Unstable Thinning of a Soap Film Composed of Sodium Dodecyl Sulfate – the Critical-Fall Phenomenon

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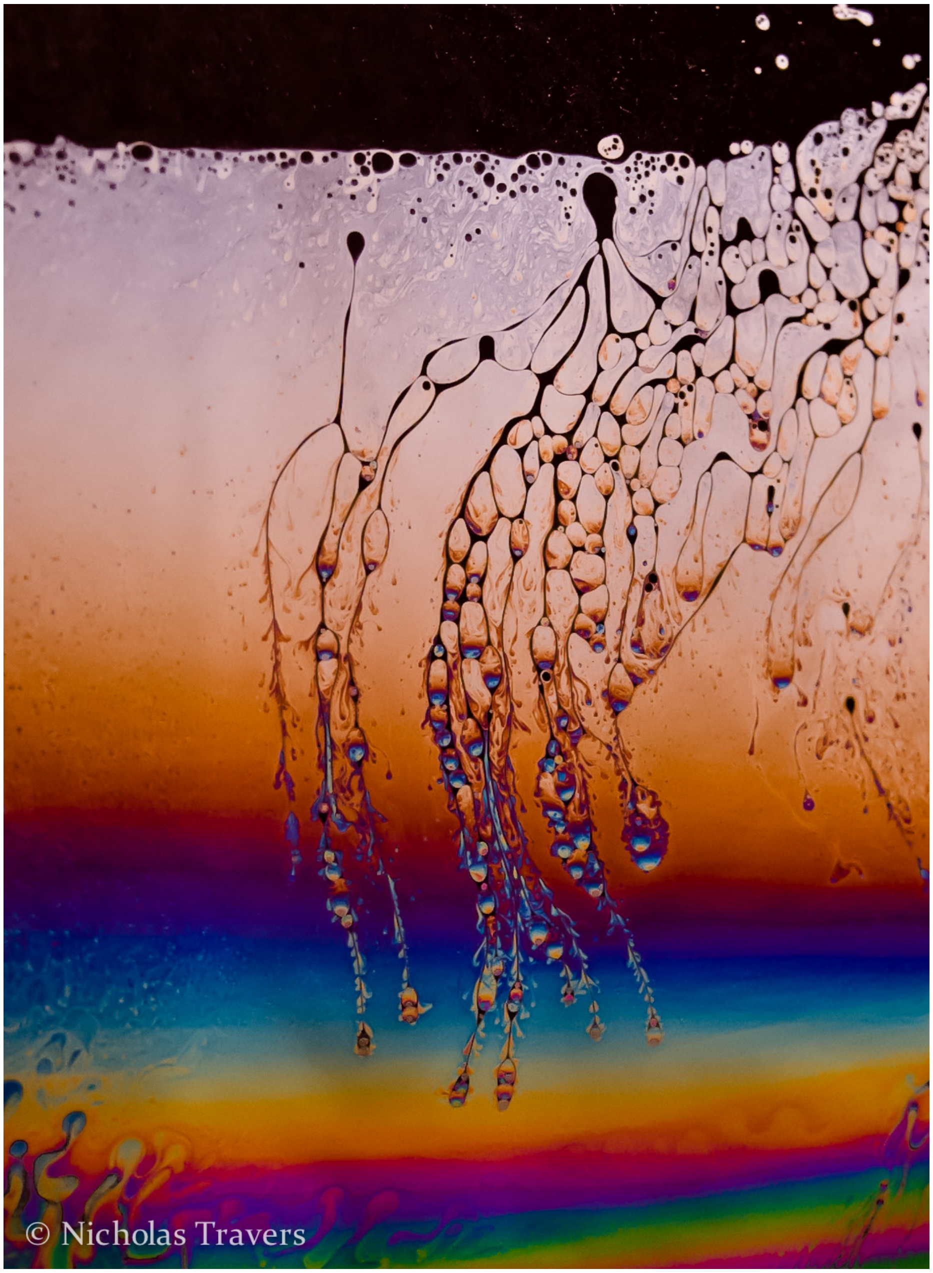
First Team Assignment – Flow Visualization 2012

University of Colorado at Boulder



An investigation was undertaken to observe and phenomenon known as critical-fall using and present it using digital photographic techniques. Critical-fall was observed in a thinning soap film composed of a single surfactant. The process of critical-fall is described, along with the physics and fluid principles involved and demonstrated in the image. The photographic setup and technique is presented and reviewed. The image was produced for the third assignment, titled *Team Project#1*, of the mechanical engineering course Flow Visualization[1] at the University of Colorado at Boulder. The purpose of the assignment is for students to design and setup an experiment to investigate a fluid phenomenon, and use an imaging technique to demonstrate the phenomenon in a visually pleasing manner.

