[1] Despite being photographed outdoors in full sunlight, a 160-mm-diagonal, color cholesteric liquid-crystal display, built with off-the-shelf electronics for demonstration purposes by Kent Displays Inc., shows a bright image. The image is produced by reflected light, not backlighting, and no power is needed to hold the image on the screen.

KENT DISPLAYS INC.

A bright new page in portable displays

IT WOULD BE A LOT EASIER to read a laptop display if the information on it looked as if it were printed on paper, as in a newspaper or magazine. The backlit screen would not wash out in bright light, but would look even brighter. One could view the screen from any angle and still be able to read it. Text and images would be sharp and details would be clear. And what if, as a bonus, the display consumed no power while it was being read?

Sounds good, doesn't it? Well, a trio of displays being developed will do all that. The goal is for them to look and work like paper. They reflect ambient light and retain images indefinitely, rather than rely on back-lighting and screen refreshing as a laptop's display does, so they need not consume power to be readable. And they can be read from any angle, because they reflect light evenly in all directions, a property referred to as Lambertian reflection.

GREGORY P. CRAWFORD
Brown University

FIRST UP

Of the three new displays, the closest to hitting the market is a liquid-crystal display (LCD) from Kent Displays Inc., Kent, Ohio. Called cholesteric because the liquid-crystal material it uses was originally derived from animal cholesterol, this LCD will be a full-color screen, 160 mm on the diagonal [Fig. 1]—or just a bit larger than today's Pocket PC screens. It also has a different kind of twist. Each color pixel in the display consists of a red, a blue, and a green cell stacked on top of each other, instead of side by side as in today's full-color laptop LCDs. Result: the new LCD's resolution can be three times better than that of current laptop displays and brighter, too.

The other two displays are based on entirely new concepts of how an electronic screen should work. One is the Gyricon from Xerox Corp.'s Palo Alto Research Center (PARC) in California, which can be rolled up into long sheets and cut by designers to fit the application [Fig. 2]. Its pixel is a tiny globe with one black and one white hemisphere. Suspended in oil and sandwiched between two thin sheets of clear plastic, these 100-µm-diameter spheres make a display that is only 200 µm thick—about the thickness of a human hair—yet as tough as plastic kitchen wrap.

E Ink, the third type of display, is being developed by the eponymous E Ink Inc., a Cambridge-based spinoff of the Massachusetts Institute of Technology (MIT). Even thinner than the Gyricon, it uses small transparent spheres filled with a liquid blue dye in which white chips float. To construct the display, the 30-µm-diameter spheres are packed tightly together between two plastic sheets, resulting in a display with half the thickness and potentially three and a third times the resolution of the Gyricon. But it is the 160-mm Kent LCD that is being delivered this month to equipment developers. A version twice that size—large enough to display this page in full—is expected within the next 18 months.

Production units for the other two types of display are not expected for at least a year. These first units will be black and white or an extremely dark blue and white, depending on the type of display. It is not clear whether it will be possible to make full-color versions of either the Gyricon or E-ink display, but the monochrome screens should cost much less than Kent Display's LCD, whose liquid-crystal material is relatively expensive.

Coming to market with an initial price of US $300 in quantity, the Kent LCDs could eventually cost as little as $50–$100 apiece. On the other hand, Xerox claims its Gyricon display, whose globes are made of an inexpensive waxy plastic, could cost "just pennies per foot." But to mass-produce either the Gyricon or E ink display, new manufacturing equipment and techniques must be developed, so the cost of producing them is not really known yet.

THE PAPER CHASE

What prompted development of these new displays was the inability of current technologies to provide a good-looking display while meeting the low-power requirements of today's, and tomorrow's, portable electronics. Attempts to reduce power consumption by creating full-color reflective instead of backlit LCD designs have met with failure [see "Why not reflective LCDs?", p. 42]. Even monochrome reflective LCDs, used today in such products as Palm Inc.'s personal digital assistant (PDA) and Handspring Inc.'s Visor PDA, are far from ideal; Handspring's founder, Jeff Hawkins, refers to them disparagingly as being "gray on gray."

On the other hand, the high-contrast, backlit displays of the new full-color Pocket PCs limit the time they can be used to 5 hours or so, after which these handhelds need to be plugged in and recharged. Besides, neither of these display types have paper's ideal light-handling qualities and high resolution. In fact, emulating paper's optical properties with any kind of display is a formidable challenge.

