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*Illusions with Plane Mirrors*



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### Cover:

Illusions with mirrors offer excellent ways to illustrate basics of geometrical optics. Our cover shows two images—a direct view of the doll through a half-silvered mirror slanted at  $45^\circ$  and a reflected image of dancers. (Photo by John Warner Photography.)

To learn more about illusions with plane mirrors, turn to the article by Michael J. Ruiz and Terry L. Robinson, which begins on page 206.



# Illusions with Plane Mirrors

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By Michael J. Ruiz and Terry L. Robinson

**I**llusions with mirrors offer excellent ways to illustrate basics of geometrical optics, especially for the nonscience major. Also, magic is becoming more popular among physics instructors as it offers many fascinating demonstrations, arousing the student's curiosity about the scientific principles involved.<sup>1</sup> If chosen carefully, illusions can stimulate interest in the fundamentals of optics, and physics in general. This article will review effective demonstrations with plane mirrors that appear in the literature and offer novel variations involving half-silvered mirrors. Ray diagrams will be provided for the latter arrangements.

Caution should be observed when discussing the physics of illusions since the workings of magic are traditionally kept secret. Students learning principles of optics through illusions should not be encouraged to divulge the secrets of illusions to everyone.

## Illusions with One Plane Mirror

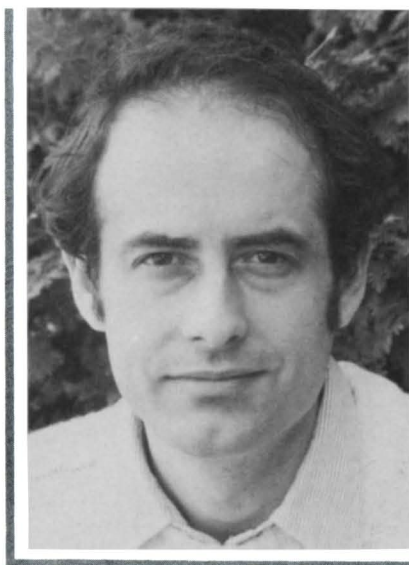
The virtual image formed by a plane mirror is often quite mysterious to the student. Many students insist that the image is in the plane of the mirror. Even after effectively demonstrating the location of a virtual image by aligning the virtual image of a ring stand with an actual

ring stand behind the mirror,<sup>2</sup> a student responds, "The image can't be behind the mirror because most plane mirrors are hung on walls." A clever variation of this demonstration matches a female face with the virtual image of a male body.<sup>3</sup>

The father-in-law of one of the authors was not convinced that the image was behind the mirror until he was able to focus a camera on a virtual image and read the camera-subject distance indicated by the camera. A demonstration can be performed where the virtual image of a meter stick, oriented along the normal to the mirror, is used to measure distances behind a mirror.<sup>4</sup> An artistic version of this last arrangement is found in a work of art by Robert Morris, where long wooden beams join their virtual images.<sup>5</sup>

A plane mirror placed diagonally in a box can create the illusion of an empty box where, in fact, objects may be concealed behind the mirror.<sup>6</sup> Rather than concealing objects, a similar arrangement with a piece of glass can be used to form reflected, ghost-like images (behind the glass)<sup>7</sup> or to transform a friend's face into a skull.<sup>8</sup>

A double-sided mirror placed along a diameter of a drinking glass (or beaker) can conceal a half-filled glass of small objects (filled to the top behind the mirror).



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When the glass is turned around, a glass full of objects appears.<sup>9</sup>

The symmetry obtained by placing the edge of a plane mirror along the center of a body can be exploited to create interesting effects.<sup>10</sup> In one case, an instructor's right arm is seen as the virtual image of his outstretched left arm, while the hidden right arm lifts a hat off his head.<sup>11</sup> An observer views with her face against the mirror at the opposite edge, blowing to raise the hat.

