A Practical Classroom iPad Shadowgraph System

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Light rays refract when passing through pockets of transparent fluids with different indices of refraction such as ordinary air pockets of varying temperature. This phenomenon makes night stars twinkle, distorts views above hot asphalt roads and hot barbeque grills, and provides an opportunity for visualizing the normally invisible movement of transparent gases and liquids. Schlieren and shadowgraph imaging allows for visualizing transparent gas density variations, allowing ordinarily unseen phenomena to be imaged and experimented with in real time. Traditional Schlieren systems require expensive equipment (DSLR camera, telephoto lens, several high-quality mirrors, an adjustable knife edge) and are difficult to align,[1-3] while shadowgraph systems trade simplicity for image sensitivity. We outline a simplified classroom shadowgraph system that uses only a single telescope mirror, an LED flashlight, and an iPad to teach topics in high school science.

Traditional Z-Pattern Schlieren system design

Light rays generated from a bright point source placed slightly off-axis at the focal length of a parabolic mirror are reflected as parallel rays to a second parabolic mirror that refocuses the rays back down to a point (see Fig. 1). A knife edge is placed at the focal length of the second mirror and a camera collects the light rays. A different density pocket of transparent material located in the area of collimated rays (the Schlieren object shown) causes the parallel rays to refract (blue lines). These deviated light rays do not pass through the focal point of the second mirror and are blocked by the knife edge or miss the camera aperture entirely. The resulting image as seen by the camera is "missing some light"—creating light and dark regions that map out the boundaries of the transparent fluid (see Figs. 2 and 3).

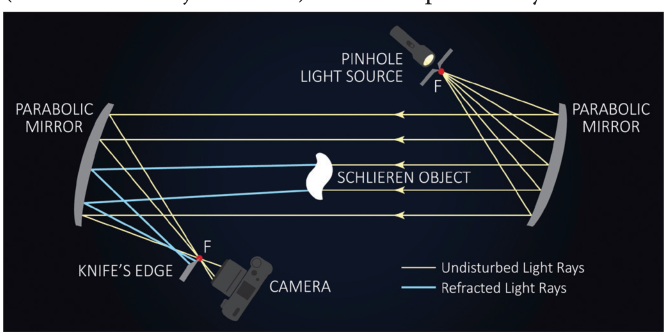

Fig. 1. Z-pattern Schlieren setup.

Theoretically, the two mirrors can be placed any distance apart allowing for a large "area of interaction" where a Schlieren object can be placed, but the Z-pattern design requires extensive laboratory apparatus space— longer than double the focal length of the mirrors and wider than several mirrors. Since a long focal length is also preferred to allow the light rays to have a greater angular deviation from their intended path, Z-pattern setups tend to be large in size, often filling dedicated rooms or a very large table. Additionally, two-mirror systems are prone to astigmatisms due to the two requisite off-axis reflections, which can cause the image to be blurry and partially out of focus, and setting and maintaining alignment for all components is quite difficult.

Fig. 2. Heated air region above a lit candle.

Fig. 3. Butane gas jet above an unlit cigarette lighter.

Single-mirror shadowgraph system

A single-mirror shadowgraph system uses one mirror that both collects and focuses light from a point source, a much smaller off-axis angle, and no knife edge (see Fig. 4). A bright point source of light is placed twice the focal length away from the mirror's surface. The resulting image formed from the reflection is collocated at twice the focal length from the mirror's surface. Light rays are deviated twice by the pocket of different density (going to and from the mirror) and a longer optical path is less necessary. Most importantly, component count and alignment issues are greatly reduced.

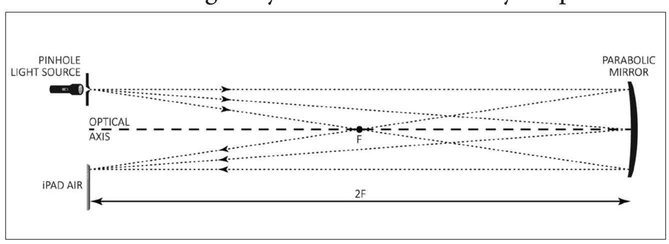

Fig. 4. Single-mirror shadowgraph system.

The simplified nature of the single-mirror approach allows the light source and camera to be placed close together (approximately 2 to 3 cm), which dramatically reduces any astigmatism effect and creates a sharper image. The size of the setup is also kept to a maximum length of twice the focal length, fitting readily on a classroom laboratory tabletop.

Schlieren vs. shadowgraph

Schlieren and shadowgraph techniques are similar in a number of ways but differ in key details.[4] For our purposes, the main differences are:

- The Schlieren method uses a knife edge placed at the focal point/plane of the collecting mirror to block deviated light rays. A shadowgraph does not use an obstruction to curate deviated from undeviated light rays. No knife edge, no Schlieren.