Introduction

Solutions of water and soap are often used to form thin films. After experimenting with several soap solutions, a solution of the surfactant sodium dodecyl sulfate (SDS), glycerin, and water was found to have a long life and produce critical-fall. The phenomenon of critical-fall occurred within 30 seconds of film creation, and was imaged approximately 100 seconds after creation of the film, which continued to thin for a further 140 seconds before rupturing.

For this investigation an enclosure was designed and built (see appended original image). The enclosure allows for the quick and reproducible creation of vertical thin films using 0.25mm fishing wire to draw a vertical film up out of a trough containing the soap solution. The enclosure also protects the film from air currents and provides a neutral background. The imaging setup is outlined in Figure 1. A 200W tungsten light bulb diffused through tissue paper was used to illuminate the film. The light reflected by the film is captured by the camera which was oriented approximately 60° from the surface of the film.

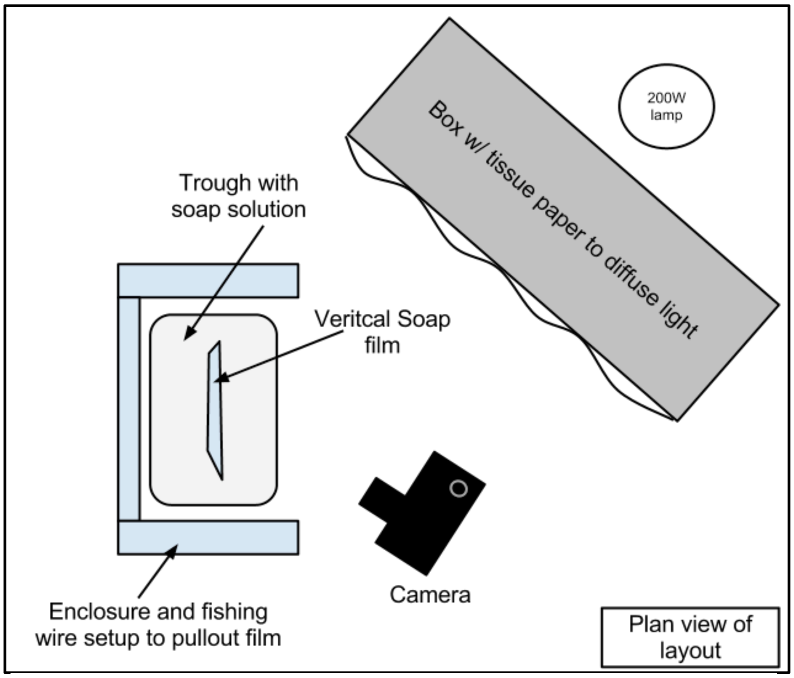


Figure 1 - Setup used for imaging of soap film formed between strands of fishing wire fixed in an enclosure (see original unedited image), and illuminated by diffuse light from the side.

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[1] The flow visualization course website can be found at: http://www.colorado.edu/MCEN/flowvis/

Background

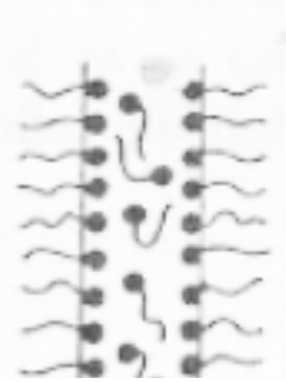

Figure 2 - Structure of soap film, with layers of surfactant at film surfaces.

Soap films are composed of a bulk fluid which is bounded at either surface by a layer of soap molecules which are amphipathetic (Figure 2). For this investigation the bulk fluid is a 17:3 mixture of water and glycerin, by weight. The soap is the surfactant SDS, and the solution's concentration is ~0.34%. SDS is an anionic surfactant consisting of a sulfate group, which is hydrophilic and attracted to the water, and a 12 carbon chain that is hydrophobic and is repelled from the water. Depending on the concentration and thickness of the film some surfactants remain in the bulk of the fluid. The critical micelle concentration of SDS, 8.2mM or approximately 13% by weight (Mukerjee & Karol, 1971), is much greater than the concentration used here; therefore the bulk fluid will simply contain individual SDS molecules, as show in Figure 2. This is in contrast to containing micelles, which form when multiple surfactant molecules clump together. The thin film visualized has surfactant molecules distributed throughout, in a addition to bounding both surfaces.