Paper has many superior optical qualities. It can reflect about 80 percent of the light that hits its surface (so-called photopic reflection), it can provide satisfactory contrast (ratios approaching 20:1), and it disperses reflected light evenly in all directions (Lambertian reflection). It is also inexpensive, robust, flexible, and foldable, and can provide full-color images. What's more, paper retains images for long periods without consuming any power. It has long-lasting memory.

Three new types of displays might make mobile devices the best way to get your newspaper

XEROX CORP.

[2] The Gyricon display material developed by Xerox Corp. at its Palo Alto Research Center is flexible enough to be manufactured in rolls, opening the possibility of creating displays that fold. A close-up of the material [inset] reveals tiny (about 100 µm in diameter) black and white spheres between its clear plastic outer skin. Images are transferred to a display by selectively orienting the balls using an electric field.

Why not reflective LCDs?

One question that often arises is this: why not simply adapt conventional liquid-crystal displays (LCDs) to a reflective mode of operation? While the backlit twisted nematic (TN) LCDs used in laptop computers have evolved into highly capable full-color devices, inherent shortcomings hamper their use in reflective mode.

Granted, reflective displays have been made by backing LCDs with foil. But this approach seems acceptable only for simple, directly addressed alphanumeric and very low-resolution displays, such as those used in inexpensive digital watches and children's toys like the Yamaguchi figures. Attempts to use this approach for full-color displays, where active-matrix drive schemes are needed to speed addressing and provide high resolution, have been stymied by poor reflectance.

This is because twisted nematic LCDs use polarizing filters and a mosaic array of red, green, and blue filters for each pixel. Polarizers selectively filter the backlight to illuminate a combination of color pixels to achieve full color; the technique is known as spatial color synthesis. However, the filters absorb a great deal of light and, in the reflective mode, this absorption is doubled because light must pass through the filters twice. Unlike backlit LCDs, where an increase in power to the backlight can compensate for light losses in the display, reflective displays can only provide high reflectance and good color selectivity through highly efficient use of the available ambient light. Coupled with the fact that they require power to retain information, that is, they are not bistable like all the other technologies discussed, twisted nematic LCDs are not suitable for color reflective displays. *—G.P.C.*

But paper does have disadvantages. It is unable to instantly change images and text the way an electronic display can, and thus cannot be reused quickly over and over. It is this inability that opens the door for the new electronic displays.

Apart from the need for high, even reflectance, the ability to retain images without using any power is the most challenging criterion that an ideal portable electronic display must meet. To do so, the reflective displays now in development make use of materials with bistable memory. Because the materials are stable in two different states, reflective and nonreflective, they need no power to continue displaying images and text, only to change them.

All the new displays are intended for electronic newspapers and books, as well as for information signs on, say, billboards, and for point-of-sale displays in stores. They could also be used to replace conventional displays used for laptop and desktop computers. But for full color, only the cholesteric LCD can serve today.

PITCHING HELICES

Kent Displays has been working on its LCD technology since 1993. While it can be manufactured in much the same way as the twisted nematic (TN) LCDs commonly used in laptop computers, the cholesteric LCD operates in a completely different way.

The TN LCD is composed of many full-color pixels, each of which contains three subpixels: one for red, one for blue, and one for green. Each subpixel is a sandwich composed of liquid-crystal material between two polarizing filters, oriented so that their light-filtering orientations are at 90-degree angles to each other.

The polarizers would block the light that tried to shine through them were it not for the twisted structure of the liquid crystal. The twisted structure rotates the light 90 degrees, letting it pass through. But if it is subjected to an electric field, the liquid-crystal material aligns itself in parallel with the field—it untwists. Therefore the light is absorbed completely by the second polarizer. Switching the liquid crystal between the twisted and field-aligned state transmits or blocks light from the light source behind the LCD.

In a full-color twisted nematic display, a red, green, or blue filter is placed over each of the subpixels that make up a single pixel. Turning on the subpixels with voltages of varying amplitude blends the red, green, and blue to produce various hues and tones, a process referred to as additive color.

Like the twisted nematic LCD, the cholesteric LCD works on the principle of additive color. Also like the TN LCD, it uses transparent electrodes made of indium–tin oxide (ITO) above and below each element to control the pixel's state. (ITO is the conducting electrode of choice for many display applications because of its low resistance and high transparency.) But the similarity ends right there. Rather than allowing light to pass through a subpixel and a color filter, cholesteric displays reflect light. By selectively reflecting different wavelengths, they produce color.

