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# The Electronic Display of the Future

Kindle, iPad, Droid—these compact mobile devices are essentially all display. But the screens aren't all we'd like them to be. Yet.

By **Jason Heikenfeld**

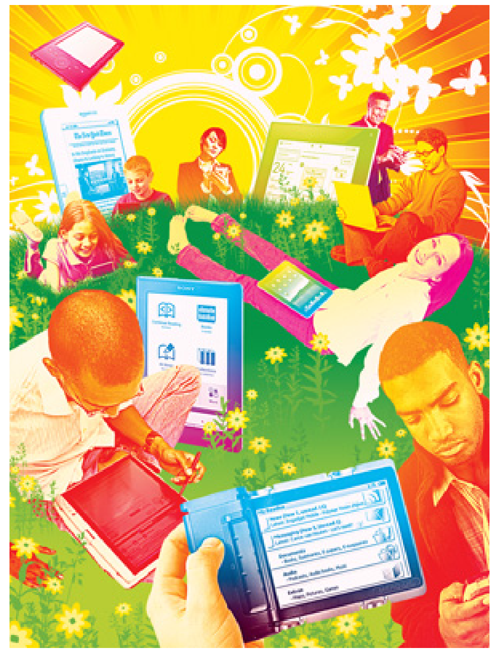
Illustration: Sean McCabe

**It's 2020, and it's sunny outside.** In fact, it's so bright in your kitchen that you have to squint to see your grapefruit. You flip on your e-reader and the most recent e-issue of *IEEE Spectrum* pops up on-screen, the colors and text sharp and brilliant in the sunlight. There's e-mail to answer, but you want to make the early commuter bus, so you roll up your e-reader and stuff it in your jacket pocket.

On the bus, you switch the device to physically rigid mode and half the screen becomes a large keyboard. You bang out a few messages, then watch a short video. All the while the unit is charging its battery through a built-in organic solar cell.

That's my vision of the future of periodical literature—or rather, the future of periodical delivery. It combines the orderly, portable, full-color format of today's print publications with the flexibility, timeliness, and multimedia capabilities of online magazines. And the only component still lacking is a screen that's easy on the eyes in all sorts of lighting conditions, displays full-motion and full-color images, is rollable and durable, and uses precious little power.

Like the jet pack, it always seems to be a decade away. So why should you believe me now when I tell you that the do-all e-reader will be available in a decade? Read on.

**No fewer than half a dozen** different technologies are emerging from laboratories to compete to be the e-reader screen of the future. The stakes are high: Research firm DisplaySearch estimates that the market will near US $10 billion by 2018, powered by a compound annual growth rate of 41 percent.

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Illustrations: Emily Cooper

*Click on the image for a larger view.*

To understand the technical challenges, first consider where we are today. Today's electronic readers, such as the Amazon Kindle and the Sony Reader, meet two of my criteria for the ideal e-reader: They're easy to read in bright light and use minimal power. These monochrome displays, sometimes called electronic paper or e-paper, use a kind of electrophoretic technology developed by E Ink Corp. (http://www.eink.com/technology/howitworks.html), a company in Cambridge, Mass., that was spun out of the MIT Media Lab in 1997. An electrophoretic pixel comprises numerous tiny capsules that contain a mixture of oppositely charged pigment particles, typically carbon for black and titanium dioxide for white. A voltage attracts or repels the pigment particles within the capsules from the screen, depending on whether a white or a black pixel is needed at that spot. Like mixing paints, with the right voltage control the system can also leave the particles in a partially mixed, or grayscale, state. It doesn't need much power, because the pigments simply reflect—or don't reflect—the ambient light, and they don't need any power to maintain their most recent state. An electrophoretic display takes 200 milliseconds to switch images. So if the image on the display changes every 60 seconds, in 1000 hours of continued use the display would effectively draw power for only about 3 hours.

E Ink has spent over a decade getting to this point and is still refining the basic technology. But already these displays are really simple to produce. Manufacturers purchase ready-made film containing the pigment-filled capsules and simply laminate it to an underlying panel that carries the drive circuitry. The first generation of E Ink displays used silicon transistors and glass panels; the second, due this year, will use organic transistors and plastic panels. This second generation includes Polymer Vision's Readius and Plastic Logic's Que; the Readius is literally paper thin, and it can be rolled and unrolled tens of thousands of times.