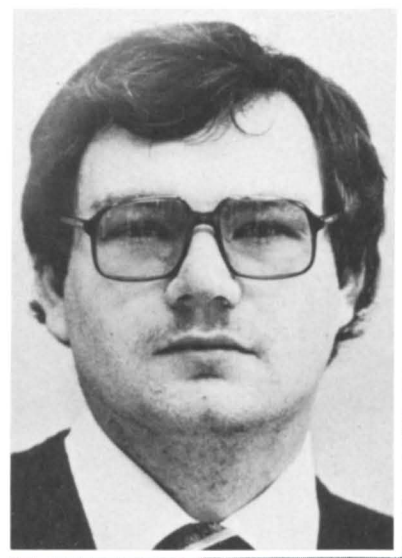
A half-silvered mirror both reflects and transmits light. Depending on the relative amounts of light available on either side, an observer can either see a reflected image or transmitted light from the other side. An observer's face can be transformed into another's using dimmer controls for each side.<sup>12</sup> One of the authors witnessed an impressive demonstration of this effect in the 1970s at the University of Maryland.<sup>13</sup> The demonstration consisted of a rectangular box divided into two sections by a half-silvered mirror, with a light bulb in each section. On each side of the half-silvered mirror was a circular opening for observers to place their heads. A student looked in one side while the instructor looked in at the other side. At the instructor's end were controls to vary the relative amounts of light emitted by the light bulbs.

A young student gave a startled cry as she saw her reflected image change gradually into the transmitted view of her instructor.

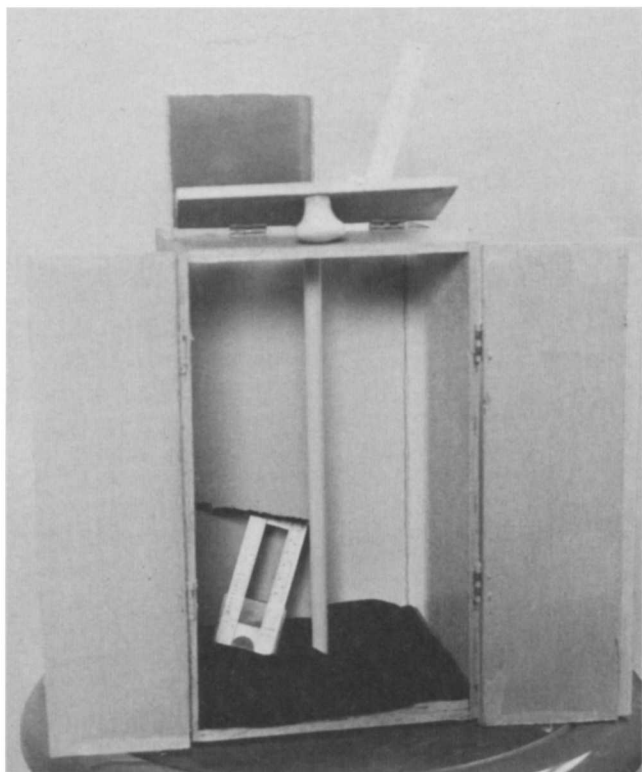
The authors have recently built this demonstration, along with others to be discussed in this article, for use in "Light and Visual Phenomena," a liberal-arts light course for the general student at UNCA.<sup>14</sup> A rectangular box, with dimensions 30 cm by 30 cm by 90 cm (open at each end), was built with 1/4-inch plywood (about 6 mm thick). A semicircular cut was made on the bottom board on each end so that observers can comfortably insert their chins. Black felt was nailed to the top at each end (to be pulled over each observer's head) in order to block out external light. A half-silvered mirror (nearly 30 cm by 30 cm) was placed in the center (45 cm from each end) during construction. A soft 50-W GE reflector light was installed in a socket mount facing down near the mirror on each side.

The GE reflectors are ideally suited because the emitted light is both soft and directional (in the forward direction of the bulb). Aiming the light down prevents light from shining directly into either of the observer's eyes. Dimmer controls are used to vary the intensity of the light bulbs. The entire apparatus is relatively

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**Fig. 1. Photograph illustrating a mirror principle employed in magic.**

inexpensive, with all parts readily available at local hardware stores and glass shops.

