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Visualizing the invisible: the construction of three low-cost schlieren imaging systems for the undergraduate laboratory

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Abstract
We describe the construction and operation of three low-cost schlieren imaging systems that can be fabricated using surplus optics and 80/20, an aluminium extrusion based construction system. Each system has a different optical configuration. The low cost and ease of construction makes these systems highly suitable for high-school and undergraduate laboratories. Undergraduate students responded enthusiastically to the experience of assembling and operating these systems. This experience also served as an introduction to issues in optical design, helping the students gain an intuition for geometrical optics.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Schlieren imaging is a technique used to visualize variations in the optical density of a medium. It is a research tool as well as a popular demonstration experiment. In an undergraduate laboratory course, it can form the basis for a number of elegant experiments of varying degrees of sophistication [1–13]. Our aim in writing this paper is twofold. First, we describe the construction of three low-cost schlieren imaging systems, including custom-built optical mounts, that were made using 80/20, a modular aluminium framing system [14]. Second, we describe their potential for use as demonstration experiments in a high-school or undergraduate science laboratory.

Our laboratory typically employs a large number of undergraduates each year who assist in almost all of the experimental projects being carried out [15]. Assigned to this project were two undergraduates (JK and TS, a final year and a third year undergraduate, respectively), and a recent high-school graduate (RJ), who spent a summer working on this project. Two of the three students had little prior experience conducting independent research. We (VG and MJZH) found that students responded enthusiastically to participating in a real and open-ended research project where 'the answers' were not known to any of us. The experience highlighted the strong positive effect that working on a real-world research problem can have on students who are just beginning their study of science.

The work was motivated by our laboratory's efforts to understand how mammals, specifically rats, track odour plumes to their source. This is important both from the point of view of fundamental biology, and also for the design of biologically inspired odour source locating robots that can be used for hazardous tasks such as locating chemical leaks or detecting land mines. We aimed to observe with high speed video cameras how rats sniffed at an odour plume and located its source. One way to visualize an odour plume is to seed the flow with small particles that scatter light and thus make the flow visible [16]. However, this technique has two drawbacks. First, it requires expensive laser sources to generate the laser light sheet that scatters off the seed particles. Second, because the particles provide the animals with visual cues, the search is no longer purely olfactory. Therefore, we decided instead to use schlieren imaging to view the path of the odour plume. By embedding the odourant in a gas such as helium or carbon dioxide, which have refractive indices that are different from air, the odour plume can be imaged without providing visual cues to the animal.

2. Background

Schlieren effects are familiar to us all; we have all seen shimmering mirages on a hot road, or the optical distortions caused by the hot air emerging from an aircraft jet engine. The word *schliere* (plural *schlieren*) comes from Old German, where it means bits or pieces. In optics, a schliere is a region where the refractive index is different from that of the surrounding medium, causing the light 'rays' passing through that region to be refracted.

In 1665 Robert Hooke made the first known study of these refractive index variations. In his book *Micrographia* [17] Hooke set down in observation LVIII his study of such phenomena, and his conclusions that 'the true cause of all these phenomena is from the *inflection*, or *multiplicate refraction* of those rays of light' that are passing through 'a medium whose parts are unequally dense.' However, schlieren imaging as it is practised today is based largely on the techniques first invented by the German physicist August Toepler [18].

Since the time of Hooke's observations, schlieren imaging has evolved into a precision tool for visualizing variations in optical density, especially in fluid flows, and is applicable in any situation where the flow is accompanied by a change in refractive index. With some imagination, many flow fields can be manipulated to make them amenable to schlieren imaging [19][4].

3. 80/20—the industrial erector set

80/20 is the brand name of an extremely versatile and fairly inexpensive system of aluminium extrusions. These extrusions can be joined to one another in different ways with a variety of connectors called joining plates. This flexibility allows the user to be imaginative and construct

[4] This book is encyclopædic in its description of schlieren imaging and is easily the most comprehensive reference available, with a vast bibliography. For the schlieren researcher or hobbyist, there is no better book to begin with. The book also contains a very large number of schlieren images of various phenomena, illustrating the versatility of the technique.