- Schlieren apparatus allows a larger working volume (the length of the parallel rays multiplied by the mirror area) for bigger phenomena to be imaged, and usually this means dedicated space.
- Traditional shadowgraphs are usually projected onto a wall or surface, and might not even use a focusing or projecting mirror at all (flat mirrors are common). Shadowgraphs are traditionally viewed by eye (Fig. 5).

Generally speaking, Schlieren devices produce high-quality, higher-contrast images and are capable of visualizing very subtle differences in temperature, density, or material type. However, in our experiences building both devices, a shadowgraph was much easier to set up and align in a classroom, and required fewer components (hence is cheaper).

Fig. 5. A shadowgraph of a flame and rising thermal plume of hot air projected on my porch using parallel Sun rays passing over an open flame. Notice the lowered contrast between light and dark regions in the projected image.

Materials and setup

• *Design and materials*

Cost and durability were the two features that influenced our shadowgraph system design decisions. Maintaining alignment with a two-mirror setup (see Fig. 1) in a high-traffic area where student interaction is expected wasn't practical. Hence, we used a single-mirror to reduce cost and decrease setup time to a matter of minutes (see Fig. 4). Further minimizing

Table I. Materials list; prices as of spring 2018.

Item	Manufacturer	Model Number	Price
iPad Air (128GB)*	Apple	N/A	N/A
SkyQuest XT8 8-inch Dobsonian Reflector**	Orion	OR-8945	$379.99
Industrial 360 LED Cap Light	Energizer	INCAP11EH	$24.95
Amazon Basics 60-inch Lightweight Tripod w/ Bag	Amazon	WT3540	$23.49
Joby Grip Tight Mount	Joby	JB01468-BWW	$39.95

* other tablets and smartphone cameras are also possible[6] and there is probably one being carried in your classroom now

** or similar telescope mirror

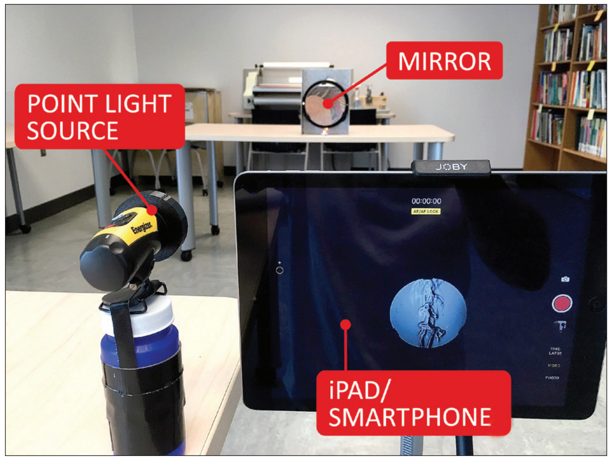

Fig. 6. Setup using LED flashlight, iPad mounted to a tripod, and a parabolic mirror.

cost, we replaced the DSLR camera with an iPad or smartphone. Our 8-in mirror was taken from an inexpensive SkyQuest telescope (avoiding expensive optics), and with a focal length of 60 in, our setup fits on a 10-ft lab tabletop.

A common bright LED flashlight[5] taped atop a water bottle was initially covered in aluminum foil with a pinhole and acted as our point light source. Later, we replaced the fragile foil with a 3D printed cap with a 1/32-in hole to increase its longevity. However, our design trades off depth of field—our interaction space was confined to the short area just in front of the mirror's surface (10^{-1} m), limiting the size of phenomena that can be investigated.

We also removed the knife edge since its sensitive placement at the focal point is easily disturbed and would not be robust enough for classroom use without mounts and an optical table, frame, or bench.

Imaging: Setup and alignment

Figure 4 provides a good overall reference, and our experience has shown it easier to roughly place then make manual adjustments rather than relying on technical specifications and measured distances. Getting clear images isn't difficult and can be done in just a few minutes.

Using the listed mirror specifications, place the light source and camera approximately twice the focal length from the plane of the mirror (see Fig. 6). Initially, you will not be in the perfect location and your image size will not match the size of the pinhole light source (see Figs. 7 and 8 looking at the iPad camera lens and back from behind and over the mirror).

It is helpful to note, adjusting the image is best done by moving the light source and keeping the mirror and camera stationary. Continue to move the light source until the image formed is approximately equal to the size of the point source (see Fig. 8), and then adjust the vertical and horizontal position of the iPad so the light enters the aperture of the camera. It is helpful to look at the camera screen while making adjustments as there is a noticeable change that occurs once the light is focused directly into the camera (see Figs. 9 and 10).