An elaborate box is not necessary to demonstrate the effect just described. A piece of glass can be used with laboratory variable transformers and lights to illustrate the same principle.<sup>15</sup> This latter arrangement is successful due to the reflective properties of glass.

A half-silvered mirror placed diagonally in a box can be used for magical transformations along similar lines. The object to be reflected must be concealed by limiting the angle of view permitted to the observer from the front. The object to be transmitted is placed behind the half-silvered mirror. By flipping a switch that controls the lighting in each section of the box, the object can be instantly transformed. The apparatus can be covered briefly with a passing cape while the light switch is flipped.

## Illusions with Two Plane Mirrors

It is well known that two plane mirrors with a common edge can produce a variety of multiple-image effects. The simple kaleidoscope is based on this principle. Specific cases where two mirrors form a right angle or are joined at  $60^\circ$  have previously been discussed.<sup>16</sup> Symmetrical patterns are achieved for angles of  $360/n$  degrees, where  $n = 3, 4, 5$ , etc. Two plane mirrors joined at an angle of  $360/n$  degrees, form  $n - 1$  images (placing the object as close as possible to the mirror vertex). If the real object is counted as an image (often

it is difficult to distinguish the real object from its virtual images), it may be stated that there are  $n$  images, and the formula is easily remembered. The case where  $n = 2$  reduces to the equivalent of one plane mirror ( $180^\circ$ ), in which case there is one object and one image. It is a challenge for the student to look into a simple kaleidoscope and determine the angle between the mirrors from the observed symmetrical pattern of images. However, beware of more complicated kaleidoscopes.

Two mirrors can be placed parallel to each other with an observer in between, creating the "hall-of-mirrors" effect.<sup>17</sup> Are there an infinite number of images? Student discussion can uncover the several reasons why the number of images must be finite.<sup>18</sup>

The periscope is a two-mirror construction. In the typical application of the periscope, light from above is reflected by the upper mirror down to the lower mirror, and into the eye of the observer. A magic trick, "The Penetrating Eye," is designed using a periscope.<sup>19</sup> The magician is covered by a metal barrel, after it is inspected. Once inside, he pulls out part of a periscope concealed in his clothing. He places the periscope tube in a small hole in the platform floor, thereby joining his section to the remaining part of the periscope built into the floor. The mirror in the platform floor is oriented at  $45^\circ$  with respect to the audience. He can then read numbers and messages from the audience, as the light enters at the bottom, reflects up the periscope tube to the upper mirror, and finally enters the eye of the hidden magician.

The contents in the rear portion of a rectangular box can be very effectively concealed by inserting two plane mirrors which join at the center of the box and extend to each of the rear corners. The angle spanned from one mirrored surface to the other is  $270^\circ$ . Fig. 1 illustrates such an arrangement. In Fig. 1, the left mirror has been raised somewhat in order to show the hidden object, in this case, part of an antiquated calculating device.

When the mirrors are fully in place, they reflect light from the sides of the box out to the audience. The audience observes the reflected sides, thinking that the rear wall of the box is being observed. Two reflected rays are illustrated in Fig. 2a. Note that a center post is inserted to camouflage the joining of the mirrors. The center post is notched out in the rear so that the mirrors will fit together conveniently. Black felt is placed on the bottom to conceal the bottom edges of the mirrors.

There is a hinged lid at the top, which allows easy access to the rear section of the box. The mirrors can be pulled out from above, and can be taped together to facilitate quick removal. When they are removed, the concealed object comes into view, as evident from the light rays in Fig. 2b.

One of the authors received such an apparatus in a magic kit for Christmas around 1960. The dimensions were comparable to those of the example seen in Fig.

