

# A Simple Classroom Demonstration of Natural Convection

Dean R. Wheeler

Brigham Young University, Provo, Utah 84602

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## **Abstract**

This article explains a simple way to demonstrate natural convection, such as from a lit candle, in the classroom using an overhead projector. The demonstration is based on the principle of schlieren imaging, commonly used to visualize variations in density for gas flows.

## **Keywords**

fluid, natural, free, convection, density, schlieren, demonstration, projector

Natural or free convection results when there is a fluid density gradient in a system with a density-based body force such as the gravitational force. In an otherwise quiescent fluid, a density gradient can be caused by temperature gradients and/or species concentration gradients. Natural-convection currents enhance heat and mass transfer relative to conduction and diffusion in a quiescent fluid. This is an important process for engineers to understand. For instance, natural convection is a key process in the passive cooling of people, machinery, and computer chips, and in the volatilization of exposed liquids in an indoor or windless environment. The topic of natural convection is covered typically during two or three classroom hours in a junior-level heat and mass transport course.

This article explains a simple way to demonstrate natural convection in the classroom using an overhead projector. The demonstration is based on the principle of schlieren imaging, commonly used to visualize variations in density for gas flows. The demonstration requires a few hours of preparation time, but very little in materials cost, assuming an overhead projector is already available. It could be prepared by the instructor or by students as part of a class-related project. I explain below the principle behind the schlieren technique, the preparation required for the demonstration, and the results that one can expect.

## Schlieren Imaging

Schlieren images, along with shadowgraphs and interferometry, are a means of visualizing density variations in transparent media [1]. These techniques work from the principle that the index of refraction of a fluid depends on its density. The path and phase of a light wave passing through the fluid therefore depends on the density and its spatial derivatives. Schlieren optics as such was invented in 1864 by August Toepler, a German chemist and physicist (*schlieren* means “streaks” in German) [2]. The technique has been used extensively to visualize shock waves in supersonic flight. The wavy appearance of the horizon above a hot road is a simple realization of schlieren imaging of natural convection.

[Figure 1 about here.]

Fig. 1 illustrates the principle of schlieren imaging. A series of two filters with periodically alternating transparent and opaque stripes is used in combination with a light source. The

fluid to be imaged has a gradient in its index of refraction, which causes spatial variations in the amount of light that passes through both filters. This produces an image in which light and dark areas correspond to variations in the fluid density gradient. Conversely, if the fluid object has a uniform density gradient then the the image will be uniformly gray.

## Demonstration Setup

[Figure 2 about here.]

How can one adapt the schlieren technique for classroom use? Fig. 2 shows how the optics that are part of an overhead projector can be used to project a schlieren image of an object onto a screen. The schematic is a view from above, which means that the overhead projector is turned on its side. This is necessary so that vertically traveling fluid currents around the free-convection object are largely orthogonal to the light path. The optical principle of this setup, including the use of striped filters, is the same as in Fig. 1, except that a focusing lens increases the brightness of the projected image by collecting and distributing the light from the projector lamp. The smaller filter (point S) is attached to the surface of the overhead projector, and both filters have their stripes in a vertical orientation.

In order for the setup in Fig. 2 to work, the optical planes associated with points O and O' must be "in focus" with each other, as must the planes associated with points S and S'. Assuming the lens is ideal, this means that

$$\frac{1}{d_O} + \frac{1}{d_{O'}} = \frac{1}{d_S} + \frac{1}{d_{S'}} = \frac{1}{f}, \quad (1)$$

where  $d_X$  indicates optical distance between the lens and point X, and  $f$  is the focal length of the lens. Because the projector lens is mounted on a movable carriage, we have a great deal of freedom in positioning the various optical elements.

[Figure 3 about here.]

