Welcome to the Wonderful World of 3D

I would like to invite you to explore the wonderful world of three-dimensional imaging. Our tour begins with this article, which explains how optics can be used to create 3D illusions. Subsequent articles in this series will provide step-by-step instructions for generating such images for yourself. My goal is to provide the utmost information using only simple, readily available materials. The rest is up to your imagination.

Kurt Wenner, Reflections, Grazie di Curtatone, Italy, 1987
In this magnificent street painting, Kurt Wenner created the illusion of depth in a pool by applying perspective to the reflections of the square stepping stones and the bodies, whose upper portions are drawn smaller than the lower ones. Wenner transformed the art of street painting through his use of the anamorphic technique—which creates a striking 3D effect when viewed from a certain perspective; it is the same approach that Michaelangelo and others used to make angels appear to float on chapel ceilings. Wenner’s work was first highlighted in “Masterpieces in Chalk,” a National Geographic Explorer documentary. For more information, visit www.KurtWenner.com.
One of the most effective means for achieving a 3D effect is by exploiting parallax—the way our left and right eyes view the same scene from two slightly different directions. The parallax effect enables most people to see 3D images. However, a small percentage of people who have poor binocular fusion cannot see the 3D effect using parallax alone. This situation is analogous to color blindness, in which some people cannot see certain colors.

As an example of how parallax works, consider a ball that lies directly in front of a viewer’s line of sight (see the figure above). The left eye sees the ball to its right, while the right sees the same object to its left. The viewer’s brain uses the information from both eyes to help judge the distance between the viewer and the ball.

You can attempt to fool the brain into seeing a 3D image on a 2D surface by using two pictures of the ball on a projection plane. The view from the left eye is projected onto the right-hand side of the plane, while that from the right is projected onto the left side. (In other words, the images are transposed.)

The light paths between the center-crossing point and the eyes are the same as the paths that would have been created by the actual ball. To the eyes, whether the line started from the object or from the projection plane does not make a difference, as long as the light looks as if it is starting from the object. The eyes perceive the object as if it were at the original location.

Simply drawing two ball pictures on a projection plane from the left and right views is not enough to create the illusion that the ball exists off the plane, however. Instead, the viewer will see a picture of two balls side by side because each eye sees both pictures on the projection plane, as indicated by the solid-line traces and the dashed-line traces in the figure.

Thus, to make the ball appear to exist off the plane—in three dimensions—each eye must be permitted to see only one picture of the ball. In other words, the parallel path (dashed-line) in the figure must be blocked while the crisscrossed one (solid-line) remains within view.

If you were to block only the dashed-line traces, you would find that the picture becomes instantly three-dimensional. One way to accomplish this would be to block the dashed-line traces with a piece of paper or a piece of tape, while leaving the solid-line traces visible. Another way would be to use a special pair of glasses that block the dashed-line traces but allow the solid-line traces to pass through.
this is by wearing a pair of horse blinder glasses, as shown in the figure above, left. You can make these yourself out of cardboard by cutting the top, bottom and innermost sides of each central square “lens,” and creating a window by pushing the square open by about 30 degrees—which is just enough to block the dashed line trace but not the solid one.

**Using polarized light**

All the methods for achieving 3D displays using the parallax effect boil down to finding ways to block the parallel path while passing the crisscross one. Another way to accomplish this is by using polarized light. Some convenient sources include the light from the liquid crystal display of a laptop computer screen, camera phone or digital video camera recorder (camcorder).

The polarization direction depends on the manufacturer. For the arrangement shown in the figure above on the right, the light is assumed to be vertically polarized. To create a 3D illusion, cover the right half of the screen with cellophane (25 µm thick), which rotates the direction of the polarization by 90°, so that the image on the left half is polarized vertically, while that on the right half is horizontally polarized.

If the viewer wears a pair of orthogonally polarized glasses with a horizontally polarized eyepiece over the left eye and a vertically polarized eyepiece over the right, the viewer’s left eye can see only the right half of the screen, while his or her right eye sees only the left half. The result is that the parallel paths are blocked by the glasses, while only the desired crisscross paths reach the viewer’s eyes.

Eye fatigue is a common concern with all 3D displays. It tends to occur if the point of accommodation is located at a different place from the point of convergence. (See the text box on p. 46 for definitions of accommodation and convergence.) With the projection type of 3D imaging, the point of convergence is located between the projection plane and the eyes, whereas the point of accommodation is located on the projection plane.