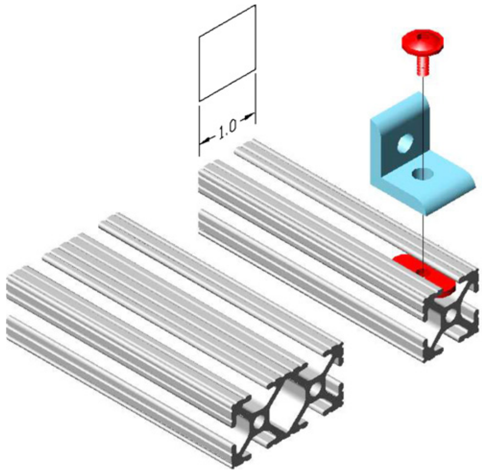

Figure 1. 80/20 assembly. Figure demonstrates how `10 series` T slotted rods are connected to a ‘joining plate’. Rods are classified according to their cross-sectional area. A `1010` (1 × 1 inch^2) and `1020` (1 × 2 inch^2) rod are shown.

a number of fairly precise and extremely rugged structures. The 80/20 product range consists of four different ‘series’ of components [14], but for our apparatus, the 10 series was more than adequate.

Figure 1 shows two examples of `10 series` extrusions along with a 90° joining plate, and demonstrates how 80/20 components are connected together. The extrusions within a series are labelled according to their cross-sectional areas, with 12 different cross-sections available in the `10 series`. The figure shows examples of a `1010` and a `1020` extrusion from the `10 series`. `1010` denotes a rod with a 1 inch^2 cross-sectional area (shown on the right in the figure), while `1020` is a 1× 2 inch^2 cross-section. We have found the `10 series` range to be ideally suited to building many simple optical mounts and assemblies. The `10 series` components have the added advantage that their bolt-hole spacing is compatible with that of the standard 1 inch spacing found on optical tables. Thus, `10 series` assemblies can easily be combined with existing experiments.

4. Some optical components

Basic optical components, even simple lens and mirror mounts, are often expensive. The optical mounts we constructed were built to hold large, non-standard size mirrors and lenses, and cost considerably less than commercially available parts of the same size. The only machining required was to cut the 80/20 rods to size. Table 1 provides a list of parts used to construct these components.

Figures 2 and 3 show lens mounts for a 3 inch diameter achromatic lens and a 6 inch diameter plano-convex lens respectively, along with exploded views to demonstrate how the components are assembled. Both these lenses are non-standard sizes for which commercially manufactured mounts are difficult to find. The ends of the extrusions can also be covered with ‘end caps’, the yellow covers seen in figure 3, which add a professional finish.

Figure 4 shows front and back views of a mount for a 4.5 inch diameter concave mirror along with an exploded view. With some machining, more complicated kinematic mounts

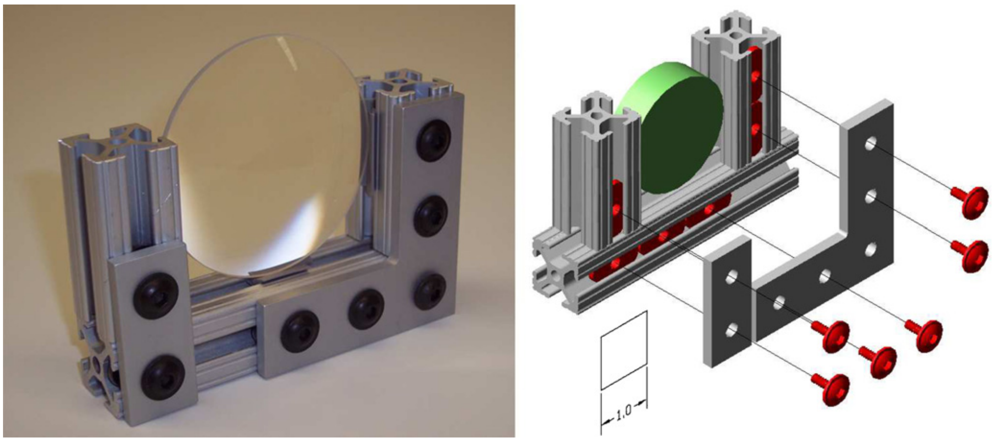

Figure 2. Mount for 3 inch diameter achromatic condenser lens.

