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A Simple and Cost-Effective Fluid Dynamics Apparatus to Engage Students in the Classroom and Laboratory

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Fluid mechanics is a subject commonly encountered in undergraduate- to graduate-level classes. The most common method of communicating the physics dictating the behavior of fluids is by reference to classroom slides or board examples and formal presentation of formulae and relationships. Conducting practical fluid dynamics experiments either as live demonstrations or as a hands-on student laboratory experiment presents a number of difficulties such as working with large amounts of liquid in the setting of a standard classroom or physics laboratory.

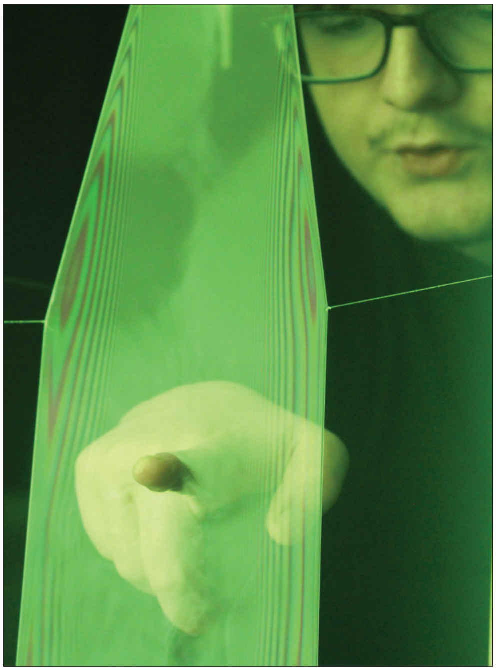

Fig. 1. An intern interferes with a soap film.

Here we present innovations to a design of a simple cost-effective, low-mess apparatus capable of generating long-lived flowing soap films to demonstrate the effects of fluid dynamics. This equipment has been designed for ease of construction, storage, and operation within the confines of a standard teaching classroom or laboratory. Only minimal engineering expertise and easily obtainable "off-the-shelf" components and tools are required to construct this equipment. This equipment affords students with a great opportunity to create 2D flowing films themselves in the lab and to think creatively in the engineering of their own experiments. This apparatus lends itself well to the observation of turbulence in a soap film as objects are inserted into the film to generate wake patterns. The increasing availability of inexpensive 3D printing technology allows students to easily and rapidly produce geometric shapes of their own design to be placed into the film to observe the effect on its flow without requiring access to workshop machinery or lengthy fabrication times.

Why soap films?

Vertically flowing soap films are an ideal tool for practical classroom demonstration and interactive student laboratory experiments (Fig. 1). They are an effective method of visualizing a number of concepts in fluid dynamics in real time and are capable of uninterrupted flow for many hours. Soap films are also the closest experimental analog to a genuine 2D fluid,[1] allowing demonstrations and experiments to be conducted for a wide range of student ability levels from high school physics classes to graduate-level research projects. Flowing soap films make excellent low-cost compact "wind tunnels" to demonstrate the behavior of fluids in the presence of obstructions introduced to the film.[1] Additionally, as the film is vertical, it makes an excellent classroom demonstration tool as it is visible to large groups of students in a classroom setting.

Design and construction

This apparatus is based on an earlier design used by the author as a student himself.[2,3] Here we have incorporated a number of important modifications to enhance reliability, versatility in the classroom, and durability so it can stand up to rigorous student use. It is also designed to be low cost, easily constructed by students with little mechanical experience, portable, and easy to store. Students can be readily involved in construction and modification, as only basic hand tools are required. The framework [Fig. 2(a)] consists of four upright columns constructed from perforated steel angle connected with nut and bolt fasteners (all readily available from any local hardware store). The availability of angle sections

