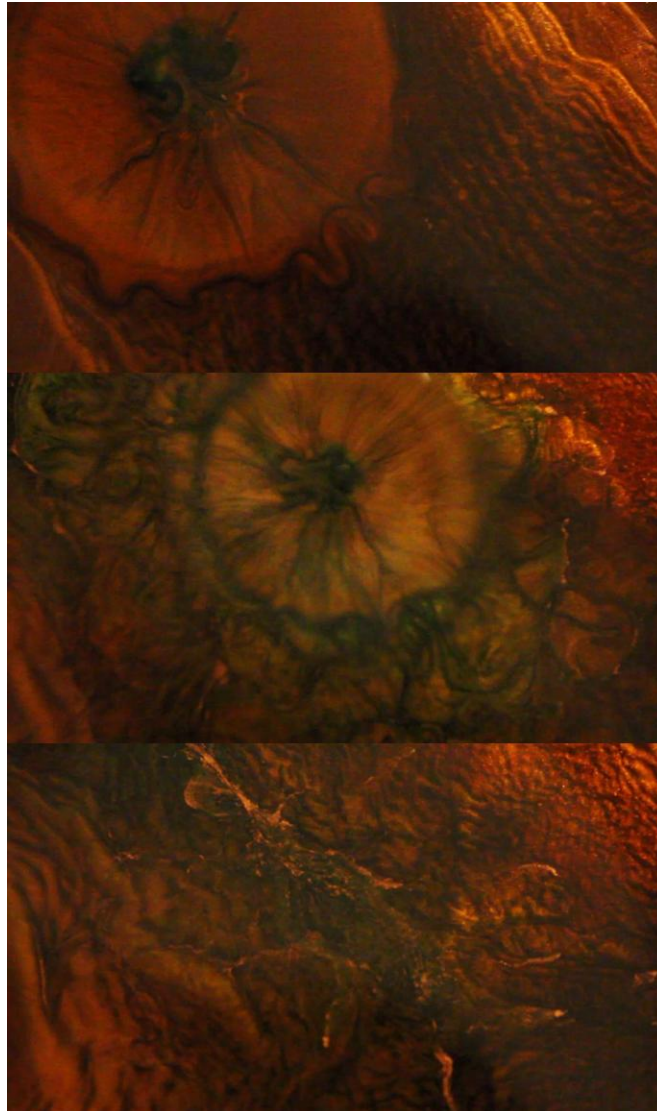




Team First

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MCEN 5151 Flow Visualization 002

1 Context and Purpose

This 14 s video was shot for the Team First assignment in MCEN 5151 Flow Visualization at the University of Colorado Boulder. Its intent was to drop alcohol based ink into glycerin and watch the two fluids diffuse into each other, on the expectation that glycerin's high viscosity would slow the mixing enough to see the diffusion pattern instead of the near-instant mixing that happens in water. Visually, the goal was a slow bloom of color across the glycerin, filmed from directly above and close enough that the pattern fills the frame. The video ended up showing something different and more interesting: each drop

is torn open across the surface by a surface tension imbalance, and the dye simply rides along as a marker, while diffusion turns out to be far too slow to see at all. My teammate (Connor Arnold) and I worked remotely; we traded ideas and bounced questions off one another throughout the project, but each of us built and filmed our own setup, and he did not physically assist with this shot, nor did I with his.

2 Experimental Setup

Figure 1 is a high level sketch of the setup. A ceramic mug with a 3 in (76 mm) inside diameter, raised on a stack of books, held a 0.5 in (12.7 mm) deep layer of NOW Solutions vegetable glycerin (16 fl oz bottle), which the manufacturer lists as pure, colorless glycerin [1]. A Canon EOS Rebel T100 on a tripod pointed straight down at the surface with the front of its lens 5 in (127 mm) above the glycerin. The ink was SigWong Lime Green alcohol ink, from the brand's alcohol ink set sold for epoxy resin art, used undiluted from its 0.35 fl oz (10 mL) dropper bottle. The bottle was squeezed with its tip held beside the lens, so each drop fell about 5 in (127 mm). The mug had already received drops of other colors in earlier takes (primarily Rose Gold Metallic with hints of Peacock Blue), so the surface was not fresh; a rippled skin of residue from those takes is visible in the background of every frame. Filming took place at about 7:00 PM indoors at sea level in Los Angeles, in 72 °F (22.2 °C) air. Figure 2 captures the three stages of flow that the video displays. All times t refer to the final video, which opens with a 2.7 s title card.