The interference colors of a thin film can be used to evaluate the film's thickness and to observe fluid dynamic behaviors within the film (Travers, 2012). As soap films drain and their thickness approaches the wavelength of light, ~1μm, these interference colors are seen. The color variations in the film are used to describe the development of critical-fall, particularly the transition from silver to black. For readers' reference, Figure 3 shows the range of color transitions from thin to thicker regions of a typical soap film. Note that the 'black film' in the left of the image has a thickness of ~30nm, and is much thinner than the wavelength of light. The light reflected from the upper and inner surfaces of the black film interferes destructively and is extinguished, such that only the black background of the enclosure is seen. The silver film is also smaller than the wavelength of light (~100nm), but destructive interference is not complete and some low intensity light is perceived (Travers, 2012).

Figure 3 - Color variation with film thickness, from 30nm left to 3000nm at right; the silver region is approximately 100nm and the second order yellow is just under 500nm thick.

Soap films have been classified by their draining behavior as: rigid films, simple mobile films, and irregular mobile films. Rigid films have plastic surfaces which slow the film's drainage, while mobile films drain quickly and exhibit gravity convection and marginal regeneration phenomena (Isenberg, 1992). The irregular mobile film is investigated here, which is characterized by instability in the development of the common black film, known as critical-fall.

Development of Critical-Fall

The explanation given here for the stages of critical-fall is adapted from *The Science of Soap Films and Soap Bubbles*, by Cyril Isenberg, and presented in conjunction with Figure 4. As the thinning film approaches the thickness of the common black film, van der Waals forces cause an equilibrium to be reached that limits further thinning and prevents the film from re-thickening. At this stage the boundary between the silver region and black region can become unstable. The black film tends to grow and thin the surrounding portions of film to the stable thickness of the black film. This results in sections of the silver film becoming isolated, as shown in (a) of Figure 4. Conservation of mass requires that as the black film develops it expel bulk fluid from between its surfaces into surrounding film elements. This thickens the surrounding film, including isolated silver portions of film which will absorb bulk fluid and thicken. The added weight of the bulk fluid makes the silver section heavier than the surrounding film and it will sink down the film, (b) in Figure 4. The negative buoyancy of the thickened region will cause it to fall according to gravity convection, which is to say it will sink until it reaches a horizontal region in the film that has similar film thickness (Isenberg, 1992). The isolated drop of silver film presented in Figure 4 was photographed descending due to gravity convection, and is an excellent example of the effect.