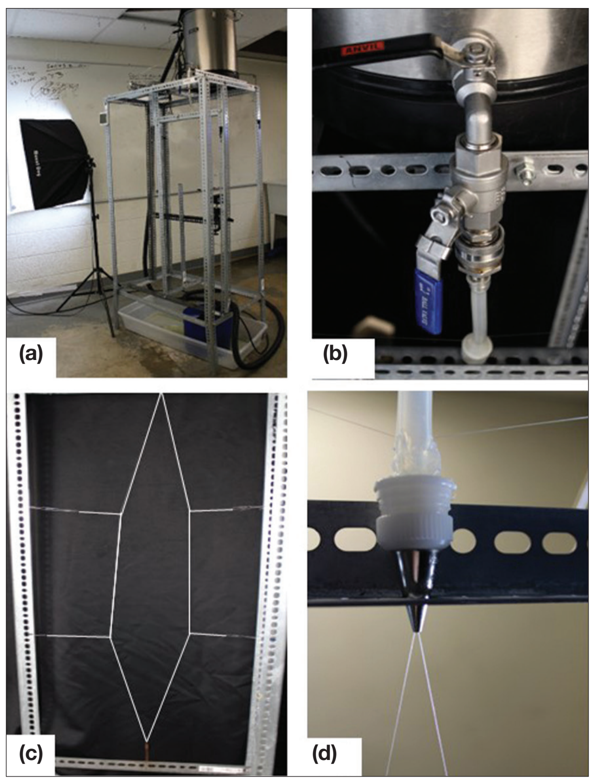

Fig. 2. (a) Generation 2 Mark 8 soap film machine. (b) Tank and valve assembly. (c) Monofilament lines. (d) Configuration of injector and monofilament lines.

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in convenient precut lengths and the use of basic nut and bolt fasteners eliminates the need for students to be trained in fabrication and workshop techniques involving power tools or cutting gear, contributing to a safer work environment for students. The many existing holes in the manufactured angle allow for ease of equipment mounting or addition of extra structural components. A reservoir containing a soap/water/glycerol solution is securely mounted to the top of the frame as seen in Fig. 2(a). A valve/spigot assembly attached to the reservoir tank [Fig. 2(b)] controls the flow of the soap fluid through an injector nozzle [Fig. 2(c)]. A length of monofilament fishing line runs through the injector nozzle and forms the framework to extrude a soap film [Fig. 2(d)].

The frame can be modified to a variety of sizes based on student specifications and needs due to its use of bolted angle section. Experimental design progressively moved toward the introduction of larger bodies with more complex geometries to the film. As such, the need became apparent for a larger "test zone" (the region in which experiments are conducted), causing our system to evolve from a modest tabletop device 1.2 m × 0.7 m in size to a much larger 1.6 m × 0.8 m version (2.2 m tall with tank) giving a 1.1 m × 0.2 m soap film, a size ultimately limited by the dimensions of the laboratory. The frame is easily folded for storage by loosening the fastening bolts seen in Fig. 3, enabling the equipment to be conveniently housed in any general physics laboratory.

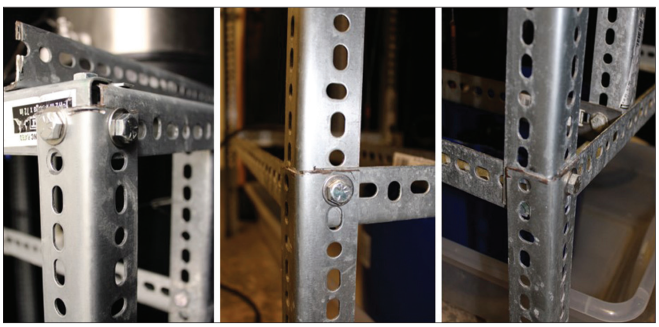

Fig. 3. Demonstration of bolted angle frame construction

A bucket or other receptacle is required to collect the soap fluid as it runs from the lines. A smaller system can be placed over a sink; however, a collecting receptacle allows for the soap to be recycled. The capacity of the soap reservoir at the top of the apparatus can be varied, ranging from a simple 2-L plastic bottle to a more capacious 28.4-L (7.5-gal) home-brewing tank as pictured in Fig. 2. Student modifications included an immersion heater to heat the soap solution before use to around 40 °C, a temperature found to create an optimum resilient film (see student experiments below). To facilitate adequate mixing of soap and water and to prevent separation of the solution inside the tank over time, students have at different times experimented with the addition of a magnetic stirrer or a small immersed pump inside the tank to agitate the solution, both proving successful with the pump proving the simpler to implement and maintain. A larger pump has been incorporated to recirculate the soap solution from the collection bucket back to the reservoir to create a theoretically perpetually flowing soap film; the immersion heater also aids in maintaining the temperature within the tank as the cold solution is reintroduced to the system. A single full tank at a flow velocity of ~2.5 m/s lasts around 85 min without recirculation.