When sandwiched between conducting electrodes, cholesteric liquid-crystal material can be switched between two stable states—the so-called focal conic and planar states—in which the liquid crystal's helical structures have different orientations [Fig.3, top left and top right]. In the focal conic state, the helical structures are unaligned, or scrambled, and the liquid crystal is transparent; light striking it passes through and is absorbed in a black substrate.

In the planar state, the helical structures' axes are all perpendicular to the display's surface. Adjusting the degree of twist of the helical structures chemically causes the cholesteric crystal to reflect a different color, say, red, blue, or green. Now here's the tricky part: because the cholesteric material will reflect one color and be transparent to the two others, red, green, and blue pixels can be stacked atop each other, with the result that they can show brilliant color images or reflect white. And the black absorbing layer provides black.

Unlike twisted nematic LCD screens, which tend to wash out in bright light, cholesteric LCDs look better in it—the brighter the light, the brighter the image, just like paper. The white reflectance of the vertically stacked color layers is greater than 40 percent, or about the same as that of a newspaper.

A pixel in the planar (reflective) state can be switched to the focal conic (transparent) state by applying 10–20 V. The voltage can then be removed and the focal conic state will remain indefinitely.

To switch back from the focal conic to the planar reflecting state, however, takes two steps. The display must first go through a highly aligned state, known as a homeotropic state, in which the helical structures disappear. This requires the application of 30–40 V. If this voltage is abruptly turned off, the liquid crystal assumes the planar structure, which will also remain in place indefinitely. If the voltage were gradually reduced, the liquid crystal would return to the scrambled, focal conic state.

To add the Lambertian quality of paper, which reflects light evenly in all directions, the liquid crystal is slightly "fractured"—

Defining terms

Focal conic alignment: in a cholesteric liquid crystal, a random distribution of pitch axes between the display's substrates, which renders it transparent (nonreflecting).

Homeotropic alignment: in a cholesteric liquid crystal, a condition in which its molecules have no helical structures or pitch axes.

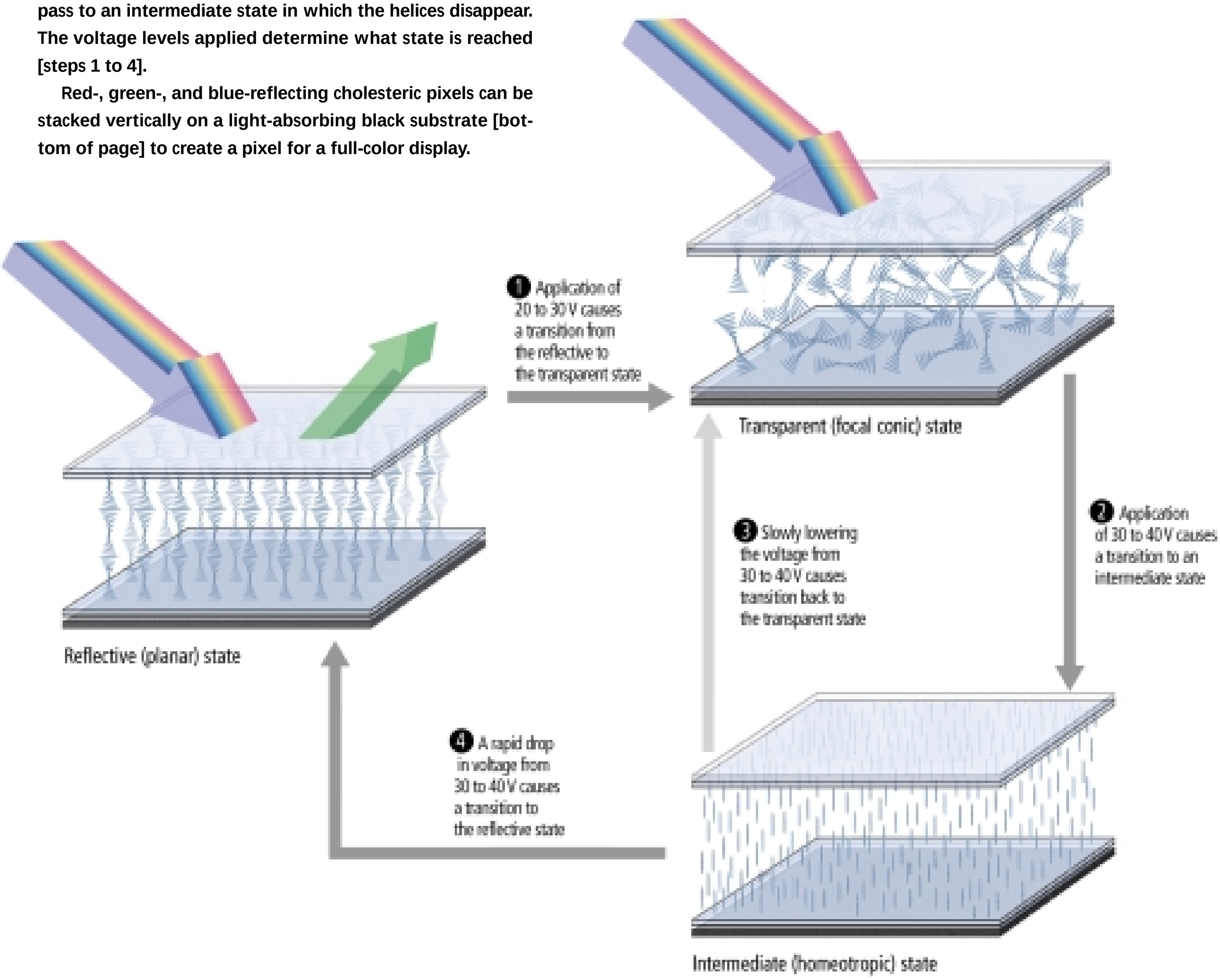
Lambertian reflection: a uniform reflection of light in all directions from a surface, such as paper.