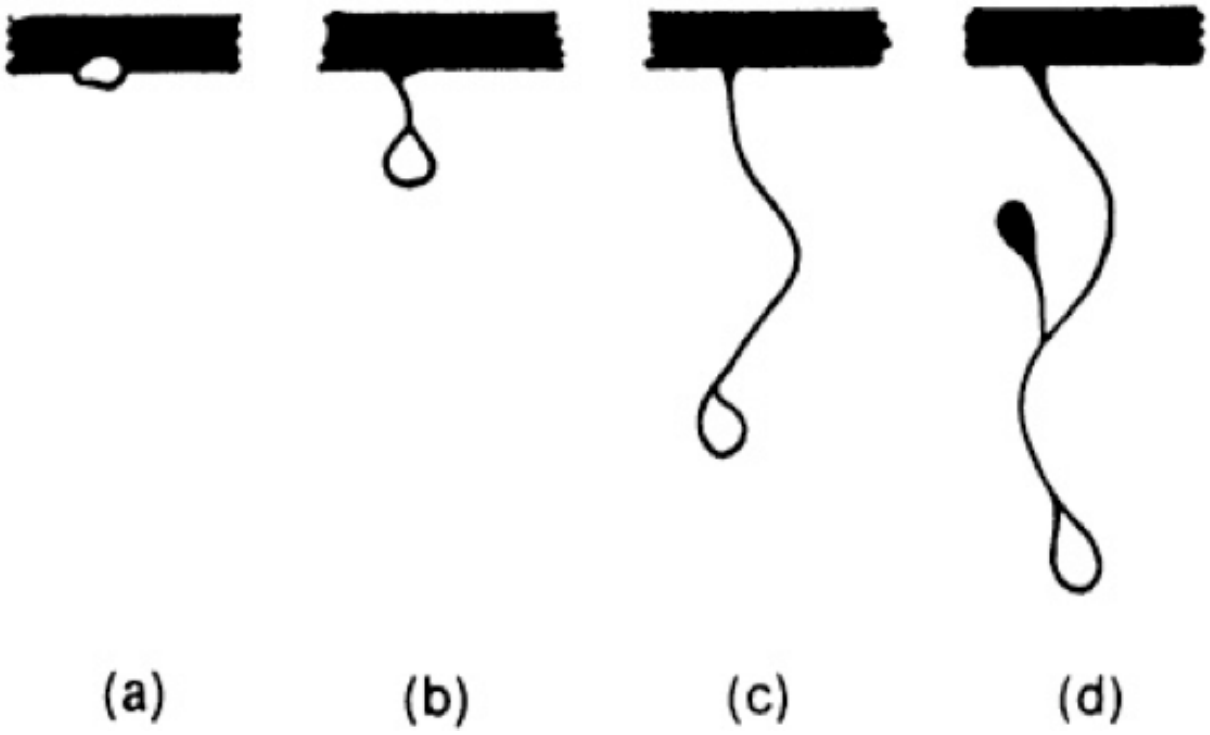

Figure 4 - Stages of critical-fall; black indicates the common black film and the white background is the surrounding film. (a) isolation of a segment of silver film (b) descent of same section of silver film (c) growth of black film which begins to rise (d) black film may build up, branch off and rise up as an isolated instance of black film (Isenberg, 1992).

As the silver section sinks down the film, the black film continues to envelope it, which causes a tributary of black film to trail behind the silver section of film, this links it to the top layer of black film. The black film also continues to grow, further thinning the surrounding film. This creates an unstable system: the surrounded silver film continues to thicken and seeks equilibrium with ever lower portions of the film.

The growth of the black film is also influenced by gravity convection. The thin film flows bodily upwards along the formed path towards the upper black-silver boundary, as represented in (c) of Figure 4. This flow explains the fairly consistent thickness of the black film channels. However, if the black film in these tributaries grows rapidly the channels may not be able to support the flow of thin film, and a swelling will form. As the swelling grows its buoyancy increases, and the swelling will rise up the film alongside the main channel, (d) in Figure 4. The selected image was chosen because of how well this stage of the film's development is represented in various areas, for example see details in Figure 6 of rising black film.

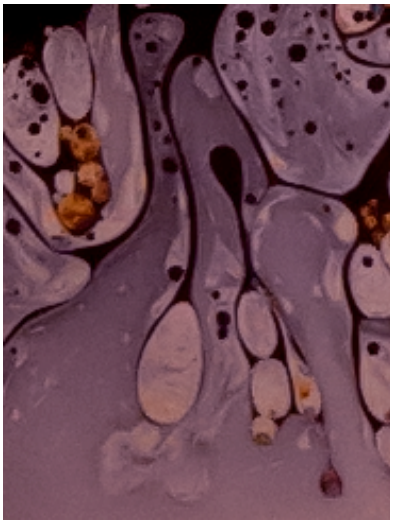
Figure 5 - Silver region of film isolated by the black film thickens and begins to descend as a drop (lower center third of frame). Note the brighter tones at the bottom of the drop indicate greater thickness.

Rising black film also leaves behind a channel of black film, with its stable thickness. When a swelling of black film rises, a section of the thicker surrounding film becomes isolated from the main film by the channels of black film. This section of film will begin to thicken, start to sink, and develop via the same series of processes detailed above. This unstable system will persist until the film has become completely black, or the film ruptures.