Fig. 3 shows the two striped filters used in my optical setup. They were made by creating the black-and-white striped patterns in a computer graphics program, laser printing onto transparent sheets, and attaching the sheets onto frames constructed from foam-core board,

purchased from the art supplies section of the campus bookstore. The smaller filter has a size comparable to the free-convection object to be imaged and has black stripes of thickness 0.5 mm and periodicity of 1 mm. (Because of the vagaries of my laser printer, it was necessary to make the black stripes 0.67 mm thick in the graphics program to affect a printed thickness close to 0.5 mm.) The larger filter is basically an enlarged image of the smaller filter—in this case enlarged by a factor of 3.7. The enlargement factor is equal to the ratio of optical distances  $d_{S'}/d_S$ .

It is advantageous to make the large filter as small as the optics allow, and customized for the overhead projector to be used. The optimal large filter is determined by the following steps:

1. Make the small filter, place it on the overhead projector surface, and project its image onto a wall.
2. Move the lens carriage to its uppermost (furthest) position relative to the surface. This maximizes distance  $d_S$  and hence minimizes  $d_{S'}$ , according to Eq. 1.
3. Move the entire projector relative to the wall until the striped image is exactly in focus. The wall is then at position  $S'$  of Fig. 2 and thus establishes distance  $d_{S'}$ .
4. Measure the thickness and periodicity of the stripes projected on the wall to determine the enlargement factor. The stripes on the large filter should exactly match the stripes of the focused wall image.

The large filter is created, as is the small filter, by printing onto transparency sheets from a computer graphics program. The sheets are mounted onto a rigid frame. Additional apparatus will be required to hold the frame in the proper position during the demonstration. For instance, I built a stand that accomplishes this from leftover pieces of foam-core board, wooden toothpicks, and glue.

In preparing for the demonstration, some optical tuning is required. The lens carriage should continue to be in its uppermost position, whereas the projector will be located further from the wall in the classroom than in the above experiment. One must first ensure that the two stripe filters are in focus with each other. This step requires patience and a steady hand. Success comes when the projected image is uniformly gray and all Moiré patterns

from the interacting filters have been eliminated. Next, the free-convection object is placed in the path between the small filter and the lens carriage (see Fig. 2). The object is then moved relative to the lens so that the object's wall image is in focus.

## Results

[Figure 4 about here.]

High quality schlieren images require precise construction and positioning of the optical elements. In this case, the precision is not as great as can be achieved in a laboratory, and hence the method is less sensitive to density variations. For this reason, the simple setup described above is only practical for imaging an object with large density variations, such as a flame. Fig. 4 shows three images obtained of the convection currents above a tea candle. Two things should be noted. First, the pictures in Fig. 4 have been rotated  $180^\circ$ . That is, using the above setup results in a projected schlieren image that is upside down. The second thing to note is that moving images are can be more exciting and instructive than static images. In this classroom demonstration, students are able to visualize the dynamic nature of free convection.

As an aid to readers, electronic versions of the graphics files used in this work are available at Ref. [3]. Videos of the projected images corresponding to Fig. 4 are available there as well. Refs. [4,5] are websites for two leaders in the field of schlieren imaging, Prof. Gary Settles of Penn State and Prof. Andrew Davidhazy of Rochester Institute of Technology. The sites contain a number of beautiful schlieren images of natural convection that can complement the live demonstration.

## References

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## Author Biographical Sketch



Dean R. Wheeler completed a B.S. in 1996 at Brigham Young University and a Ph.D. in 2002 at the University of California, Berkeley, both in chemical engineering. Returning to his Utah roots, he started as an assistant professor at Brigham Young University in 2003. His research area is electrochemical engineering, with ongoing projects to optimize processes in lithium batteries and in metal electrodeposition.