When focused, the amount of light entering the camera is initially overwhelming for the software, and bright light washes out nearly everything on-screen. A partially filled mirror is

Fig. 7. The large pinhole image size projected onto the back of the iPad below the camera indicates the iPad camera lens is not located at the focal plane.

Fig. 8. The pinhole image size is now approximately equal to the point source, indicating the camera lens is located at the focal plane.

an indication that your camera is not at the focal point or that the aperture is blocking light rays from entering the camera sensor. You will need to adjust your light source until the mirror is fully and brightly illuminated.

To adjust the iPad camera exposure and focus for the best view (AutoExposure/AutoFocus Lock), tap in the center of the image of your mirror on-screen. After adjustment, the mirror will become gray in appearance, and depending on the quality of your mirror, you may see a small concentric circle in the center of the mirror[7] (see Fig. 11). If your mirror is not fully gray, or appears "grainy" or "blurry," it may be necessary to move your light source around until your view looks similar to Fig. 11. The shadowgraph system is now ready for use. Try placing a lit candle in front of the mirror while adjusting your light source to maximize the sensitivity and clarity of the image.

Classroom application and examples

Beyond the "wow" factor associated with visualizing the flow of transparent gas and liquid, the iPad shadowgraph system has tremendous instructional power in the science classroom. The optical properties of a gas or liquid can be manipulated by altering the temperature, density, or material type, and any combination of these changes can make for an interesting viewing opportunity.

• *Suggested phenomena*

A standard phenomena associated with this technique is to view the gas and heat given off above a burning candle flame. Our setup, however, is even capable enough to view the heat exchanged between our bodies and the environment around us (see Fig. 12).

The phenomena shown in Figs. 12-15 by no means represents an exhaustive list of interesting things to visualize, but should provide enough inspiration to get started.

• *Suggested uses: Standards and curriculum*

As well as being a cool standalone demonstration project, there are several direct links to relevant curricula that could use our shadowgraph system. Energy represents one of the crosscutting concepts included in the Next Generation Science Standards,[8] requiring students as early as 4th grade to "4-PS3-2 Energy: Make observations and provide evidence that energy can be transferred from place to place by sound, light, heat, and electric currents" (p. 31). Unit 8-Energy in the Modeling Physics[9] curriculum accounts for thermal energy transferred into the surroundings by a frictional force (E_{th}), a concept that isn't easy to develop given the invisible nature of the transfer mechanism. And the Physics and Everyday Thinking[10] (PET) curriculum uses temperature changes as evidence for "thermal energy" changes in a system due to "heat interactions" and "friction-type push/pull interactions" that transfer energy from solid object into the surrounding air. Our iPad shadowgraph system provides a unique opportunity to directly observe and experiment with energy transfers in real time that are typically invisible to the human eye.

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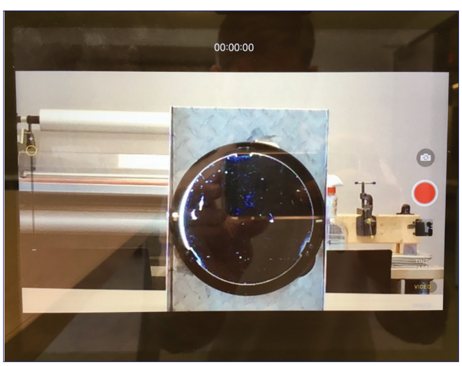

Fig. 9. iPad screen image before focusing light into the camera.

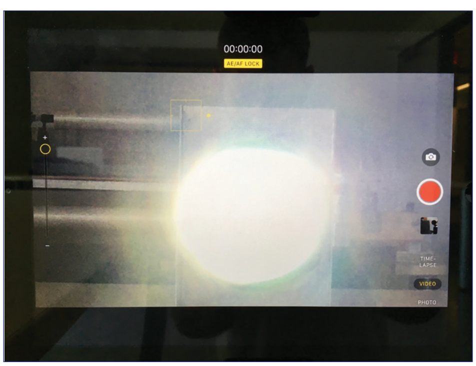

Fig. 10. iPad screen image after focusing light into the camera.

Fig. 11. Camera view after tapping image to adjust AE/AF lock.

Fig. 12. Rising convected air shows heat exchange between a warm hand and the surrounding air.