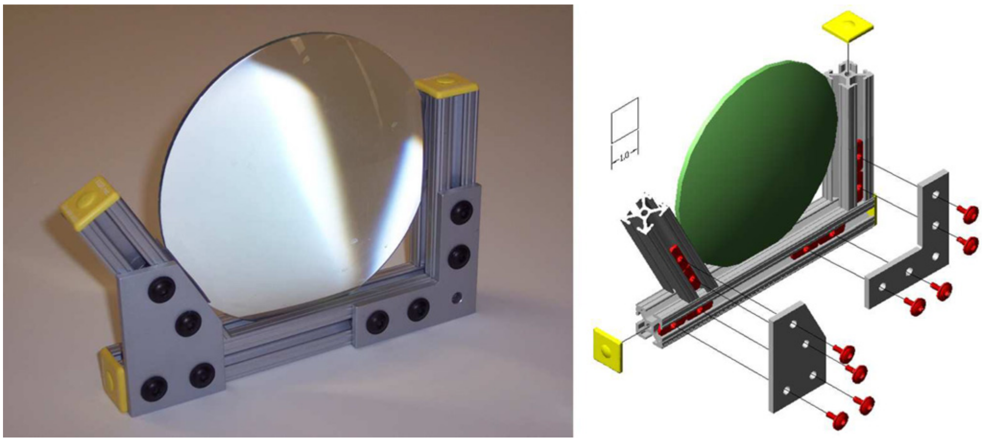

Figure 3. Mount for 6 inch diameter schlieren field lens (see figure 6(a)).

Table 1. List of components used to construct the optical mounts shown in figures 2–5. Part numbers and quantities needed for each of the mounts can be determined from the respective figures and using the online catalogue available at www.8020.net. The total cost of the items used was less than 14 euros for any of the mounts.

Part number and description	
1010	1010 rod
4081	5 hole L joining plate
4107	2 hole joining strip
4164	4 hole 60° joining plate
2015	1010 end cap
4265	2 hole slotted inside corner
4128	12 hole 90° joining plate
1030	1030 rod
4138	8 hole inside gusset corner

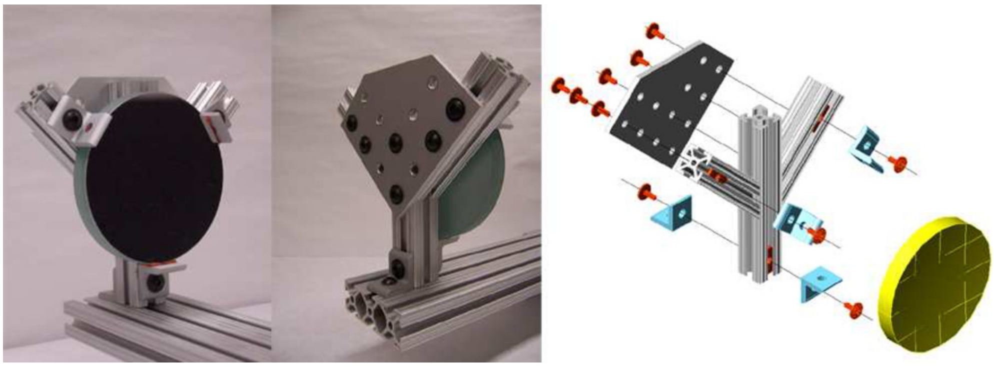

Figure 4. Front and back views of mount for 4.5 inch diameter mirror. Small pieces of soft rubber are used to cushion the mirror at the three points where it is held by the mount.

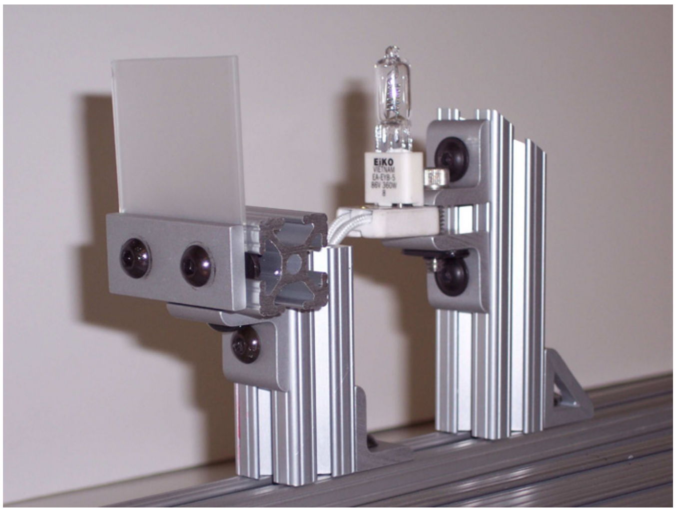

Figure 5. A simple mount for a lamp and a filter holder. The filter is a square, 2 inches on a side.

capable of tilting about multiple axes can be made. We did not attempt this, but helpful hints can be found in the excellent paper by Quericoli *et al* [20].