In keeping with our low-cost approach, older computers and 4:3 aspect ratio monitors discarded from our physics teaching laboratory were used to view and record remote images and video footage of the film. A standard single-lens reflex (SLR) camera was connected to a computer via USB and mounted with a 546.1-nm (green) Mercury optical filter to image interference[4] patterns within the film more effectively; these features become more apparent when the thickness of the film is close to the wavelength of the light being observed, and so the available filter was used.

Photography was conducted through the monochromatic filter, allowing the constructive and destructive interference pattern of the light from the film to be clearly observed. This aids in flow visualization and is an indicator of the thickness of the soap film. The thickness of the film can be calculated from observations of the number of interference orders in our images and videos. This will form a future side experiment for students to investigate optics and optical path difference within thin films. This separate experiment is outside the scope of this paper and will form the subject of future work. The available 546.1-nm filter used here provided bright, high-contrast images of interference patterns for flow visualization in our films; however, any available monochromatic filter will aid in the resolution of interference fringes within the film.

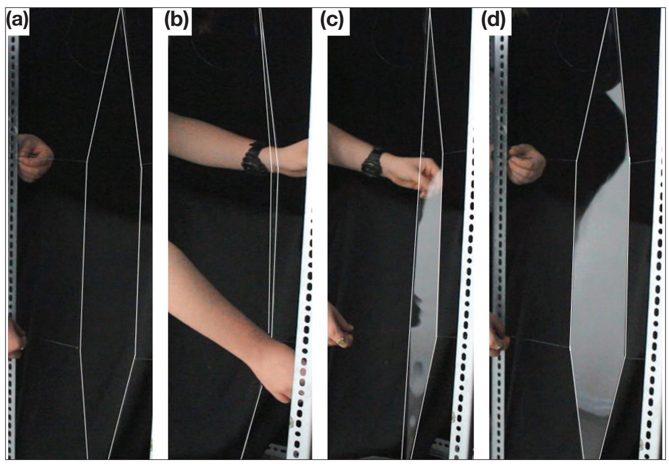

Fig. 4. Steps in creation of a flowing soap film. (a) Allow soap solution to flow over the monofilament fishing line running through the injector. (b) Bring the lines into contact. (c) Separate the lines, drawing out a soap film. (d) Anchor the lines to the surrounding frame. A complete video demonstration of this procedure can be seen on our YouTube channel: https://www.youtube.com/@gufluiddynamicslab.

Operation

Operation is a simple matter for the student, as shown in Fig. 4. A stable flowing soap film is formed by performing the following steps: (a) Allow soap solution to flow over the monofilament fishing line running through the injector. (b) Bring the lines into contact. (c) Separate the lines, drawing

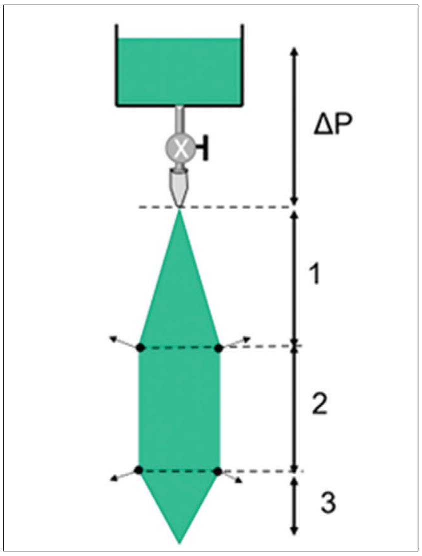

Fig. 5. Anatomy of a soap film[3]: ΔP = pressure head; 1 = expansion zone; 2 = test zone; 3 = contraction zone.

out a soap film. (d). Anchor them to the surrounding frame using the attached paper clips and existing holes in the angle section frame.

Attaching a valve to the reservoir outlet assists in variation of flow rate (flow rates typically vary from 0.5 to 5 m/s), the increased injection rate of a faster-flowing film results in an increase in film thickness, making them more resilient to touch.[2] Shapes can be introduced to the film more easily at a higher flow rate, and the rate is reduced once a shape is inserted. When extruded, a vertically flowing soap film is formed with three distinct zones[2] as shown in Fig. 5, giving a stable flowing film in which to perform experiments within the test zone. With practice, a stable resilient film can be drawn out each time with relative ease.