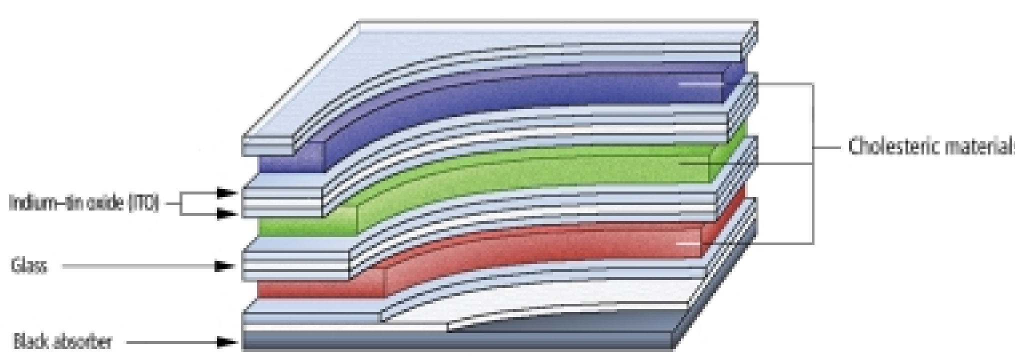
Photopic reflectance: a measurement of the reflectance off a surface, weighted by the sensitivity function of the human eye.

Planar alignment: in a cholesteric liquid crystal, a condition in which pitch axes are aligned parallel to a display substrate, so it reflects light.

[3] A pixel in a cholesteric liquid-crystal display has three states [shown clockwise from below left]. In its reflective state , the aligned helical structures are tuned to reflect one color. In its transparent state, the scrambled helices let all light be absorbed. To switch back to the reflective state, the pixel must pass to an intermediate state in which the helices disappear. The voltage levels applied determine what state is reached [steps 1 to 4].

Red-, green-, and blue-reflecting cholesteric pixels can be stacked vertically on a light-absorbing black substrate [bottom of page] to create a pixel for a full-color display.





The importance of thresholds

Materials used to make reflective displays either have or do not have a threshold. Those that have a threshold are unresponsive to voltages below a well-defined voltage level—that is, nothing happens to them below that level. Materials that do not have a threshold respond to some degree at all voltage levels. The presence or absence of a threshold in a material determines the type of addressing scheme that can be used to place images on the display. More precisely, it determines which type of addressing scheme cannot be used.

The two basic types of addressing schemes are called active and passive. A seven-segment liquid-crystal display (LCD), like those used to display numbers in digital clocks, is a simple active addressing scheme. Every segment has its own electrodes, which turn it on or off independently of other segments' electrodes. Because each segment is turned on or off independently, the lack of a threshold is irrelevant in a display with just a few segments.