A set of prisms with a 3° deviation angle can be used for the purpose of translating the formed 3D image to the plane of the projection without distorting it. The points of convergence and accommodation now coincide, thereby relieving
eye fatigue. The addition of the prisms aids binocular fusion as well.

3D movies are also made by means of polarized light. Two movie projectors are used to create the effect: One vertically polarizes the picture while the other works horizontally. The projected light is polarized using a polarizing beam splitter.

The position of the projection screen almost coincides with the location of the 3D image. The audience wears polarizer glasses with one eyepiece polarized vertically and the other horizontally, so that each eye sees only the picture of the specific polarization. As in the case of the liquid crystal displays, a crisscross path is established.

The Brewster’s and Wheatstone stereoscopes

For this approach, the plane of projection coincides with the 3D image plane. As shown in the figure on the facing page, the picture viewed from the left is placed on the left, while that viewed from the right is put on the right. A pair of prisms is used to shift a side-by-side stereoscopic pair of images toward the center, where the two images meet.

The merits of Brewster’s method are not only simplicity of construction, but also a lesser degree of eye fatigue because the position of convergence is situated close to that of the accommodation of the eyes.

How does this arrangement generate a three-dimensional image? You can discover the answer by focusing on the movement of a particular point of the image. For example, concentrate on the point where the color bands of the ball converge, which we will call the “navel” of the ball. The navel of the right image \( R \) is denoted by \( r \), and the corresponding navel of the left image \( L \) is denoted by \( l \). The combined image in the center reveals how these two points move. The red line connecting point \( r \) to the right eye and the red line connecting point \( l \) to the left eye form the crisscross light path.

As a result, the points represented by \( r \) and \( l \) are seen as one point located at the intersection \( c \), which is lifted above the
plane of the pictures. This type of image is sometimes referred to as a “pop-out” because of the sensation that the image is bursting toward the viewer.

With the Wheatstone stereoscope, views from the left and right eyes are posted on the left and right vertical walls, and a set of vertical mirrors creates the superimposed stereoscopic images in the center. In the figure, notice that the mirror upsets the orientation of the left and right images. The pictures have to be oriented so that the images $L$ and $R$ reflected by the 45° mirror are oriented properly.

Similar to Brewster’s stereoscope, the points $l$ and $r$ are connected to the respective eyes in red lines. The points converge to make a pop-out image at point $c$.

The anaglyph

The anaglyph uses complementary colors to separate the views from the left and right. For example, if the left and right views are converted into a red and green colored stereoscopic pair of images, the image is viewed by wearing a pair of glasses with red and green filters. Like the Brewster’s method, the merit of the anaglyph is that the locations of convergence and accommodation of the eye coincide, resulting in much less eye fatigue. A disadvantage is the loss of color information of the scene.

Focus your attention on the viewer’s right eye in the figure above on the right. Since the eye is covered with a red filter, the green light from the stereoscopic image is incident on this eye and thus does not reach it. As a result, the green lines appear as dark lines to the viewer. On the other hand, when the light from the red stereoscopic image is incident to the red filter, it passes into the eye as red lines; at the same time, the white light background also becomes red after passing through the filter.

As a result, the red lines, no longer distinguishable from the background, disappear and the eye covered with the red filter can recognize only the green image as a dark line-sketch. Similarly, the left eye can recognize only the red lines. The navel of the ball viewed from the left is connected to the left eye of the viewer, and the same point viewed from the right is connected to the right eye. As with both Brewster’s and Wheatstone’s stereograms, a pop-out image is formed at point $c$.

Like the Brewster’s method, the merit of the anaglyph is that the locations of convergence and accommodation in the eye coincide, resulting in much less eye fatigue. A disadvantage is the loss of color information of the scene.
Head-mounted displays are commonly used to train professionals in the fields of aviation, medical operations and military maneuvers.

Time sharing and head mounts
The time-sharing method requires the viewer to wear glasses with a liquid crystal optical switch that can be turned on and off. A monitor is used to display the left and right images alternately in time. The switch on the glasses turns on and off to separate the two pictures. When the monitor is showing the left view, the glasses’ right eyepiece shuts off, and vice versa for the right view.

A typical switching cycle is kept at about 120 Hz in order to avoid flickering. This method has the advantage of using the whole screen. The downside is the complexity of the scheme and the necessity of having to wear the viewing glasses.