Now for the downside. Electrophoretic technology has limited potential for displaying full-color images. That's because it hasn't really solved the brightness challenge. Imagine that you're going to paint a wall white that's now a very dark brown. You'll need at least three coats of white paint to cover that brown. Electrophoretic pixels have a similar problem, because the black particles are never fully hidden by the white ones. So the white reflectance is only about 40 percent, compared to 80 percent for a sheet of paper.

If you try to get around this problem by using more particles, you run into problems with switching speed. Electrophoretic pixels already switch slowly because the layer of electrophoretic ink is relatively thick, about 40 micrometers, and the voltage applied to the pixel must be spread across the entire thickness. The level of liquid crystal material in LCDs is only a few micrometers thick, and that's one reason they're so much faster. Electrophoretic technology also can't do video; the switching speed is just too slow.

Want color? The current approach is to add a red-green-blue color filter array over the pixels. The problem is that this reduces the brightness by a factor of three, because each primary color filter passes through only one-third of the visible spectrum of light. So, at each color pixel the display can reflect only 10 to 15 percent of the available light. The first color electrophoretic displays, expected to reach consumers late in 2010, will use very weak color filters; this will crank up the brightness at the cost of color saturation.

For bright, full-motion color images on portable screens, LCDs dominate. First developed in the early 1970s and almost continuously improved since then, LCDs are hard to beat for almost any characteristic *except* efficiency. That's why Time Inc. recently presented its futuristic concept version of an electronic *Sports Illustrated* on a standard LCD, and Apple's new iPad sticks with this established technology.

LCDs are energy hogs for several reasons. For one, an LCD works by polarization, which means that at least 50 percent of available light is lost because it doesn't pass through the polarizer. It loses more light to color filters, ultimately wasting about 90 percent of the light from its backlight. So the backlight has to be intense, and it saps power, but that's the only way you can get a bright, crisp, vivid image. The upshot is that LCDs convert electricity to viewable light with pitifully low power efficiency—just 2 to 3 percent.

Worse yet, the readability of both LCDs and the newer organic LED displays, which must also rely on electrically generated light, dramatically deteriorates outdoors. The displays simply cannot compete with direct sunlight, which is about a thousand times as bright as typical indoor lighting. Even a slight sunlight reflection is far brighter than the light coming out of an LCD screen.

The final blow against LCD as the ultimate display technology is that for many people, long-term viewing of an LCD strains the eyes. E-paper displays generally don't cause eyestrain because they automatically reflect—literally—the brightness of your surroundings.

So today's e-paper has readability and low power, and LCDs have brilliant colors and full video motion. Is there a technology that can do it all? A few of the contenders are bistable liquid crystal, cholesteric liquid crystal, microelectromechanical systems (MEMS), electrowetting, and electrofluidic technology, as well as new generations of electrophoretic technology.

These technologies exploit radically different principles and offer varied features. None of them yet provide the ultimate 2020 display experience of low power, readability, bright color, and full-motion video. But at least a few of them are getting close to providing color e-paper that would be as bright as the monochrome Kindle.

**First out of the lab** later this year will be the multimode display (http://www.pixelqi.com/products), from Pixel Qi, in San Bruno, Calif. This display takes a brute-force approach, combining reflective and transmissive liquid crystal technologies in an attempt to get the best of both worlds. The display, called 3Qi, operates in three different settings: standard color LCD, black-and-white e-paper, and a limited color e-paper mode. If you're using your laptop in bright sunlight, you would manually switch to the e-paper mode, relying on reflected light; in a dark environment you would switch to the backlit LCD. Combining all these features into a single product causes some loss of maximum brightness and color, but the versatility and low power consumption may make it compelling for consumers, at least for now. [See "Pixel Qi's Everywhere Display (/computing/hardware/winner-pixel-qis-everywhere-display)," *IEEE Spectrum*, January 2010.]