The appropriate combination of segments is determined by dedicated logic circuitry. Every segment is independently driven by its own external voltage source. Such a direct, or active, addressing scheme can always be used, regardless of whether the material has a threshold or not.

But to use an inexpensive multiplexing, or passive, addressing solution, the display material must have a threshold. This is because of the way passive addressing applies voltages to the display's rows and columns of pixels.

In a passive addressing scheme, the display's top substrate has electrode rows and its bottom substrate, electrode columns. Every point at which a row and a column electrode overlap is a pixel, so if a display has N rows and M columns, it will have N x M pixels.

With passive addressing, the display is driven one row at a time. A row is first selected by placing a voltage on it while all of the display's columns are addressed with voltages. The rows are selected by voltages that, when added to the column voltages, provide a voltage across the pixel that will drive the pixel into the desired optical state. Once the operation is completed for one row, the next row is selected, then the next, and so on, until the image is built line by line.

When a row is selected, all the other rows are driven with voltages that, when added to the column voltages, will not affect the image already there. The catch is, there must always be a voltage on the rows. So to prevent the unselected rows from being addressed, the display material must have some well-defined threshold below which their current state will not be affected by some minimum voltage.

Thus passive addressing makes it is possible to address N x M pixels with only N + M connections. On the other hand, if each pixel had to be addressed directly, N x M connections would be needed. Thus, the number of connections needed grows rapidly when direct addressing is used.

Cholesteric materials have a well-defined threshold, approximately 10 V, below which neither of its two states, focal conic or reflective, is affected. Researchers at Kent State University in Kent, Ohio, realized the importance of the threshold behavior and bistability of these materials in 1990, thus lighting the path to commercialization of cholesteric liquid-crystal technology.

On the other hand, the Gyricon and electrophoretic materials produced to date are all thresholdless—something happens at any threshold— so if passive addressing were used for these displays, the voltages on the non-select rows would inadvertently alter the state of the other pixels. Thus, these displays require an active-matrix addressing scheme, which is used by most laptop LCDs today, anyway.

With active-matrix addressing, it does not matter whether the material has a threshold or not. A discrete nonlinear switch, such as a diode or thin-film transistor, is placed at each pixel on the display substrate to activate it. However, the inherent complexity of such a substrate is one reason why laptop LCDs are so expensive—on the order of $500.

But there is hope; on the horizon are all-organic transistors and printable electronics that, if they prove practical, could reduce the cost of such active-matrix schemes [see "The dawn of organic electronics," *IEEE Spectrum*, July 2000, pp. 29–34]. *—G. P. C.*

that is, the rows of helical structures are slightly misaligned. Kent Displays does this with a proprietary alignment technique that spreads the reflection over a broader viewing angle, at the expense of on-axis, reflection.

Another advantage of this type of display over paper is that it can show videos. The dynamic response times of cholesteric materials are on the order of 30–100 ms, which is close to the switching speed needed to show video (about 20 ms). Special addressing schemes that, for instance, exploit the fact that some elements in a video image do not change from frame to frame allow these LCDs to display moving images. However, this consumes more power than simply putting an image on the screen once and leaving it there; the image must be erased every time it changes. Without erasing, the image will stay on the display for at least a year.

From a price-performance standpoint, the best thing about cholesteric liquid crystals is that they have a well-defined voltage threshold. Consequently, engineers can build displays using inexpensive passive, or multiplexed, addressing schemes, which greatly reduces the cost of manufacturing a system [see "The importance of thresholds," at left].

While the cholesteric LCD has several advantages, primary among them easy manufacturing and full color, way it reflects light is not quite as good as paper. So, to achieve a more paper-like (Lambertian) appearance using even less expensive materials, researchers are continuing development of the Gyricon and E Ink.

A TURN FOR THE BETTER

In addition to the electronic book and billboard applications, the developers of the Gyricon at the Xerox Palo Alto Research Center (PARC) foresee a unique use for their display: as a substitute for copier paper. The display could be fed through a special Xerox machine that would erase the old image and replace it with a new one. Another way to create an image would be by pulling a digital wand with a built-in scanner across the display, making the wand–display system a scanner and copier/printer all in one. It could also be turned into a fax machine.

The Gyricon is made of millions of small round beads, much like the toner particles used in a copier, randomly dispersed and held in place between two plastic sheets by a flexible elastomeric matrix of oil-filled cavities [Fig. 4]. This flexible display can be manufactured in long rolls much like plastic wrap [see Fig. 2, again].