1 (approximately 15 cm by 15 cm at the bottom and 25 cm high). The mirrors were taped together and could be easily removed from the top. During a demonstration, objects from the audience were tossed in from the top while the doors were closed. Then, the doors were opened to show that the objects had disappeared. Finally, the doors were closed once again, a magic veil thrown over the box, the veil removed (with the mirrors drawn up and hidden in the veil), and the objects mysteriously reappeared.

During a famous stage illusion employing the same mirror principle, an automobile vanishes.<sup>20</sup> The car is parked in a garage consisting of a wooden grid of spaced vertical beams with a roof. The car is easily seen through the spaces between the vertical beams. When it's time for the disappearance, mirrors slide out of the wooden slats filling the empty spaces. The side walls of the stage are designed so that the reflected light from the side matches the backdrop of the stage, with no car visible. A startling presentation of the effect is achieved when the car (with passengers) vanishes instantly right before the eyes of the audience—a strobe light is used to conceal the brief motion of the mirrors.<sup>21</sup>

#### An Illusion with Two Half-Silvered Mirrors

The illusion illustrated in the series of photos and diagrams in Fig. 3, 4, and 5 consists of a rectangular box with dimensions 30 cm by 30 cm at the base and approximately 50 cm high. There are two half-silvered mirrors (HSM) in the construction, one along the diagonal and one at the front side. The diagonal mirror is placed so that a picture attached to the right wall (when looking in through the front half-silvered mirror) will reflect out toward the front observer, given the appropriate lighting conditions.

There are two light bulbs in the box, labeled A and B in Fig. 3b, 4b, and 5b. These three figures are top views, for the purpose of ray-tracing analysis. Light source A is a 50-W GE reflector light, and source B is a 150-W GE spot light. Source B is more powerful since it needs to supply enough light to penetrate two half-silvered mirrors in order to reach the observer looking in from the front. The reflector light, A, is aimed at the picture, P, on the right wall, while the spotlight, B, is directed at the doll, D, which is enclosed in a glass case at the rear of the box. The light sources are positioned above the mirror, high enough to be concealed.

There are three basic modes of light settings for viewing 1) reflections from the front mirror showing virtual images of external objects, 2) the picture in the box, and 3) the doll in the box. Fig. 3 illustrates the first case. Light sources A and B are turned off so that the front half-silvered mirrors acts like a typical mirror. See Fig. 3a for a photograph made under these conditions. Notice that in the ray diagram of Fig. 3b some light enters the box, a portion of which is reflected and