Figure 5 shows a photograph of a holder for a projection lamp (the light source for the schlieren system), and a simple filter holder. The entire schlieren system was set up on a long `1030` rod, which can easily be used as an optical bench (figure 7).

In all these figures, the essential simplicity of the `80/20` system can clearly be seen. None of these components takes more than 10 min to assemble, once the design is decided upon. To save time, we found it convenient to have a ‘toy-chest’ of commonly used `80/20` parts and extrusions always on hand to rapidly try out new designs and ideas.

Finally, we note that the large optical mounts described in this section may be particularly useful for demonstration experiments. Demonstration experiments must be large in size because they are viewed by many students at the same time, but do not generally require precision tolerances. The `80/20` system provides an easy, low-cost method to construct these types of large optical mounts.

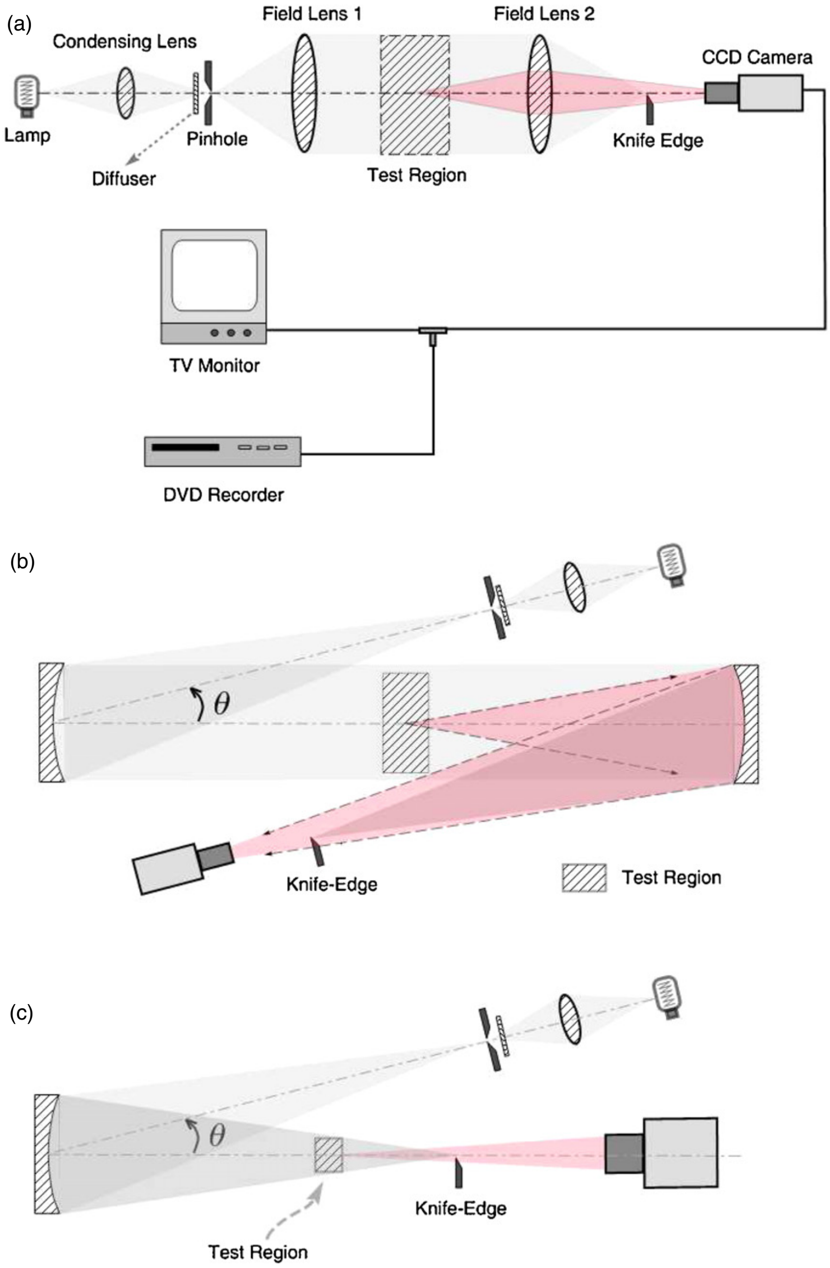

Figure 6. Schlieren imaging configurations: (a) a two-lens, in-line system, (b) a two-mirror, Z-type system and (c) a single mirror system. The test region is shown hatched in all figures. Typical ray paths imaged by the camera are shown in red.