## List of Figures

1	The principle of schlieren imaging. Rays of light, moving from bottom to top, encounter a filter, a refractive object, a second filter, and then the image plane. Density gradients in the refractive object bend light rays such that some are screened out by the second filter, resulting in intensity variations on the imaging surface. . . . .	8
2	View of the optical setup from above. Point L indicates the overhead-projector carriage lens. Points S and S' indicate the small and large stripe filters, respectively. Points O and O' indicate the free-convection object and its projected schlieren image, respectively. . . . .	9
3	Schematic of the small and large stripe filters. The dotted lines indicate boundaries of single-page transparencies that are taped onto frames made of foam-core board. . . . .	10
4	Projected images of convection currents above a tea candle. . . . .	11



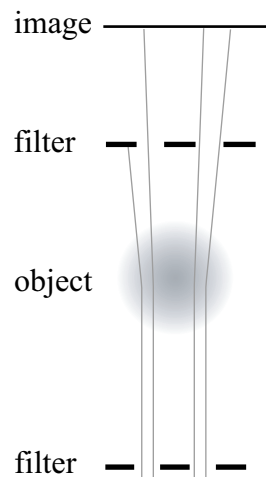


Figure 1: The principle of schlieren imaging. Rays of light, moving from bottom to top, encounter a filter, a refractive object, a second filter, and then the image plane. Density gradients in the refractive object bend light rays such that some are screened out by the second filter, resulting in intensity variations on the imaging surface.

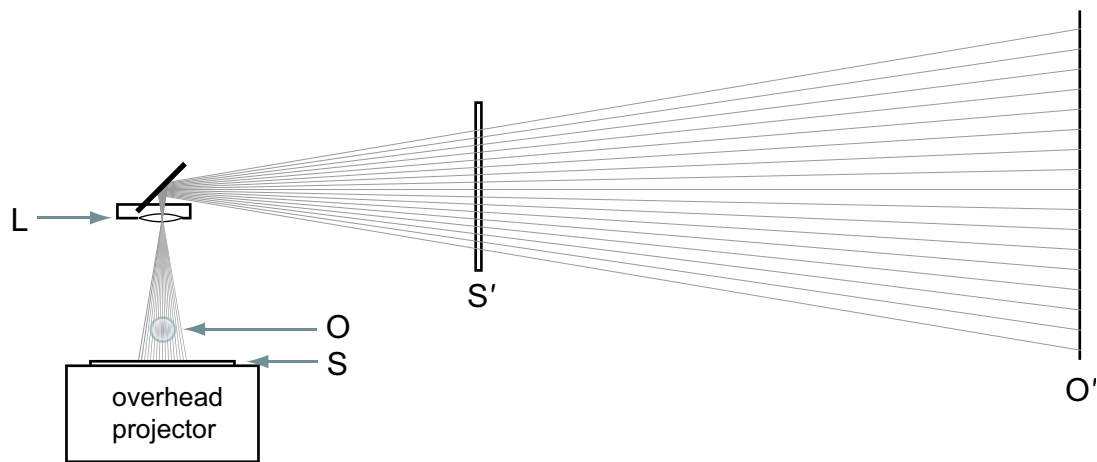


Figure 2: View of the optical setup from above. Point L indicates the overhead-projector carriage lens. Points S and S' indicate the small and large stripe filters, respectively. Points O and O' indicate the free-convection object and its projected schlieren image, respectively.