Demonstrations

The system is capable of demonstrating a number of concepts in fluid dynamics, including interference of light in thin films,[4] wake patterns, vortex–vortex interactions, the transition of laminar to turbulent flow in a fluid,[5] and the effects of film thickness and buoyancy.[6]

Student experiments

Students can perform a variety of experiments, make observations, design and innovate regarding experimental/engineering problems, and test their ideas in a practical "hands-on" fashion. Students engaged in experiments in our laboratory ranged from high school seniors to senior undergraduates under the professor's guidance.

Initially, students are asked to observe a flowing film and postulate on the cause of the interference patterns formed by the film [Fig. 6(a)].[7] They are encouraged to increase and

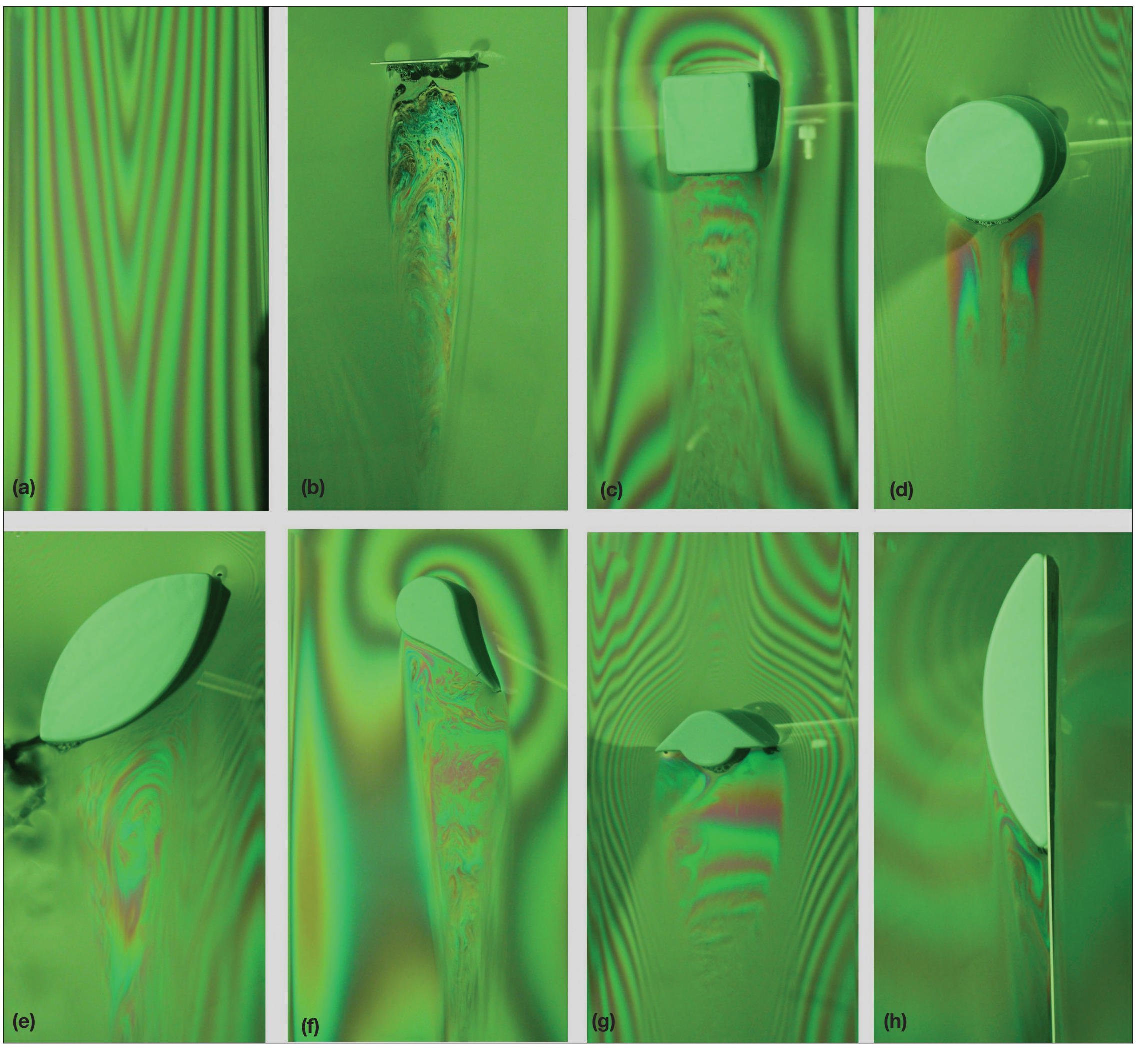

Fig. 6. Student experimental results: (a) free-flowing film, (b) flat plate, (c) cube, (d) cylinder, (e) ellipse, (f) wing cross section, (g) streamlined body, and (h) half ellipse with plate.

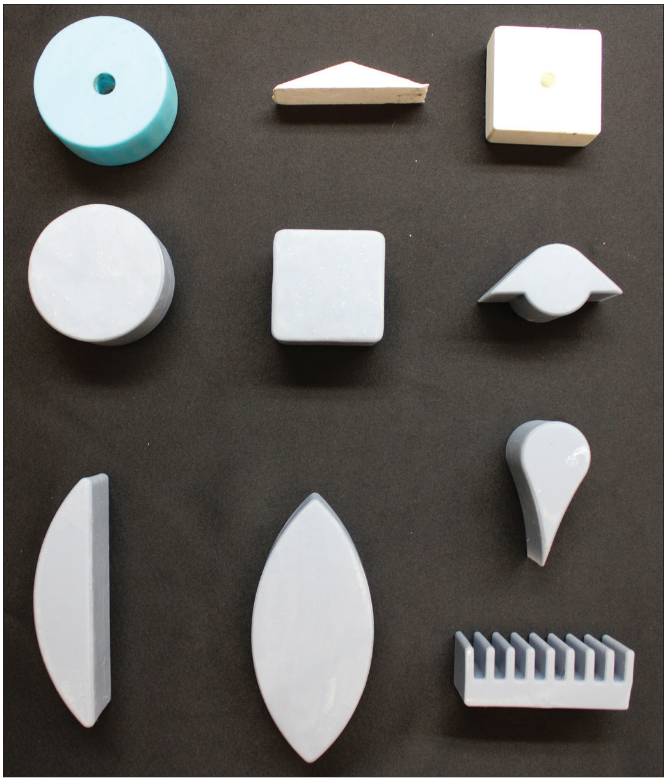

Fig. 7. Student-designed and printed 3D shapes.

decrease the flow rate and observe the overall effects on the film, demonstrating how the interaction of light with the film can change for differing flow rates and film thicknesses.[6,7]