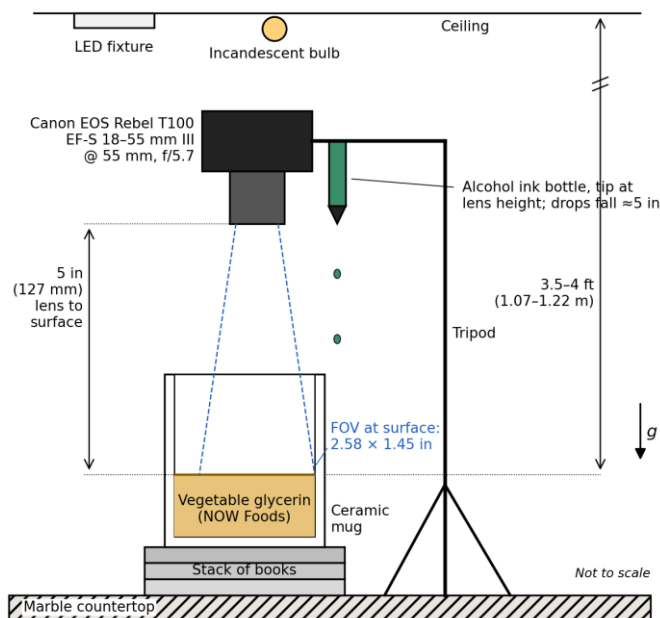


Figure 1. Side view of the setup (not to scale).

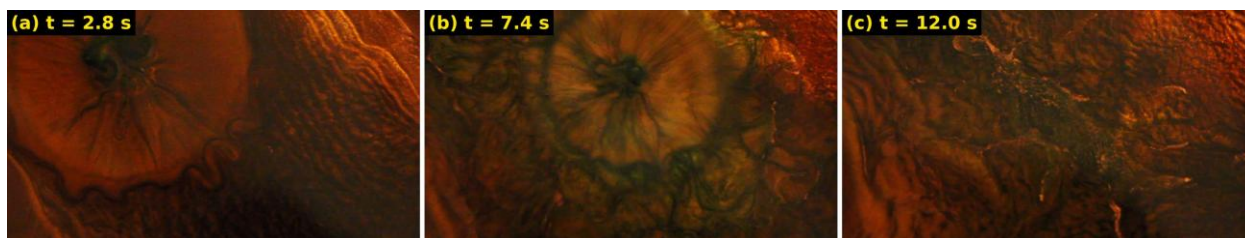


Figure 2. Frames from the video: (a) the first drop's alcohol film spread out ahead of the dye, with a fingered rim, (b) a fresh burst landing on the cellular web left by earlier drops, and (c) the frozen, lacy veins after the drops stop.

Stage 1, first drop (t = 2.7 to 2.9 s). The first drop strikes the surface about 0.05 s before the footage begins, after falling the 5 in from the bottle tip at a speed of

$$v_i = \sqrt{2gh_d} = \sqrt{2(9.81 \text{ m/s}^2)(0.127 \text{ m})} = 1.6 \text{ m/s (5.2 ft/s)} \quad (1)$$

taken from the potential and kinetic energy relationship, with air drag neglected over so short a fall. In Fig. 2a a clear, smooth disk of alcohol has spread outward ahead of the dye, which lags behind at the center as a dark cluster with radial streaks, and the edge of the disk has broken into scalloped fingers, just as reported for alcohol films spreading on deep water layers [2]. The force behind this is a surface tension imbalance. A liquid spreads over another when the spreading coefficient $S = \sigma_g - \sigma_a - \sigma_{ga}$ is positive [3]. Here σ_g and σ_a are the surface tensions of glycerin and alcohol, corrected from 20 °C to 22.2 °C with the linear temperature coefficients tabulated in [4],

$$\sigma_g = 64.00 - 0.0598(22.2 - 20) = 63.9 \frac{\text{mN}}{\text{m}}, \sigma_a = 23.00 - 0.0789(22.2 - 20) = 22.8 \frac{\text{mN}}{\text{m}} \quad (2)$$

and the interfacial tension σ_{ga} is taken as zero because the two liquids are miscible, so

$$S \approx \sigma_g - \sigma_a = 63.9 - 22.8 \approx 41 \frac{\text{mN}}{\text{m}} \quad (3)$$

