In-situ characterization of low-viscosity direct ink writing

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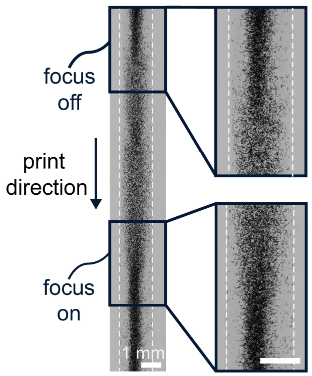
Acoustic focusing enables control of composite microstructures.

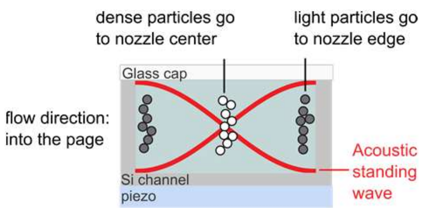
Varying strength, stiffness, conductivity, and other properties along the print path can expand the complexity of 3D printed parts.

We can print two-phase materials with properties that vary along the print line using **direct ink writing** with **acoustic focusing.**

Direct ink writing (DIW): Layer-by-layer printing of fluid inks which are solidified after deposition

Acoustic focusing: Aligning and moving particles in microfluidic channels using acoustic waves



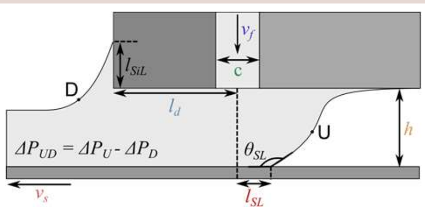


Viscous drag hinders focusing, requiring low-viscosity inks.

At low viscosities, **capillarity** and **viscous dissipation** both influence print bead stability.

Lubrication theory predicts print bead morphology.

Using a viscocapillary model developed for slot die coating, we can
- **Monitor** stability using meniscus geometry
- **Predict** stability using printing parameters



Laplace pressure differential | Pressure differential due to viscous dissipation | Viscosity

$$\Delta P_{UD,L} = \Delta P_{UD,V} = -\frac{6\mu v_s}{h^2} l_{SL} - \frac{6\mu l_d v_s}{h^2} + \frac{12\mu l_d v_f c}{h^3}$$

R. R. Collino, T. R. Ray, R. C. Fleming, J. D. Cornell, B. G. Compton, M. R. Begley, *Extreme Mechanics Letters* **2016**, DOI 10.1016/j.eml.2016.04.003.
L. Friedrich, M. Begley, *J. Colloid Interface Sci.* **2018**, DOI 10.1016/j.jcis.2018.05.110

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We can monitor stability and wetting *in-situ* using digital image analysis.

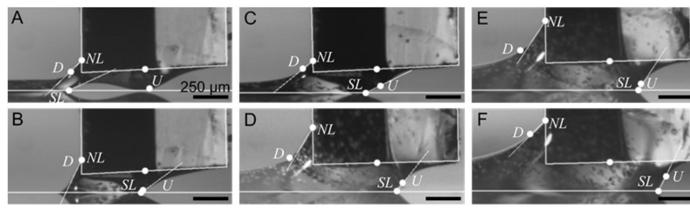
By capturing videos of the print bead *in-situ*, we can monitor
- filament-substrate (SL) contact line position and angle
- nozzle-substrate (NL) contact line position and angle
- upstream and downstream meniscus curvatures, used to calculate P_L

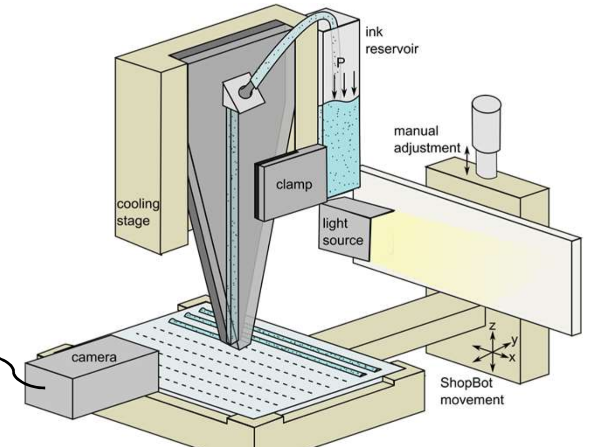
Print bead behaviors fall under three regimes.

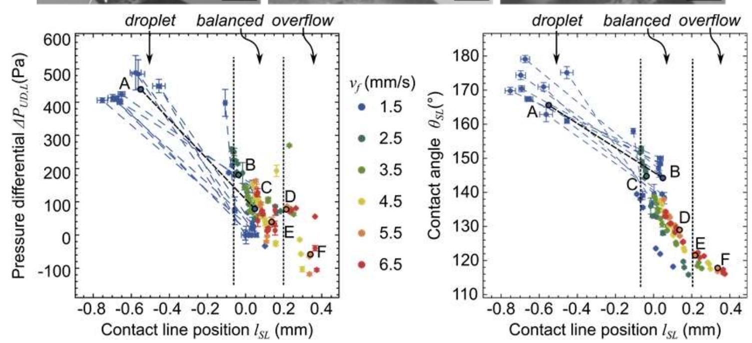
Droplet: the contact line position and angle oscillate, and the filament ruptures

Balanced: the contact line stays near the nozzle exit

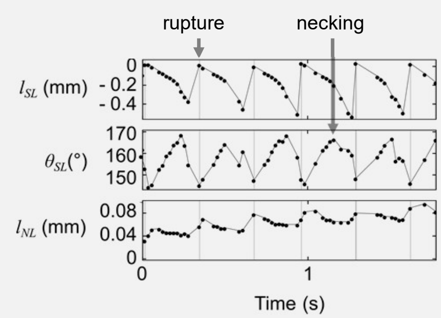
Overflow: the contact line moves far upstream of the nozzle exit







The viscocapillary model predicts that the pressure differential should decrease as the contact line moves upstream, which we observe by measuring both metrics at varying stage speeds and flow speeds. For a faster and more reliable *in-situ* metric, the contact angle can serve as a proxy for pressure differential. The relative rates of change of the contact angle and contact line position indicate the print bead stability.



In the droplet regime, the nozzle-liquid contact line climbs the nozzle every time the filament ruptures and a new contact line forms. Thus, to limit nozzle wetting, it is important to prevent rupture.

We can predict stability from printing parameters.

The viscocapillary model can be used to select combinations of stage speed, flow speed, and stand-off distance which produce balanced filaments. However, the two-dimensional model anticipates that ink will drip out of the front edge of the nozzle (l_{SL} = 0.5) before it actually does.