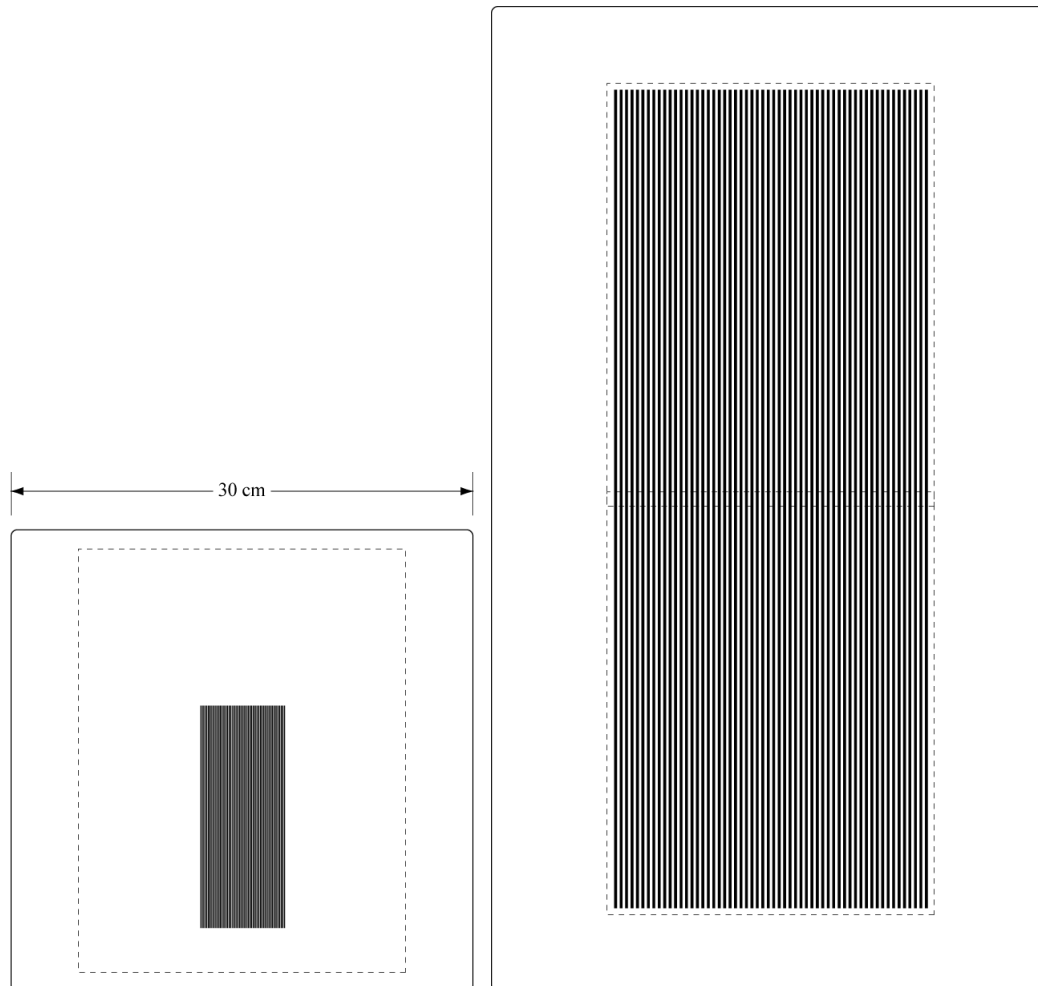


Figure 3: Schematic of the small and large stripe filters. The dotted lines indicate boundaries of single-page transparencies that are taped onto frames made of foam-core board.

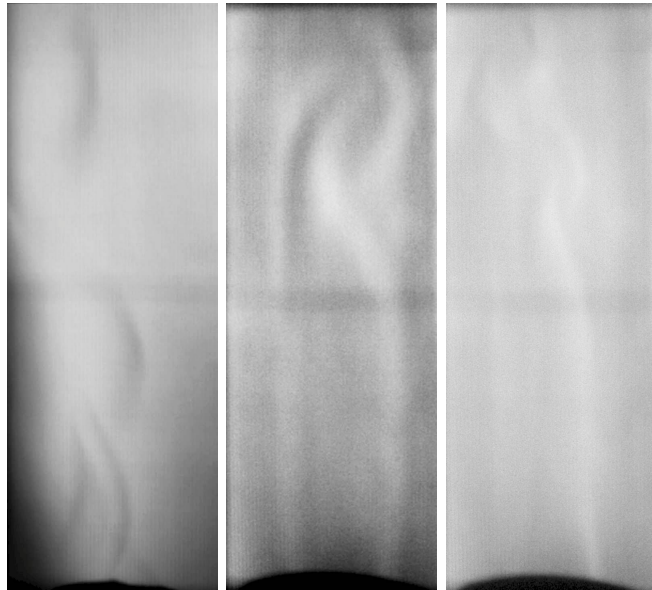


Figure 4: Projected images of convection currents above a tea candle.