With a head-mounted display, two liquid crystal displays for each eye are installed onto goggles, so that the stereoscopic pictures are directly displayed to each eye. A set of lenses are added to create the illusion of viewing a wide scene. The electrical signal from the head tracker changes the display in accordance with the head’s movement.

Head-mounted displays are commonly used to train professionals in the fields of aviation, medical operations and military maneuvers. They are also used for architectural displays and entertainment. Prolonged use may create strain on the head and neck muscles.

Interception display
Thus far, all the approaches described have rendered 3D images that appear to have been projected in front of the plane. With the “interception” type of 3D display, the constructed 3D image appears behind the interception screen.

For this method, the view from the left eye should be placed on the left-hand side of the picture plane, and that from the right eye, on the right-hand side. There is no transposition of the images. The crisscross path shown in green dotted lines in the figure has to be obstructed by an optical fence and there is no transposition of the image in this case. The 3D image is located at the intersection of the lines projected from the eyes toward the images on the screen. Hence, the wider the separation of the two images, the deeper the generated 3D image.

The projection method usually produces a more dramatic 3D effect because

>> Milestones in 3D Imaging

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>280 B.C.E.</td>
<td>Euclid of Greece recognizes that simultaneously looking at slightly different scenes of the same object, as viewed from the left and right, produces a 3D effect.</td>
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<tr>
<td>1600</td>
<td>Giovanni Battista della Porta of Italy tries to create a 3D image by arranging pictures of objects viewed from the left and right.</td>
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<td>1838</td>
<td>Sir Charles Wheatstone of England demonstrates a 3D display using mirrors to combine stereoscopic images.</td>
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<tr>
<td>1849</td>
<td>In Scotland, Sir David Brewster uses a set of prisms and convex lenses to combine stereoscopic pictures.</td>
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<td>1853-8</td>
<td>Wilhelm Rollman of Germany demonstrates the anaglyph, which was further developed by Joseph D’Almeida of France five years later. In an anaglyph, left and right views are drawn in complementary colors, one over the other, in the same plane. The viewer wears glasses made of these colors.</td>
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<tr>
<td>1895</td>
<td>British scientist John Anderton obtains a U.S. patent for his “magic lantern,” in which a polarizer such as a Nicole prism is installed to project polarized light onto a screen. Viewers had to wear cumbersome glasses of polarizing beam splitters.</td>
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<td>1903</td>
<td>F.E. Ives of the United States invents the parallax barrier, an opaque screen that has an array of strategically spaced fine slits. It is placed over the stereoscopic pictures and aligned so that a particular slit matches the line of sight of one of the viewer’s eyes but not the other.</td>
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the image is pushed out of the screen toward the viewer. The interception plane is not necessarily between the eyes and the 3D image. Often, the plane of the interception is placed almost in the same location as the 3D image plane. In this way, it has the previously mentioned advantages of lessening eye fatigue and improving binocular fusion because there is less displacement between the points of accommodation and convergence.

**Parallax barrier stereogram**

The stereogram for the parallax barrier method is made by interspersing the left and right views, which are sliced into columns. As shown in the figure on the next page, only even-numbered columns are used in the left view and only odd ones are used in the right; the rest are discarded. The parallax barrier stereogram is fabricated by interspersing the columns of the two views into one sheet.

A parallax barrier sheet separates the left and right views in the parallax barrier stereogram. The barrier is an array of narrow slits on an opaque sheet. In the vicinity of any slit, there is always a small region that only the right eye ray can reach (let’s call this region the right column) and a small region that only the left eye ray can reach (let’s call this region the left column). Even-numbered columns can be seen only by the left eye and the odd-numbered columns can be seen only by the right eye. A particular column that matches the line of sight of one of the viewer’s eyes does not match the line of sight of the other eye.

The approximate point of the navel $r$ of the ball is connected by the heavier green line to the right eye, and the corresponding point $l$ is connected by the heavier green line to the left eye. With the “interception” type of 3D display, the constructed 3D image appears behind the interception screen.

**1908-30**

The lens sheet method is proposed by Gabriel Lippmann of France and further developed by H.E. Ives (son of F.E. Ives). An array of cylindrical lenses called a lenticular sheet is placed over an array of slits wider than parallax barrier slits.

**1935**

Polaroid founder Edwin H. Land replaces cumbersome glasses of polarizing beam splitters used in Anderton’s magic lantern method by a pair of glasses of polarizer sheets.

**1948**

The idea of the hologram is conceived by Dennis Gabor of Hungary. (Later, in 1971, Gabor wins the Nobel Prize for his invention.)