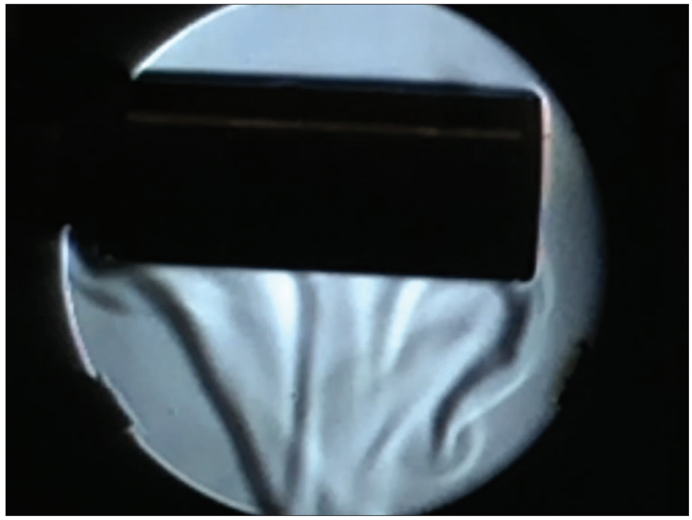

Fig. 13. Cold air sinking around a chilled soda can.

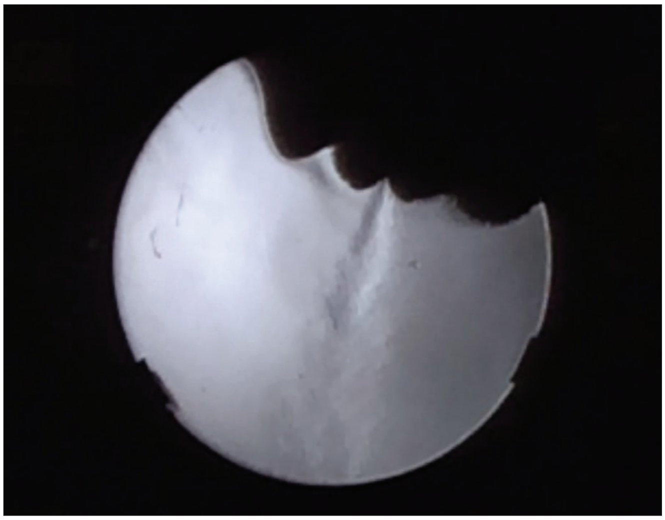

Fig. 14. A warm breath.

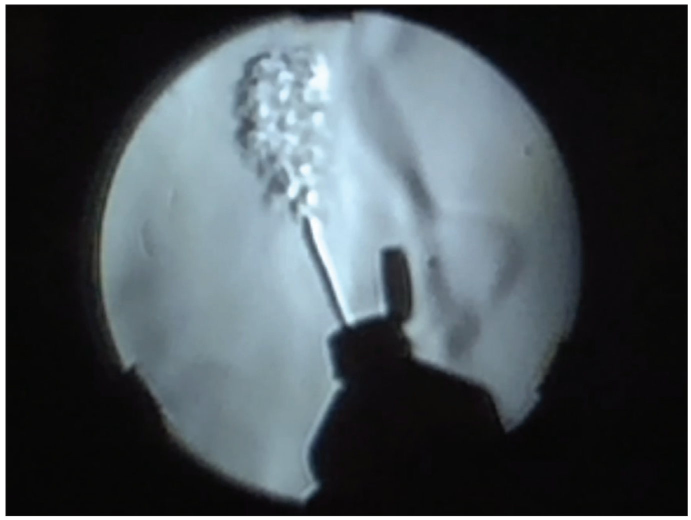

Fig. 15. Puffs of 70% isopropyl alcohol vapor from a squeeze bottle.

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2. NPR, "What Does Sound Look Like? | SKUNK BEAR," YouTube, https://m.youtube.com/watch?v=px3oVGXr4mo .
3. "Schlieren Optics," Harvard Natural Sciences Lecture Demonstrations website, https://sciencedemonstrations.fas.harvard.edu/presentations/schlieren-optics.
4. G. A. Settles, *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media* (Springer-Verlag, Heidelberg, Germany, 2001).
5. The light must be a single white LED as multiple LEDs will cause "shadowing" and "ghosting" effects.
6. We successfully tested an iPad Air, iPad Mini (2nd Generation) iPad Pro 10.5 in, iPhone SE, iPhone 7, LG V10, Samsung Galaxy S6, Microsoft Surface 3, and Ipevo Ziggi-HD Document Camera.
7. The concentric circle in the center of the mirror is due to the manufacturing process, but provides a valuable reference during setup. Given the choice, opt for a mirror with this "defect."
8. NGSS Lead States, *Next Generation Science Standards: For States, By States* (The National Academic Press, Washington, DC, 2013).
9. *Modeling Instruction in High School Physic*s, Mechanics-v3 (April 6, 2018), https://www.modelinginstruction.org . Curriculum available for paid members, located in AMTA Instructional Resources link under the Membership tab.
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