5. Three different schlieren imaging systems

Three schlieren imaging systems were constructed, each with a different optical configuration, which are shown in figure 6. Images were captured by a low-cost, 8-bit CCD camera

Figure 7. The final single mirror schlieren setup (figure 6(c)). The knife edge is seen mounted on a translation stage. The pinhole has been moved further away from the diffuser for clarity. During operation, the diffuser is placed as close to the pinhole as possible.

(SuperCircuits B/W C-Mount PC-242C). Using a T connector, the camera output was sent to a monitor for real-time viewing and also saved to a disc using a DVD recorder (figure 6(a)). The saved data was processed using Adobe Premiere^{TM} (v. 6.0) and Matlab^{TM}(v. 7.0).

Our first prototype system was a very simple, in-line, lens based system (figure 6(a)). To increase the size of the test region, we used large, 6 inch diameter, lenses ($f = 50$ cm) that we obtained from a surplus optics retailer [21][5]. While the setup was very easy to align and operate, the image quality was very poor, with severe chromatic aberration. Chromatic aberration can of course be minimized by replacing all the lenses with achromats, but 6 inch diameter achromats are prohibitively expensive and would have completely defeated our purpose of building a low-cost, proof-of-concept, prototype system.

We then constructed a two-mirror 'Z-type' system (figure 6(b)). Again, our search for inexpensive optics on the internet met with great success[6], and we were able to get two 4.5 inch diameter ($f = 50$ cm), parabolic, telescope primary mirrors, for only ~20 euros each. These mirrors were of very high quality, with broadband enhanced reflection coatings, and a surface accuracy of $\lambda/5$. The two mirror system eliminated chromatic aberrations and formed a sharp and clear image. However, in light of our ultimate aim which was to have a rat explore an odour plume within an arena placed in the test region, this configuration had a serious drawback. The Z-type system is an off-axis system, and off-axis aberrations, such as coma, are minimized by keeping the angle θ small. To have enough room to fit the rat arena within the test area, one has to either increase θ, by increasing off-axis errors, or make the distance between the mirrors inconveniently large.

At this point, we finally converged on a single mirror design that is shown in figure 6(c). An image of the final prototype system is shown in figure 7. We used this system to successfully image the exhalation of air from a lightly anesthetized rat. During inhalation, the inflow of air into the nostrils did not cause a large enough change in refractive index to be

[5] Anchor Optics is an excellent source for low-cost optics, both mounting hardware as well as optical elements. The company website also has a very nice collection of old instruction manuals that can be downloaded for no cost, including one for a now discontinued schlieren imaging system. (Anchor Optics, 101 E Gloucester Pike Barrington, NJ 08007, USA).

[6] The Sylvan Company (http://www.sylvancompany.com). This company limits its sales exclusively to internet purchases. However, similar parts may be obtained from manufacturers who specialize in making mirrors for amateur telescope makers.

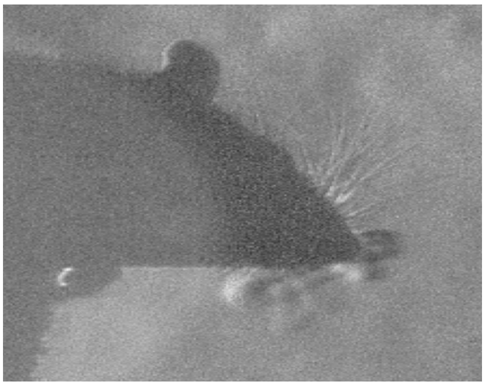

Figure 8. Schlieren image of air exhaled from a deeply anesthetized rat. The image was taken with a single mirror schlieren system that used a 12 inch diameter mirror and a high speed camera (Photron Fastcam-1024PCI, 1 KHz frame rate). The slightly brighter semi-circular region in the image is light reflected from a beam-splitter.

seen in the video recording. In contrast, exhalation could be clearly seen, most likely because of the moisture and warmth of the expelled air. The success of this prototype system convinced us to construct a larger, research grade imaging system, and figure 8 shows one video frame of data taken with this system that shows the air exhaled by a deeply anesthetized rat.

5.1. Alignment and operation

The alignment procedure for each of the three systems is quite similar and relatively straightforward. Our light source, shown in figure 5, consisted of a 300 W projector bulb illuminating a 500 μm diameter pinhole (not shown in the figure). A 3 inch diameter, $f =$ 5 cm achromat (figure 2), was used to collect light from the bulb and focus it onto the pinhole. A small piece of ground glass was placed in front of the pinhole to uniformly illuminate the aperture. Without the ground glass, the bulb filament is imaged instead, providing a non-uniform background to the schlieren images (see [19, p 174]).