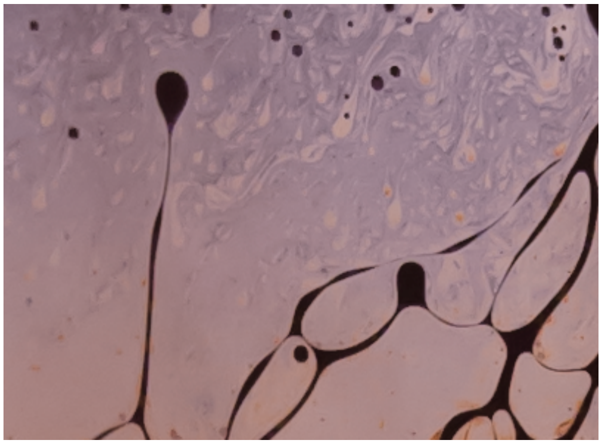
Figure 6 - Crop of original image shows stages of black film swelling and rising separate from the main channel. At far left the swelling has separated and is rising to the black-silver border above; at lower right a swelling is beginning to rise from the main channel; at low far right the intersection of several black film channels is swelling and may begin to rise.

To characterize the flow around the rising black film in Figure 6, the Reynolds number was used. Based on a fluid density of approximately unity (that of water) and based on measurements of velocity and diameter taken from successive images, the Reynolds number in this situation is on the order of 10^{-6}. This indicates that viscous forces are dominant and corresponds to creeping flow. Indeed the deformation of the black section appears laminar and similar to other images of creeping flow (Van Dyke, 1982).

Visualization Technique

To effectively visualize the phenomenon of critical-fall in a thinning soap film, the interference patterns due to reflected light were used. A 200W tungsten light bulb behind tissue paper was used to create diffuse light approximately 6 inches from the film. The camera was positioned to capture the most vivid interference colors, while minimizing the presence of the camera's own reflection. The black background of the enclosure absorbs light to provide a pleasingly dark and neutral backdrop. The soap solution is a 500:65 mixture of water and glycerin by volume, the concentration of the SDS surfactant (Aldrich 99%) in the solution is ~0.34% by weight. The solution was mixed thoroughly and allowed to sit overnight to ensure that the solid SDS had completely dissolved. Approximately 100ml of solution was placed in the trough of the enclosure for creating thin films.

To produce thin films in the enclosure the fishing wire was lowered into the fluid, and then extracted slowly. A weight on the end of the wires, outside of the enclosure, helps keep the wires taught and stable. Thin films with a lower height to width ratio were observed to last longer. The imaged film is approximately 4.5 inches high by 3 inches wide, enclosed at the top and sides by the fishing line and at the bottom by the soap solution. Critical-fall occurred naturally after the film had drained for approximately 30 seconds. To improve the lifetime of the films, a small vessel of hot water was placed near the film to increase local humidity, which reduced evaporation from the film.

The final image is 1147 x 1567 pixels in size, and shows approximately 2 x 3 inches of the soap film. The plane of the soap film was approximately 3 inches from the camera and tilted approximately 60 degrees from the camera's line of sight. The settings of the camera were adjusted to achieve crisp details in the photograph. A fast shutter speed was desired to capture crisp color transitions without blurring the dynamic patterns. To capture the fine details a low ISO was desired, but was limited because the scene was somewhat underlit. To capture the most light a large aperture was used, though the aperture was closed down somewhat to provide greater depth of field. To avoid the noise and color aberrations inherent in low ISO settings, the shutter speed was set to 1/160th of a second and the aperture set to f/3.5 which allowed the ISO to be set at 200. The white balance was adjusted for tungsten lighting, but not calibrated precisely. The camera was in macro mode with an effective focal length of 6mm, which has a 35mm equivalent focal length of 28mm. The camera used was a NIKON Coolpix P7100 which has a 6.0-42.6mm, f2.8 lens with image stabilizer. The camera settings are summarized in Table 1.

Table 1: Camera's Image Capture Settings

Original Image Size	2736 x 3648 pixels
Final Image Size	1147 x 1567 pixels
Resolution	240 pixels/inch
Shutter Speed	1/160
Aperture	f/3.5
ISO Speed Rating	200
Focal Length	6.0mm
Lens	6.0-42.6mm f/2.8
Camera	NIKON P7100

Some editing of the original image file was done to produce a clean and visually appealing final image. The most significant edit was to crop the image to show only a portion of the soap film. This was done to remove the enclosure and highlight details of the flow phenomena. Because the distance of the camera from the film was limited by the presence of the camera's own reflection on the film, and to achieve the level of detail desired, the image had to be cropped to show only a portion of the film exhibiting the critical-fall phenomenon. Cropping also removed the camera's reflection from the field of view. By removing the enclosure distracting elements are also removed, and the viewer is directed to focus on the fluid phenomena. The blacks were enhanced using a selective mask. Slight color adjustments were made by increasing the clarity. The clarity function increases the saturation of colors at transitions to make color borders more vivid. To bring out details in the image mild sharpening was done, and the noise from using a 200 ISO setting was reduced using the luminance and detail recovery functions. The initial and final images are appended to this report for comparison.