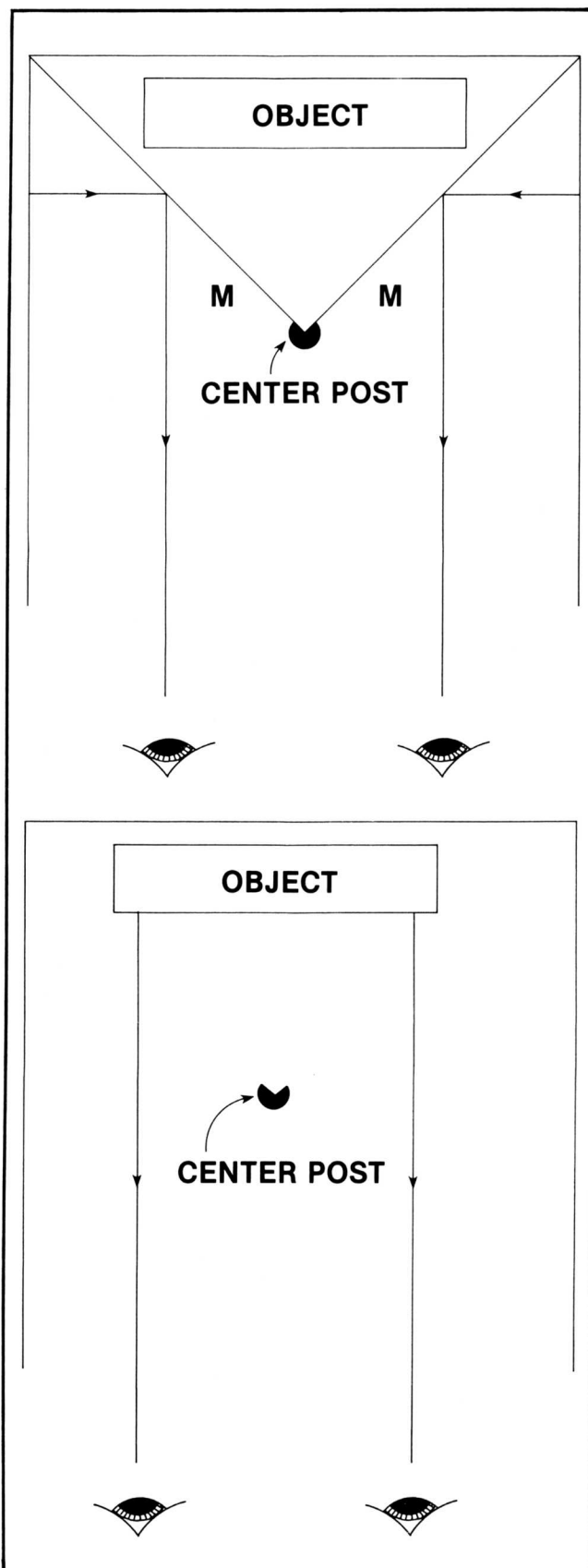
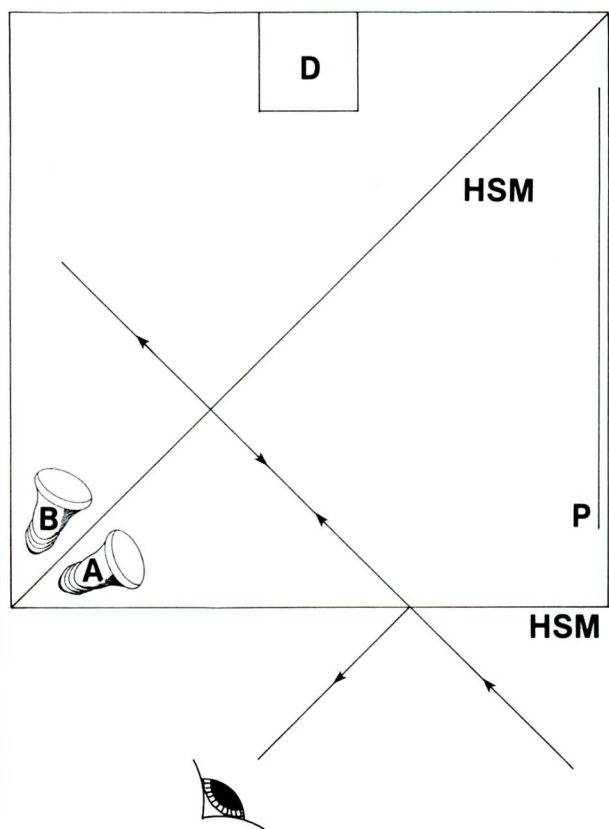
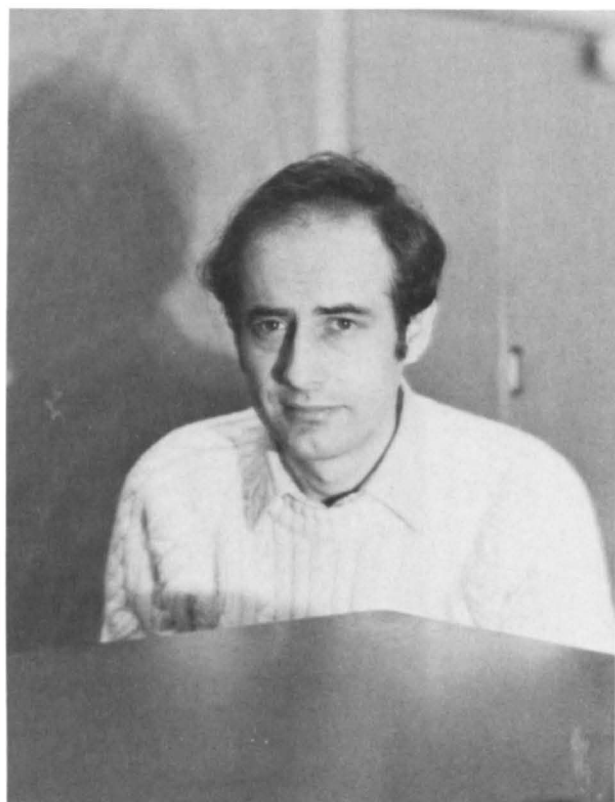