The ink's carrier was assumed to be isopropanol, the usual solvent in alcohol inks; if it were ethanol (22.1 mN/m at 20 °C [4]), S would change by only $\approx 2\%$. Additionally, because S is positive, the surrounding glycerin pulls the surface away from the drop, from low tension toward high, and viscosity drags the liquid beneath along with it. Glycerin's viscosity and density at $T = 22.2$ °C follow from Cheng's correlations for pure glycerol [5],

$$\mu = 12100 \exp \left[\frac{(-1233 + T)T}{9900 + 70T} \right] \text{ cP} \approx 1155 \text{ cP} \approx 1.16 \text{ Pa} \cdot \text{s} \quad (4)$$

$$\rho = 1277 - 0.654T \approx 1262 \text{ kg/m}^3 \quad (5)$$

The radius of the disk's continuous edge was read frame by frame from the original clip, which also holds the frame hidden under the title card, using the image scale derived in Section 4. Readings were taken along the downward direction, where the rim is sharpest. They show two distinct phases. In the first frame after contact, at most one frame interval (0.033 s) later, the edge is already at $r_1 \approx 15$ mm. This phase is driven mainly by the drop's momentum and is not resolved in time. After it, the edge decelerates sharply: in the next 3 frames it sits roughly at r_2 through $r_4 \approx 15.5, 16.5$, and 17 mm. Over those intervals, it advances at

$$\bar{u}_f = \frac{r_4 - r_1}{3\Delta t} = \frac{(17 - 15) \text{ mm}}{3(0.033 \text{ s})} \approx 20 \frac{\text{mm}}{\text{s}} \quad (6)$$

and using the mean radius over the measured interval, $\bar{r} = 16$ mm as the length scale, the Reynolds number [6] is

$$\text{Re} = \frac{\rho \bar{u}_f \bar{r}}{\mu} = \frac{(1262 \text{ kg/m}^3)(0.02 \text{ m/s})(0.016 \text{ m})}{1.16 \text{ Pa} \cdot \text{s}} \approx 0.35 \quad (7)$$

so viscous forces dominate inertia, and the flow is laminar. At this Reynolds number, the inertia is negligible, so after the impact phase, the film's motion is set by a balance between the surface tension pull and the viscous drag of the glycerin beneath it, not by the drop's momentum. This is contributing to why the fingers and streaks stay smooth.

Stage 2, repeated bursts (t = 3 to 8 s). A second drop lands at $t = 3$ s, before the first has finished spreading, and from then on new bursts appear every 4 to 6 frames (0.13 to 0.20 s), roughly 30 to 40 drops in all. Each burst repeats Stage 1 on a surface already loaded with alcohol, so neighboring fronts

collide and fold the earlier dye into a web of cells (Fig. 2b). As the alcohol evaporates it cools the surface and leaves its concentration uneven, and both effects make the surface tension vary from place to place.

Stage 3, relaxation ($t = 8$ to 14 s). After the last drop lands, no new bursts appear and the dye pattern stops changing visibly. The likely explanation is that the remaining alcohol evaporates and mixes into the glycerin, removing the surface tension difference that drives the flow. Stage 3 also settles the original question about diffusion. The Stokes Einstein equation [7] gives the diffusivity of a sphere of radius a in a liquid of viscosity μ ,

$$D = \frac{k_B T_K}{6\pi\mu a} = \frac{(1.381 \times 10^{-23} \text{ J/K})(295.4 \text{ K})}{6\pi(1.16 \text{ Pa}\cdot\text{s})(5 \times 10^{-10} \text{ m})} \approx 3.7 \times 10^{-13} \text{ m}^2/\text{s} \quad (8)$$