Concluding Remarks

The primary focus of the investigation was to observe the phenomena of critical-fall in a thin soap film and understand their development. The effect, and stages of development, is well demonstrated by the image. However, the image could be improved by macro shots to provide better resolution of the black film channels. This investigation was able to explain broadly the fluid phenomena involved, but greater resolution could bring further understanding to this thinning phenomenon that allows the black film to grow. A discussion of the repetitive, fractal like nature of the phenomena would be interesting and may be pursued later. The image could be improved by bringing more of the subject into focus, which would require better illumination. Illuminating the film from behind and using transmitted interference patterns to evaluate the film might be more effective at resolving small details. The success of this investigation leads to further questions about the effects of surfactant concentration on film behavior, and questions about the mechanisms of film rupture also arise. I am confident that further investigations would reveal more wonderful and exciting fluid phenomena.

References

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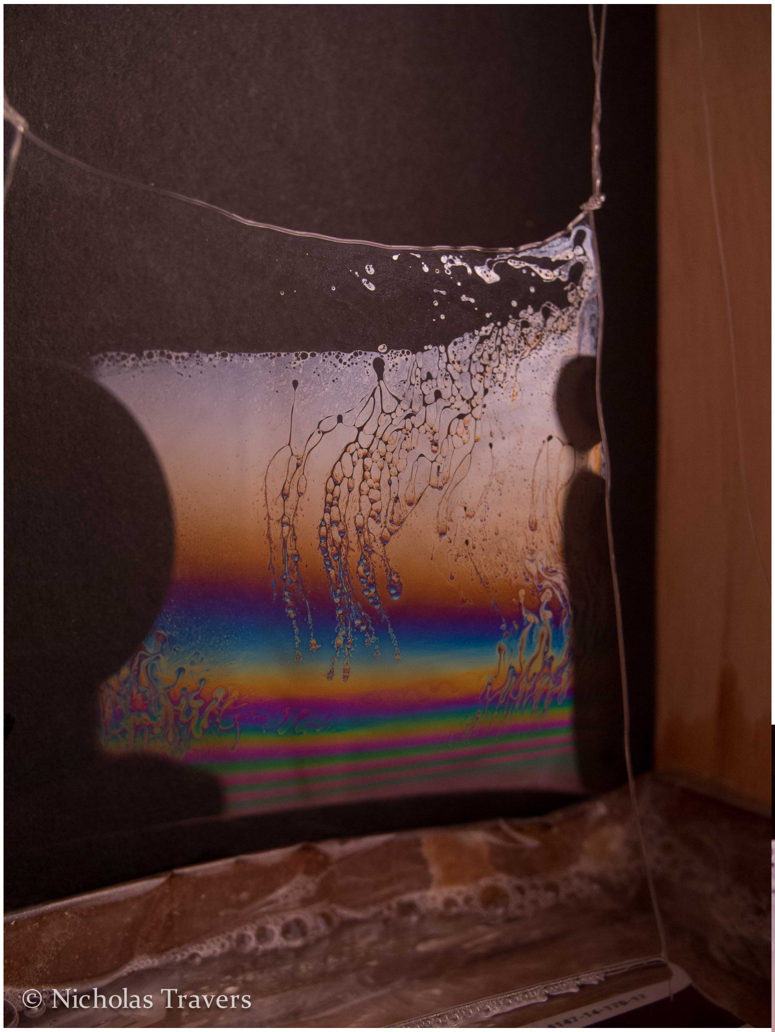

Original, as shot, image of draining soap film undergoing critical-fall. Part of the wood enclosure, with matte-board backdrop, is shown. Note there are two strands of fishing wire on the right, one is slack and is pulled through a slot in the bottom of the trough where it becomes taught and supports all sides of the soap film. This wire (a) is tied to the second wire (b) which tensions wire (a) as it has weights attached to its end. Wire (a) continues to the left side of the film, where it is pulled taught in the same manner before going through a second slot and becoming slack. The use of knots to attach the strands together could be improved upon.

Edited Image:
cropped, removal of enclosure and frame, increased contrast, noise reduction.