Fig. 2a. (top) Ray diagram indicating how the mirror principle is used to conceal an object. Fig. 2b. (bottom) Rays from object reaching observer since mirrors in Fig. 2a have been removed.



**Fig. 3a. (top) Photograph of virtual image due to external room light and half-silvered mirror on front of box. Fig. 3b. (bottom) Observer viewing reflected light from front half-silvered mirror since sources A and B are turned off.**

transmitted at the diagonal mirror. If one shines a light in through the front half-silvered mirror, much light will enter the box and an appreciable amount will leak out, revealing the picture, doll, or both.

The photograph in Fig. 4a was taken with source A on and source B off in a darkened room to eliminate external light totally (see Fig. 4b). Light from A illuminates the picture, P, a virtual image of which is formed by the diagonal half-silvered mirror. The picture appears to be on the rear wall of the box. Notice that some light is transmitted by the diagonal half-silvered mirror and some light is reflected by the front half-silvered mirror. If you look carefully at the packing material on the floor in Fig. 4a, you will observe that some of the objects appear dimmer than those in the foreground. This is because some light is lost behind the diagonal half-silvered mirror due to transmission. The light transmitted toward the back of the box cuts down on the amount of light reflected to the front observer. However, grazing angles of incidence give relatively brighter virtual images. This feature can give away the fact that a diagonal half-silvered mirror is present. For demonstrations, replacing the white packing material with a dark material provides for a more uniform floor appearance.

The photograph in Fig. 5a was taken with source B on and source A off in a darkened room (refer to Fig. 5b). The doll can now be seen. Fig. 5b illustrates transmitted and reflected light rays at each half-silvered mirror. Notice that a faint image of the picture is superimposed in Fig. 5a. Stray light from source B passes through the half-silvered diagonal mirror, illuminating the picture, P. Light from the picture eventually gets to the observer after reflection (at the diagonal mirror) and transmission (at the front half-silvered mirror). Black pieces of construction paper, taped on the rear wall, are visible in Fig. 5a. When the picture is observed under the lighting conditions in Fig. 4, the construction paper is not seen because the rear wall of the box is not illuminated.

It is very effective to turn on B gradually as A is dimmed, using variable controls, so that the three-dimensional doll mysteriously appears. With dimmer controls, a great number of light settings is possible, and many superimposed-image effects may be achieved.

## An Illusion with Several Mirrors

The illusion illustrated in Fig. 6 is a variation of an old trick called the "X-Ray Machine."<sup>22</sup> To obtain the configuration for this illustration, replace the half-silvered mirror in Fig. 6 with a regular plane mirror. In a toy version of this trick, a coin is inserted from the top (see Fig. 6) and the observer peers right through the coin, acquiring "x-ray" vision.