**1967**

Alan Traub invents the varifocal mirror. The mirror material is evaporated over a thin membrane to form a concave mirror. The membrane is then stretched over a cup whose radius of curvature is varied by controlling the degree of vacuum in the cup. An image is produced by relaying image components at varying focal lengths.

**1968**

The white light hologram, which does not require a laser to be viewed, is invented at the Polaroid Corporation by Stephen A. Benton. Also this year, Ivan Sutherland develops the head-mounted display needed to create a 3D movie.

**1985**

JVC of Japan markets a 3D-display system that uses a time-sharing method. The left and right images are displayed alternately in the same monitor. The observer sees the respective views by wearing glasses whose left and right views are switched by liquid crystal optical switches.
A drawback of the parallax barrier method is that the viewer’s position is rather restricted. Moreover, even when a person’s head moves within this restriction, the image does not change, resulting in an unnatural look to the 3D image.

The lenticular sheet method has the advantage of not requiring glasses, but it has the following drawbacks. Not only does the resolution of the 3D image become half of the original, the brightness is also reduced by half. It is preferable to use backlit illumination, such as that from a computer monitor. An additional drawback is that it requires critical relative positioning of the viewer’s eyes, barrier sheet and stereogram.

Horse blinder barriers and lenticular sheet method

This scheme works on the same principle as the horse blinder method described earlier—except in this case, the screen wears the blinders rather than the viewer. On top of the stereoscopic pair of images, a series of slanted blinds is installed. Similar to Venetian blinds, this arrangement channels the transmitted light from the stereoscopic pair of images toward the appropriate eye of the observer. One advantage that this method has over the parallax barrier method is that the size and spacing of the blinds can be adjusted as the image is viewed.

A drawback of the parallax barrier method is that the viewer’s position is rather restricted. Moreover, even when a person’s head moves within this restriction, the image does not change, resulting in an unnatural look to the 3D image. The lenticular method helps to correct deficits posed by the parallax barrier method by replacing the slits of the parallax barrier sheet with an array of convex cylindrical lenses—a lenticular sheet. This makes the left and right views into smaller images by the converging lenses, and the views are small enough to accommodate more than one in each column.

As shown in the figure, each column is divided into three sampled sub-columns of the images taken by three sets of left and right TV cameras. The viewer’s left and right eyes see sub-column 2 and 5 made from the images taken by TV camera 2 and 5, respectively. If the viewer moves his head to the right, he or she sees sub-column 1 and 4 made from the images taken by TV camera 1 and 4, which are located to the right of camera 2 and 5.

The viewer can see a new view from the cameras shifted to the right in real time. Moreover, the viewer sees a 3D image in real color without wearing glasses and the 3D image appears more natural.
Integral photography

3D imaging by integral photography (IP) has much in common with the lenticular sheet method. Integral photography takes the stereogram by using an array of fly’s eye lenslets, which is equivalent to a much larger number of cameras than the six that were used for the lenticular method. Usually, the same lenslet array that was used for taking the stereogram is used for viewing the 3D image.

Integral photography involves two-step processing of the imagelets. As the first step, the prime IP stereogram is taken using a fly’s eye lens sheet. This stereogram is an array of the real images of the object that differs from the adjacent imagelet by a perspective shift of the lenslet diameter. Each real image is inverted.

In the second step, each image is individually inverted by a 180° rotation. This process creates the secondary IP stereogram with an array of correctly erected images. The same fly’s eye lens sheet is placed in front of the secondary IP stereogram to view the 3D image.

How do such imagelets, which superficially look redundant, converge into one big 3D image? Consider the ray paths of the zeroth and third imagelets of the particular row of the IP stereogram. This figure demonstrates how the virtual images of these two imagelets grow into one big 3D image as the distance between the stereogram and the lens sheet increases. Not only is the distance $x$ to the virtual images increased but the size of the images is enlarged at the same time and the adjacent images start overlapping each other.

The correct amount of overlap can be determined by observing the overlap of a particular point in both images. For instance, in the figure (above, right) the images of the eye in the two imagelets overlap. This is the desired position $x=b$ of the virtual image. The second part of the figure shows the amalgamated virtual imagelets of one entire row. The most significant advantage of this method is that the 3D image can be viewed without having to have the eyes horizontally oriented.

Now that you have learned how 3D imaging works, you can have fun performing the experiments yourself. Stay tuned for my next three articles, which will show you how.

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