The system allows easy analysis of 2D flow patterns generated by obstructions introduced to the film.[3–5] Changes to wake patterns can be observed, and practical demonstration of the transition from laminar to turbulent flow around obstructions is apparent. For more advanced students, discussions/experiments could easily extend to fluid dynamics principles such as Reynold's number and velocity flow profiles if desired. With access to low-cost modern 3D printing, shapes to use as obstructions can be easily designed and rapidly fabricated by students (Fig. 7). In the absence of such facilities, simple objects such as wrench handles, forks, combs, metal plates, or other everyday objects can be placed within the film.

Students are asked to investigate the effect of a basic flat plate placed in the film at a number of angles [Fig. 6(b)] and to observe its effects. They are then given the opportunity to analyze the flow patterns and effects on the film of a selection of basic geometric shapes such as squares, circles, and ellipses [see Figs. 6(c)–(e)]. Students are subsequently given the opportunity to create bodies of their own design (Fig. 7) to test in the film. Student designs have led to progressively more ambitious shapes being printed and tested, including an aircraft wing cross section, a "winged cylinder," and an ellipse with a constrained flow plate designed to represent part of the Great Red Spot of Jupiter [Figs. 6 (f)–(h)] among others. Other student experiments have included the rotation of a shape within the film to test its effect on vortex shedding and the addition of a sound unit, in which a speaker is placed in contact with the film to observe the effects of waves propagating through the fluid[8]; video footage of both can be seen on our student-run YouTube channel.[9]

