the critical condition predicted by our model (see Fig. 3c).

The same concept can also be applied to other driving forces than gravity such as viscous drag by ambient flows of air or of a second immiscible fluid. Figure 4 shows an example of an air jet impinging on a solid surface, as used, for example, in cleaning applications to remove drops from surfaces. Under these conditions, the drag force scales with the square of the volumetric air flux \( J^2 \). Consequently, the critical pinning condition of glycerol–water drops on a surface with an electrical defect follows the expected scaling \( F_t \propto F_g \propto U^2 \) (Fig. 4). Experiments in oil–water two-phase flow microfluidic devices fall into the purely viscous regime due to the damping caused by the ambient oil and display an excellent agreement between the critical trapping and the viscous drag forces\(^{29} \).

Finally, we want to point out that the trapping principle described above can also be applied to steer drops along certain directions on the surface. Figure 5 illustrates the principle for linear electrical defects oriented at an inclination angle of 45° with respect to the sliding direction. While previous attempts using surfaces with inclined stripes of a different chemical nature\(^{30} \) and roughness and contact angle hysteresis\(^{31} \) displayed a
Methods

Sample preparation. The substrates for the experiments with electrical defects consist of glass plates covered by a 30-nm-thin transparent electrode of indium tin oxide. HCl is used to etch a gap of 0.5 mm width into the indium tin oxide layer to form two electrodes isostatic at 40 μm, respectively. Defects and guides are readily designed and allow for steering electrically addressable defects used here, arbitrary geometries of the substrate are captured by the defect, the drop moves along the defect under the influence of the electric trap resulting in a contact angle for trapped drops of (78 ± 5°).

Electrical trapping. When the conductive water drop reaches the gap, it forms two capacitors \( C(x) \) and \( C_0(x) \) with the two electrodes on the substrate. Both capacitors depend on the geometric overlap \( A(x) \) of the drop with electrode i: \( C(x) = \varepsilon_0 \varepsilon_i d A(x) \) (i = 1,2) where \( \varepsilon_i = d/\varepsilon \) is the capacitance per unit area between the drop and the electrodes. Neglecting the finite width of the gap between the electrodes, the resulting net capacitance of the system (see effective circuit model in Fig. 1b) is \( C(x) = C_0(x) / C_0(x) + C(x) = C_0(x) \phi(x) \), where \( \phi(x) = 1/4 \pi \sin(\pi x/R) + x/R \sqrt{1 - (x/R)^2} \) / \( 2^n \). Note that the electrically isolated drop chooses its potential between the potential of the two electrodes according to its position. For \( x = 0 \), the voltage between the drop at the electrodes is U/2.

Calibration of dissipation coefficient. To determine the damping coefficient of the sliding drops on the homogeneous surface, we measured the steady sliding velocity \( v_0 \) away from the trap as a function of inclination angle. Figure 6 shows the expected linear relation with sliding \( v_0 \) and \( \sin(\alpha) \). Owing to the finite residual hysteresis, the curves intercept the abscissa at a finite value \( v_0 \). The balance between gravity, viscous friction and pinning is

\[
mg \sin \alpha = 2R \lambda v_0 + F_p
\]

we can determine both \( \lambda \) and \( F_p \) from the these calibration measurements. The pinning forces are related to contact angle hysteresis by \( F_p = 2R(\cos\alpha - \cos\alpha^\circ) \), where \( \theta_1 \) and \( \theta_2 \) are the receding and the advancing contact angle, respectively. From this expression, we find \( \sin \theta_1 = 2R(\cos\alpha - \cos\alpha^\circ)/mg \), leading to a critical sliding angle \( \theta_1 = 0 \)…

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Author contributions
D.M., A.P., S.G., R.L. and S.O. carried out the inclined plane experiments. D.M., C.B. and J.Z. designed and executed the air jet experiments. D.M. and D. vdE. analysed the experimental data. F.M. designed the research. D.M. and F.M. wrote the manuscript.

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