where $T_K = 22.2 + 273.15 = 295.4 \text{ K}$ is the room temperature in kelvin and μ is from Eq. (4). The dye's molecular radius is not known, so $a = 0.5 \text{ nm}$ is an assumption, typical of small dye molecules. The root-mean-square distance a diffusing molecule moves in one direction in a time t is $\sqrt{2Dt}$ [8], so over the full 14.4 s video the dye moves only

$$\ell_D = \sqrt{2Dt} = \sqrt{2(3.7 \times 10^{-13} \text{ m}^2/\text{s})(14.4 \text{ s})} \approx 3.3 \mu\text{m} \quad (9)$$

which is about 10% of one $34 \mu\text{m}$ pixel (Section 4). Rearranging Eq. (9), diffusing $L = 1 \text{ mm}$ would take $t = L^2/(2D) \approx 1.4 \times 10^6 \text{ s}$, about 16 days. The Péclet number $Pe = UL/D$ compares transport by the flow with transport by diffusion [9]; with $U = \bar{u}_f$ from Eq. (6) and $L = \bar{r} = 16 \text{ mm}$,

$$Pe = \frac{UL}{D} = \frac{(0.02 \text{ m/s})(0.016 \text{ m})}{3.7 \times 10^{-13} \text{ m}^2/\text{s}} \approx 9 \times 10^8 \quad (10)$$

so the surface flow outruns diffusion by about nine orders of magnitude. The premise of the original plan therefore had a flaw: Eq. (8) shows $D \propto 1/\mu$, so the high viscosity chosen to slow the mixing also slows diffusion in direct proportion, and what the video records is the surface tension flow of Stages 1 and 2, not diffusion.

3 Visualization Technique

No seed particles or additional tracers were added; the ink was both the driving fluid and the marker. Its dye shows where the alcohol has carried it, while the leading alcohol film, which carries little dye, appears to be visible mainly because it changes the slope and smoothness of the surface and therefore how the lights reflect from it. This is why the expanding disk in Fig. 2a looks brighter and smoother than the rippled glycerin around it. The only illumination came from two ceiling sources 3.5 to 4 ft (1.07 to 1.22 m) above the glycerin: an LED fixture, estimated at 10 to 15 W, and an incandescent bulb, estimated at 60 W. Since the camera sat directly below the lights, its body casts the dark diagonal shadow across the frame, and the bright orange patch at the upper right is the specular reflection of the incandescent bulb, which flickers as the surface moves. The warm tungsten light under automatic white balance renders the colorless glycerin amber.

4 Photographic Technique

The camera was a Canon EOS Rebel T100 on a tripod, pointed straight down and recording 1920×1080 px video at 29.97 fps; the original clip is 15.75 s long (472 frames). The lens was a Canon EF-S 18 - 55 mm f/3.5 - 5.6 III set to 55 mm and focused manually, with the aperture wide open at f/5.7 (as recorded in the file metadata) and its front 5 in (127 mm) above the glycerin. The camera recorded a focus distance of 0.25 m, which is this lens's closest focusing distance, where its rated maximum magnification is $m = 0.34$ [10]. Assuming the 16:9 video frame spans the full 22.3 mm width of the sensor [11], the field of view at the surface is

$$W = \frac{w_s}{m} = \frac{22.3 \text{ mm}}{0.34} \approx 65.6 \text{ mm} \quad (11)$$

or 2.6 in across. The image scale is therefore $1920 \text{ px} / 65.6 \text{ mm} \approx 29.3 \text{ px/mm}$, so each pixel spans about 0.034 mm ($34 \text{ }\mu\text{m}$). The camera ran in automatic movie exposure with Auto ISO and automatic white balance; the T100 does not record shutter speed or ISO in its movie files, so neither can be reported. The exposure of each frame can be no longer than the interval between frames,

$$\Delta t = \frac{1}{29.97 \text{ fps}} \approx 0.0334 \text{ s} \quad (12)$$

and in that time the Stage 1 edge, moving at $\bar{u}_f$ from Eq. (6), travels

$$\Delta x = \bar{u}_f \Delta t = (20 \text{ mm/s})(0.0334 \text{ s}) \approx 0.67 \text{ mm} \quad (13)$$

or about 20 px, so the spreading after the first frame is resolved in time, while the impact phase, which covers about 15 mm within one frame, is not. Post-processing was done in iMovie. The clip was trimmed to 11.68 s (2.10 to 13.77 s of the original) at unchanged speed, and a 2.74 s title card was added at the start. The frame was cropped to a $1524 \times 857 \text{ px}$ region of the original, which removes the mug wall in one corner, and scaled back to $1920 \times 1080 \text{ px}$. Contrast was increased in the color-correction panel, with saturation and color temperature left at their defaults. Figure 3 compares one frame before and after editing. The final video is $1920 \times 1080 \text{ px}$ at 29.97 fps, played back at the capture rate, and 14.41 s long.