To assemble a schlieren system, the mirrors or lenses are first arranged according to any of the configurations shown in figure 6 and adjusted to form a clear and undistorted image of the pinhole on a screen or piece of white cardboard (for the mirror-based setups, $\theta \simeq 5°–10°$). The position of the screen sets the position of the knife-edge plane. The schlieren test object that is to be imaged is first placed in the test region and brought into focus by the CCD camera, and then removed.

At this point, the image acquired by the CCD camera should be a bright, uniformly illuminated circle. If not, the camera position should be changed until this is the case. The intensity of the lamp is then adjusted so that the brightness of the circle is roughly half way between being completely dark and saturating the camera. Now, the knife-edge is introduced into the image plane and moved to cut-off half the image of the pinhole. Accurately positioning the knife-edge is crucial to obtaining good schlieren images.

To obtain a uniform background, the knife-edge must be positioned exactly in the image plane. When the knife-edge is initially placed to block the image of the source aperture, the intensity of the image on the monitor will change from bright to dark. If the knife-edge is placed exactly in the image plane, the bright circle will turn dark almost uniformly. If the knife edge lies outside the image plane, then a dark shadow will pass across the bright circle from either one side or the other. The direction from which the shadow passes across

Figure 9. Schlieren image of a jet of helium gas taken with the prototype single-mirror system (figures 6(c) and 7). The large dynamic range of the image and the low bit-depth of the camera (8 bits) causes many parts of the image to be saturated.

the image reverses itself as the position of the focal plane is crossed. Thus, by iteration, the position where the circle turns uniformly dark can be found. A more detailed description of this procedure can be found in Settles' book [19, p 180].

Once a uniform cutoff has been achieved, schlieren images should be easily visible. We have found that as we approach the cutoff, we begin to see air currents in the room quite clearly. Also, if the palm of the hand is placed facing upwards in the test region, convective plumes due to body heat can be clearly seen. The sensitivity of the schlieren system increases with the degree of cutoff, while the dynamic range decreases. Thus, depending on the magnitude of Δn, the refractive index difference between the test object and the background air, the cutoff must be accordingly adjusted. For example, 'strong' schlieren objects such as a burning candle require cutting off a very small amount of the source, otherwise the intensity changes exceed the dynamic range of the system and saturate the image. Figure 9 shows an image of a jet of helium gas. Because the range of Δn was large, and our camera had only an 8-bit dynamic range, large parts of the image are saturated. Once the system has been aligned, a variety of schlieren objects can be imaged. Classic examples include breath from the nostrils, a hot soldering iron, vapours from an organic solvent (both heavier and lighter than air) and jets of helium and carbon dioxide gas.

6. Summary

Pedagogically, we found this work to be of interest for three reasons. First, setting up and using the schlieren system helped the students working on the project gain an intuition for simple ray-based geometrical optics. Schlieren images are visually striking and the dynamic nature of these images makes for a vivid demonstration of the principles of ray optics. More quantitative explanations of the formation of schlieren images using the eikonal equation, or even Fourier optics, can also be introduced at this point (see the appendices in [19]).

Second, constructing these systems provided an excellent setting in which to discuss common issues in optical design, such as tradeoff, calculating a light budget, evaluating different designs and so forth. For example, as discussed in the previous section, positioning the cutoff depends on the magnitude of Δn that will be observed. This tradeoff between resolution and dynamic range demonstrated how a 'one-size-fits-all' approach fails to work, and one needs a sound grasp of the physics of the situation to design a good experiment.

Third, and perhaps most importantly, the students were exposed to a research environment which gave them a flavour of how real experiments are conducted. The students first clearly defined a goal—to image airflow from a breathing rat. To achieve this goal, they constructed three different prototype schlieren systems. Using these systems, they conducted preliminary experiments that allowed them to conclude that schlieren imaging was indeed a suitable experimental technique to image respiratory airflow. Finally, by examining the experimental constraints, they were able to select one of the three experimental geometries as being best suited for the task. In work only mentioned in passing in this paper, the students then went on to design, construct and operate a research-grade schlieren imaging system. This also gave the students, all of whom were engineers, an experience of the typical engineering design cycle which begins with a design that is then tested on a prototype, and finally leads to a finished product. That exposure to a research environment can be an exciting introduction to science for undergraduates is by no means a new idea [25–29]; however, to watch it first hand is a deeply satisfying experience.

Acknowledgments

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