The balls have strongly contrasting hemispheres, black on one side and white on the other. The white side is highly reflective (near-Lambertian), while the black side absorbs light. Since the balls and oil have nearly matched specific gravities, the balls will not easily move once positioned by an electric field. So after the voltage is removed, Gyricon images can last for hours or even days, depending on how roughly the display is handled.

To create an electrically addressable display, indium–tin-oxide electrodes are printed on the constraining plastic sheets. A voltage pulse to the electrodes lifts the balls in their fluid-filled cavities, causing them to rotate and move across the cavity. The side of the ball presented for display depends on the polarity of the voltage applied to the electrode. The polarity of the balls and the amount of charge they have are determined by the materials used to make them, so the speed of rotation and movement can be controlled by design.

The two-color balls are inexpensive, not only because the materials used are inexpensive, but also because manufacturing them is surprisingly simple. They are made by spraying molten white and black wax-like plastics on opposite sides of a spinning disk. The spinning forces the material to flow outward and form a large number of ligaments, or small jets, protruding past the edge of the disk. The jets are black on one side and white on the other, and quickly break up into two-color balls as they travel through the air and solidify. The speed of the spinning disk controls the balls' diameter.

Xerox, which has been perfecting its Gyricon technology since the mid-1970s, recently partnered with 3M Co. to commercialize it by developing the means for mass-producing the display material. Gyricon displays will typically be made with 100-µm-diameter spheres that have contrast ratios exceeding 6:1. Switching voltages and switching times, which depend on the electrical properties of the materials used, the size of the balls, and the amount of damping created by the oil, are in the 50–150-V and 80–100-ms ranges, respectively. Faster switching times and lower drive voltages are possible with smaller ball diameters, but at the expense of overall contrast.

The display reflects white (broadband) light back to the viewer, with photopic reflectance efficiencies of about 20 percent, or about half as good as newsprint. Gray-scale images can be produced by an intermediate-level switching voltage, so that some balls rotate before slightly larger ones and/or cause partial alignment of the balls. The thin elastomeric Gyricon layers are stable; prototypes have been operated for more than three million cycles without any noticeable degradation.

One issue with Gyricon displays is their lack of a threshold—that is, any voltage will cause them to change state somewhat. Ultimately, this limits the resolution that can be realized in practice. Since each thresholdless pixel must be addressed directly, the display's control electronics becomes highly complex as the number of pixels grows. Direct addressing schemes can always be employed with thresholdless materials for simple—that is, low-resolution—applications; but active-matrix substrates such as thin-film transistor devices would be needed for high-resolution applications, significantly increasing the display's cost.

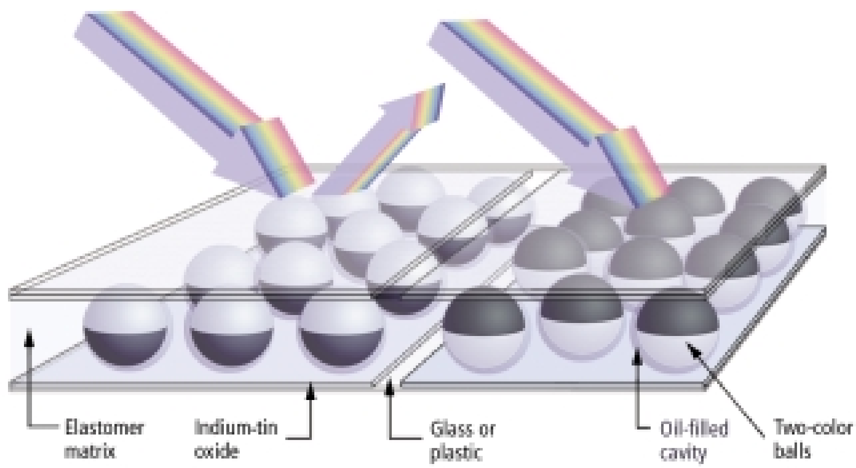
Researchers are trying to capitalize on recent signs of a slight threshold behavior in the two-color balls; this would let them use simple passive addressing schemes and thereby increase resolution. Also, the possibility of making these displays in color is being studied. One option is to use transparent balls with very thin, translucent, colored-filter disks integrated at their equators. When the disks are perpendicular to the display's surface, they are invisible; when they are parallel, color appears. Vertically stacking cyan, magenta, and yellow layers could thus produce full-color displays.