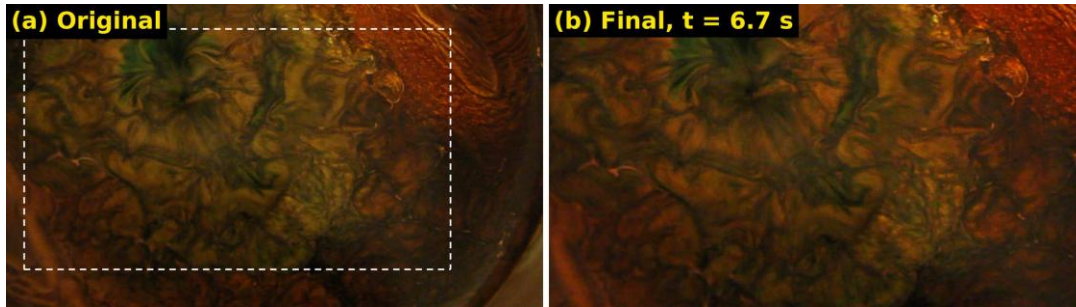


Figure 3. The same instant (a) in the original frame, with the dashed box marking the region kept by the crop, and (b) in the final video after cropping and color correction.

5 Video Dissection

The video captures three regimes: a drop thrown open by its impact and then spread more slowly by surface tension, a train of bursts that folds the dye into cells, and a relaxation in which the pattern stops changing. The scientific intent shifted from diffusion to surface tension flow, and the video shows why: at this scale diffusion moves the dye less than one pixel over the whole clip (Eq. 9), so the motion that is visible is the surface tension flow. Visually, the strongest moments are the scalloped rim of the first burst and the starbursts landing on the cellular web, and the close, top-down framing fills the frame with texture. The main weaknesses are photographic: the dim scene left the footage noisy, the camera's own shadow and the glare from the bulb sit in the frame, and the warm light shifts every color toward orange. The drop train was also uncontrolled, so bursts landed on top of one another. It is also unclear how much residue from earlier takes slowed the spreading compared with a fresh glycerin surface. Repeating the first drop on a fresh surface, with a drop of known volume, would greatly help.

The analysis rests on the following assumptions. (1) The ink's carrier is isopropanol; if it were ethanol, S would change by about 2% (Section 2). (2) The glycerin is pure and at the $72 \text{ }^\circ\text{F}$ room temperature. Glycerin absorbs water from the air, which would lower μ and raise Re . (3) The ink and glycerin have zero interfacial tension and the surface starts clean, so S is an upper bound on the actual driving force. (4) The image scale uses the lens's rated maximum magnification, which applies because the recorded focus distance equals the lens's closest focusing distance, and the 16:9 frame is taken to span the full sensor width. (5) Edge radii are read to about $\pm 1 \text{ mm}$, the thickness of the rim, and contact is known only to

within one frame (0.033 s), so the impact phase is not resolved. (6) The dye molecule's radius is about 0.5 nm; even a radius ten times smaller would leave the diffusion length well below one pixel ($\sqrt{10} \times 3.3 \mu\text{m} \approx 10 \mu\text{m}$). (7) Air drag on the falling drop is negligible over 5 in. (8) The light wattages are estimates.

Natural next steps are to use fresh glycerin for each run, release single drops of known size from a syringe at a fixed height, lock the exposure manually so shutter speed and ISO are known, light the mug diffusely from the side with a matching white balance, and film at a higher frame rate to resolve the impact phase. Repeating the experiment with glycerin water mixtures would show how the spreading changes with viscosity.

6 References

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