Students also experiment with the properties of the soap film itself and have learned much about the nature of soap solutions. Different soap mixtures have been tested to alter film resilience and plasticity, settling on a soap:water:glycerol mix of 15:1:0.025. Students control the soap solution temperature using an immersion heater in the reservoir tank. A temperature of around 40 °C provides a film with an optimal resilience and plastic nature while remaining comfortable for human contact. An older-model PASCO temperature sensor and lab interface box no longer used in our teaching lab was added to allow tank internal temperature to be monitored in real time. Students have also opted to monitor environmental effects such as the optimal temperature and humidity of the laboratory, finding an ambient temperature of around 20–25 °C with humidity in excess of 40% to favor soap film creation. Lab temperature remains relatively stable in our basement environment, while humidity is regulated using a standard home humidifier.

Video and images of turbulence within the soap film are currently captured using a standard "off-the-shelf" SLR camera connected to a computer and external monitors. With the exception of the camera and the angle framing, which was specifically purchased for this project, all equipment was obtained from surplus college laboratory supplies, keeping costs to a minimum and encouraging the students to be resourceful. Subsequent generations of students have developed this experiment from a basic sink-top 1.6-m-high frame supporting just a 2-L soda bottle to the larger, more complex 2.2-m version seen in Fig. 2, providing the ability to conduct serious research experiments.

Students have taken to posting their research results to online platforms such as YouTube[9] and TikTok.[10] Students take great pride in disseminating their work to family, colleagues, and the public at large in this fashion, and this provides them with an outlet to immediately and casually disseminate their work. Last, a current student research project aims to translate our observations of 2D vortex dynamics to a functioning computational model through the analysis of captured movies and images using custom Interactive Data Language (IDL) scripts.

Teaching impact

As a practical physics demonstration, the apparatus performs extremely well, and its visually spectacular results are an excellent outreach tool that garners immediate attention. The construction and modification of the system appeals to non-physics majors who may be enrolled in engineering or similar courses, giving them an access point to begin working in an experimental physics laboratory.

Studying the effects of wakes and vortices allows students to visually engage in real time with fluid dynamics phenomena usually only discussed in static pictures or theoretical discussion.

The experiments conducted with this apparatus and the physics that can be gleaned from them are wide ranging in scope and complexity, lending themselves to a range of ability levels. The project's striking visual and interactive nature provides an excellent medium to inspire students to hypothesize, observe, and test ideas, receiving immediate and satisfying visual feedback on their experiments. An in-depth investigation of 2D fluid dynamics can require advanced mathematical techniques and programming skills. These more advanced projects lend themselves to advanced undergraduate- to graduate-level projects, providing scope for students to continue this avenue of research further into their academic career should they choose to.

Conclusions

The apparatus presented here is capable of consistently producing stable flowing soap films suitable for public demonstration and student experimentation. The design is relatively simple to fabricate using only basic hand tools and off-the-shelf hardware store supplies, making it ideal for smaller teaching facilities. Operating costs are low and require only the purchase of easily available soap and glycerol for continued operation.

The use of 3D-printed shapes as test bodies to be placed in the soap film was successful and an excellent and safe fabrication method for students to use.

The use of a flowing soap film for demonstrations and a variety of student experimental projects applicable to a wide range of educational levels is valid, and the visually striking nature of the results, especially under monochromatic light, is inspiring to students.

Allowing students to post their results to social media platforms almost immediately is an excellent method of engagement for students at the high school or early college level, and they take great pride in sharing with friends and family in this way.

Experimental tips

- Encourage starting small; building a sink-top unit to start is an excellent way to gain experience and understand the mechanics of forming soap films.
- Monitor the environmental temperature of the laboratory as well as the temperature of the soap solution; both of these factors can affect film longevity and resilience.
- A soap:water:glycerol mix of 15:1:0.025 held at a temperature of 40 °C was found to produce the most resilient film for testing.
- Our equipment operates best at ambient laboratory temperatures in excess of 20° and a humidity of 40% or more; figure out the optimal conditions for your lab for consistent results.
- Filter the light: even though the interference patterns of a soap film can be seen under normal visual lighting conditions,[5] they become more apparent under filtered light. If a camera is unavailable, students may hold a filter to observe the film.
- Beware of reflection: direct lighting causes reflection from bulbs or LEDs and masks detail in a soap film. A diffuse light source at approximately 45° to the film is very effective.

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