INCARCERATING DISPERSIONS

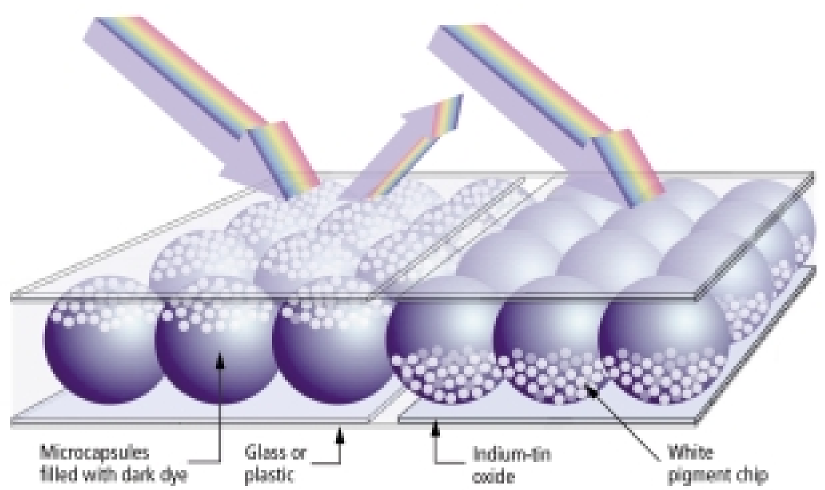
The third technology, similar optically to the Gyricon, is based on a completely different phenomenon called electrophoretics—the rapid migration of microparticles in colloidal suspensions. Recently MIT spinoff E Ink pioneered a technique to create microcapsules, 30–300 µm in diameter, for encasing the electrophoretic materials [Fig. 5]. It coined the term "electrophoretic ink," or simply e ink, for its technology. E Ink researchers are now exploring inexpensive display-drive schemes and ways to produce full-color displays.

Any kind of electrophoretic display relies on electrostatic migration of light-scattering particles in a dyed colloidal suspension. When a positive voltage is applied, the particles migrate electrostatically toward the electrode on the viewer side. If white light-scattering particles are used, a near-Lambertian reflection can be obtained. When a negative voltage is applied, the particles move to the electrode on the side away from the viewer and become hidden behind the dye; the viewer sees the color of the dye. Once migration occurs under either polarity and the voltage is removed, the white particles stay in place, creating a bistable memory device.

Electrophoretic displays made of white particles and a dark blue dye have an attractive appearance, much like ink on paper. Until recently, though, colloidal instability—the tendency for the suspended materials to clot together over time—has kept their lifetimes short and prevented their commercialization.



[4] The spheres of the Gyricon display are trapped in the oil-filled cavities of an elastomer. Positioning them with a positive or negative voltage puts them into the reflecting [left] or light-absorbing [right] black state. Prototypes have been fabricated at Xerox' PARC.



[5] The electronic ink display from E Ink is based on encapsulated electrophoretics—microcapsules containing many tiny white pigment chips, or particles, that are suspended in a blue-black liquid dye. Applying an electric field moves the particles about; the microcapsules can be switched into the reflecting [left] or absorbing [right] state by applying a positive or negative voltage across the indium–tin oxide (ITO) electrodes.

1. Characteristics of some highly readable yet low-power displays

Parameter / Display type	Paper	Cholesteric LCD	Gyricon	Electrophoretic	Reflective twisted nematic LCD
Contrast	20:1 laser print 7-10:1 newspaper	20-30:1	10:1	10-30:1	<5:1
Reflectivity	80% laser print 50% newspaper	40%	20%	40%	<5%
Viewing angle	All angles	All angles			Narrow
Flexibility	Yes	Moderately	Yes	Yes	No
Full color	Yes	Yes	No[a]	No[b]	No
Reflection type	Lambertian	Near Lambertian	Lambertian	Lambertian	Highly specular
Characteristics of electronic displays only					
Response time		30–100 ms	80 ms	100 ms	20 ms
Maximum voltage		40 V	90 V	90 V	5 V
Substrate		Plastic or glass	Plastic or glass	Plastic or glass	Glass
High-resolution drive scheme		Passive	Active	Active	Active
Multiplexing capability		High	None	None	Low

[a] Development is under way of cyan, magenta, and yellow cell stacks for subtractive color techniques

[b] Color filter arrays may be possible.