The variation given in Fig. 6 replaces one of the mirrors



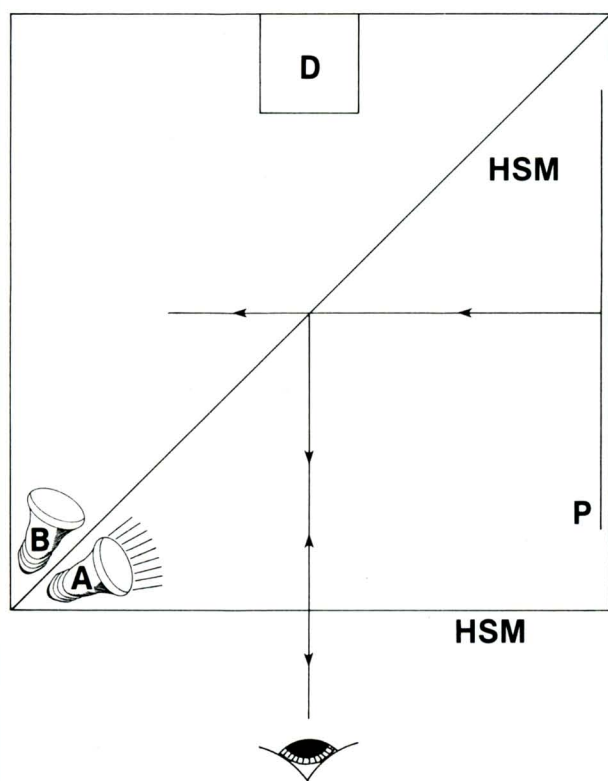


Fig. 4a. (top) Photograph of virtual image of picture, P. Fig. 4b. (bottom) Observer viewing reflected image of picture, P, due to illumination from source A; B is off.

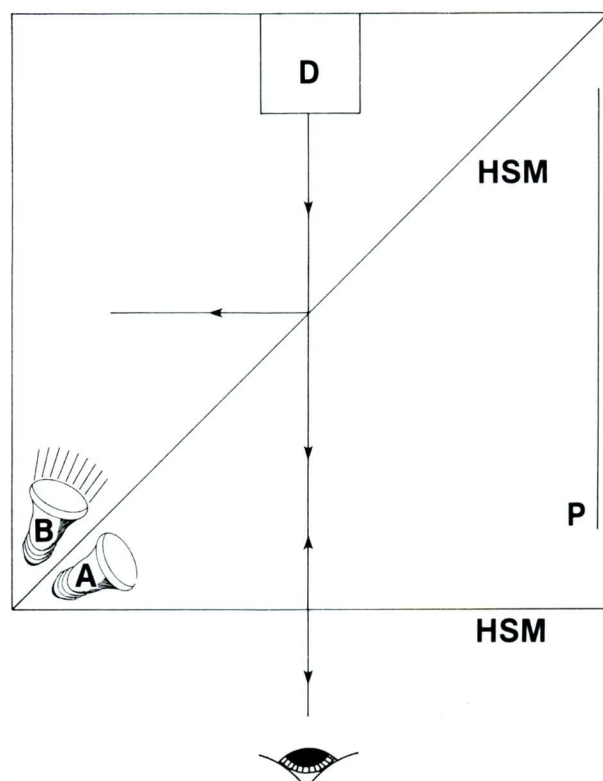
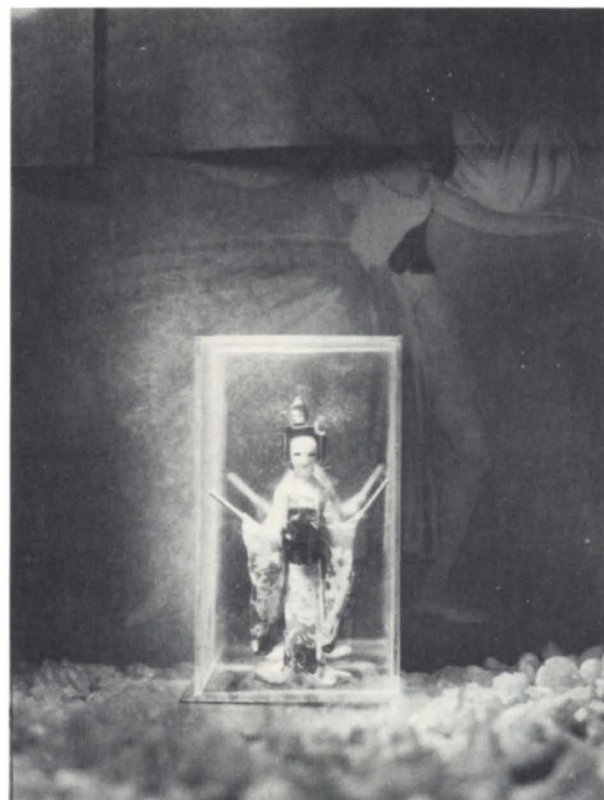