LCD = liquid-crystal display

Recently E Ink found a way to overcome this problem by using microcapsules. Inside the transparent microcapsules, reflective microparticles are dispersed in a dielectric fluid whose density is matched to the particles. The particles are evenly distributed in the liquid and the whole mixture encapsulated within a transparent coating to form the capsule. Single-particle systems (white particles in a dark dye fluid) or two-particle dispersions (black and white particles in a clear fluid) can be engineered. The microcapsules, whose diameters are 300 µm or less, are then coated onto transparent conducting substrates.

The encapsulation process solves long-standing issues over the stability of electrophoretic materials, namely the tendency with time for particles to form clusters, or agglomerate, and move to one side (lateral migration). By "incarcerating" the dispersion in discrete capsules, the particles can neither diffuse nor agglomerate on a scale larger than the capsule size. Additionally, the microcapsules can be "printed" directly on flexible substrates to create an inexpensive flexible display.

The E ink capsules can be made as small as 30 µm in diameter and packed closely so that even higher resolutions are possible than with the Gyricon, where resolution is limited by the size and spacing of the balls. E ink has a Lambertian, paper-like appearance, with photopic reflection efficiencies exceeding 40 percent, or slightly better than newsprint. Controlling the degree of particle migration with applied voltage makes gray scale possible. Current drive voltages are about 90 V, with display contrast ratios approaching 10:1. The time it takes for the particles to migrate from one side of the capsule to the other is on the order of 100 ms, which is too slow for video applications.

E ink materials have proven reliable and stable, with materials being subjected to 10 million switching cycles without any degradation in device performance. As with Gyricon displays, though, encapsulated electrophoretics are thresholdless, which limits their resolution when passive drive schemes are employed. Therefore, direct drive can be implemented for low information-content applications, or an active matrix can be used for higher resolution.

WHAT'S NEXT?

The display engineer's adage, "There is no such thing as a perfect display technology," still holds true. None of these three technologies will be in a position to satisfy all the performance demands of every application, and thereby dominate the market. Reviewing the performance parameters of the displays discussed [Table 1], it is clear that the cholesteric LCD is superior to the other displays in terms of contrast and color. Further, it has faster switching times and requires lower switching voltages.

However, it does not have the mechanical flexibility of the Gyricon or E ink, which would give them an advantage in foldable-display applications that might be developed in the future. Gyricon and e ink displays could compete head to head in the market, provided that a high-voltage active matrix can be developed and manufactured cheaply—a significant challenge—and ways are found to produce the displays economically in high volume.

The cholesteric display, on the other hand, offers better resolution without the need for an active matrix, and is certainly well positioned to move into the full-color market. Cholesteric displays have the advantage that the manufacturing process on glass is similar to the mature LCD process and is already practicable.◆

TO PROBE FURTHER

Descriptions of the techniques used by Kent Displays Inc. to produce the cholesteric liquid-crystal display (LCD) can be found in two papers. One is "Multiple Color High Resolution Reflective Cholesteric Liquid Crystal Displays," by D. Davis, *et al.* (*Journal for the Society for Information Display*, 1999, Vol. 7, Part 1, pp. 43–47), and the other is "Unipolar Implementation for the Dynamic Drive Scheme of Bistable Reflective Cholesteric Displays," by X. Y. Huang, N. Miller, and J. W. Doane (*Digest of Technical Papers XXVIII,* Society for Information Display, 1997, pp. 899–902).

"The Gyricon Rotating Ball Display," by N. K. Sheridon, *et al.* (*Journal for the Society for Information Display,* 1999, Vol. 7, Part 2, pp. 141–44) fully describes the display developed by researchers at Xerox Palo Alto Research Center (PARC).

"An Electrophoretic Ink for All-Printed Reflective Electronic Displays," by B. Comiskey, J. D. Albert, H. Yoshizawa, and J. Jacobson (*Nature,* 1998, Issue 394, pp. 253–55) provides a technical description of e ink by its originators.

ABOUT THE AUTHOR

Gregory P. Crawford is the Richard and Edna Salomon Assistant Professor and assistant professor of engineering at Brown University, in Providence, R.I. He is also the principal investigator for the development of a CD-ROM tutorial on flat-panel displays for the U.S. display industry, funded by the United States Display Consortium. Formerly, he was a visiting research scientist at Philips Research Laboratory in Eindhoven, the Netherlands, as well as a member of the research staff at Xerox Palo Alto Research Center.

Spectrum editor: Richard Comerford