Fig. 5a. (top) Photograph of doll, D. Fig. 5b. (bottom) Observer viewing doll, D, illuminated by source B; A is off.

with a half-silvered mirror and adds a light source to illuminate the inserted object. A black cloth can be used to block light coming from outside sources at the far right. An observer can then view the inserted object without interference from external objects. As the observer is watching the object in the box, the light source can be turned off and the black cloth raised simultaneously. Suddenly, the observer can see right through the object previously observed. In constructing this demonstration, good quality mirrors should be used with minimal optical path lengths. Also, an extended tube at the far left for viewing (see Fig. 6) may be necessary to prevent the observer from seeing light directly from the mirrors below.

## Concluding Remarks

This article has given a brief review of simple illusions that can be created using plane mirrors. Such illusions stimulate student interest and can serve as fine examples to illustrate some of the basic principles of geometrical optics. They are very appropriate in general physics courses for the nonscience major where, often, a whole range of interdisciplinary topics is covered. This is especially true for nonmathematical courses where light is a main theme. The demonstrations are easily constructed with relatively inexpensive materials found in local hardware stores.

## Acknowledgments

The authors would like to thank Rick Frizzell from the Graphics and Publication Office at UNCA for reproducing the ray-tracing figures. □

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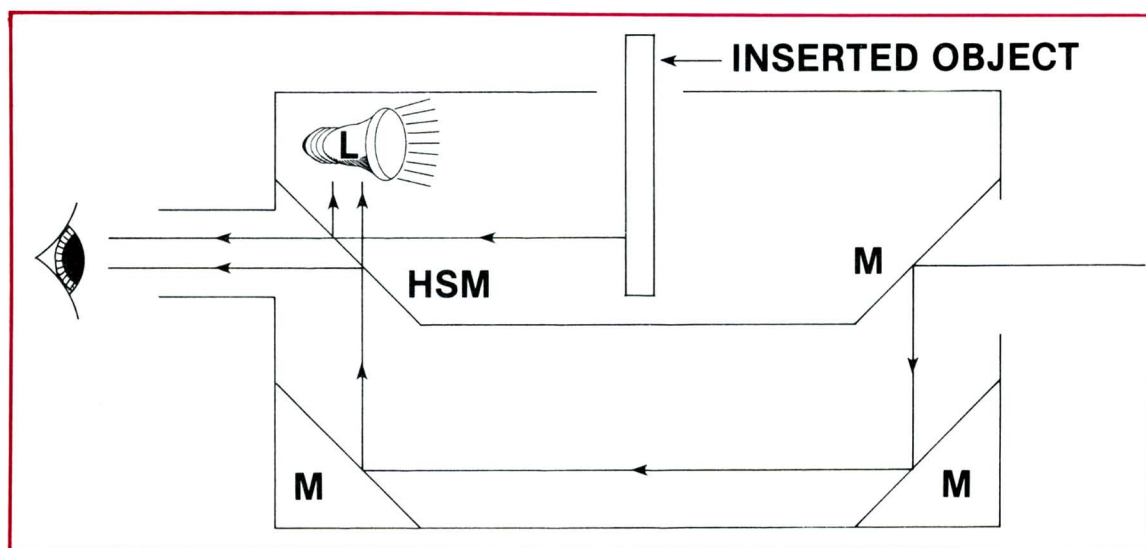


Fig. 6. A variation of the old trick, the "X-Ray Machine," where one of the four mirrors is replaced by a half-silvered mirror.