Other developers are trying to push LCD technology into a new realm of performance. Reflective displays based on liquid crystals have been around for decades but have so far failed to impress—think of the drab greenish-gray displays on cheap calculators and digital watches. We should be able to do better, and Kent Displays (http://www.kentdisplays.com/products.html), in Ohio, spun out of the Liquid Crystal Institute at Kent State University, is doing just that. The company's cholesteric liquid crystal molecules have a helical structure (like a spring or DNA). Shine white light on a layer of cholesteric liquid crystal and, in theory, half of the light will have a circular polarization (left or right rotation) that matches up with the liquid crystal. Also, as it travels through the liquid crystal the light encounters a periodically changing refractive index, so in total it can reflect a little less than half the light associated with a certain color. Like regular LCDs, the cholesteric liquid crystal can be reoriented with the voltage so that the reflectance can be switched on or off.

*To Market, to Market*

AMAZON KINDLE

DISPLAY *Electrophoretic pixel from E Ink*

RELEASED 2007

G-CORE MINI-CADDY

DISPLAY *Mirasol from Qualcomm*

RELEASED 2009

QUE PROREADER

DISPLAY *Electrophoretic pixel from E Ink on proprietary plastic display*

RELEASED *2010 (planned)*

To produce a full-color display, Kent makes three separate primary-color films of liquid crystals, each with its own electrodes and voltage control. Then the company laminates the three liquid crystal films into a single paper-thin sheet. That means each color can seem relatively bright, because the other color sheets can turn transparent when necessary.

Each layer of film is not perfectly efficient, optically speaking, so with three laminated layers the reflectance is about 30 percent—still far from what we'd want for our ideal display a decade from now. Interestingly, Kent has also demonstrated panels with solar cells integrated beneath the display, so its products can satisfy our 2020 requirement of making battery charging an infrequent inconvenience.

These cholesteric displays have potential uses beyond the e-reader of the future. Kent recently demonstrated color-changing e-skins that can conform to a 3-D surface. Just as the iPhone made the keypad disappear, technology like Kent's might make the entire cellphone case a reconfigurable display.

**Think of the wings** of a blue morpho butterfly. Beautiful, eh? That kind of intensity would certainly satisfy our 2020 display criteria. Back in 1996, inspired by those butterfly wings, MIT launched a spin-out company called Iridigm Display Corp. (from *iri*descent reflection and para*digm* shift). Qualcomm MEMS Technologies acquired Iridigm in 2004 and tagged the technology Mirasol (http://www.mirasoldisplays.com/mobile-display-imod-technology.php?p=2&techID=2).

The display exploits a principle called interferometric modulation. Iridescence, like that on a butterfly, relies on the thickness of a resonant microcavity, the thickness being just a fraction of the wavelength of light to be reflected. The physics are similar to those of the cholesteric liquid crystal but without the strong dependence on polarization. The Mirasol display creates these microcavities using a combination of MEMS mirrors and a stack of thin optical film.

When ambient light hits the structure, the height of the optical microcavity between the MEMS mirrors and the optical film resonates with just a narrow set of wavelengths of light (a single color), and the mirrors reflect only that color. Pixels have preset mirror heights that reflect red, green, and blue light, with multiple mirrors arranged side by side. Apply voltage and the MEMS mirrors move closer to the optical film, the microcavity disappears, and the pixel reflection turns black.

This scheme can easily produce a pixel with intense color, but making a pixel that switches between more than two colors is a challenge. In displays, manufacturing has to be ultrasimple to keep costs low. Think about the $200 you pay for a 24-inch LCD monitor; displays, unlike tiny microprocessors, must be really inexpensive per unit of area. Right now, it isn't economically feasible to make MEMS pixels that switch between numerous microcavity heights.

Today these full-color displays reflect about 25 percent of ambient light—much better than full-color electrophoretic displays but not yet approaching our 2020 goal of the 80 percent reflectance of paper. Like electrophoretic displays, they're viewable in sunlight and they're bistable, with the huge power savings advantage that provides; they also can be rapidly refreshed in microseconds, allowing full-motion video. The speed is fast because the mirrors need to move only a very short distance—just hundreds of nanometers.

**Nature has other lessons** for designers of color screens. The adaptive, color-changing skin of chameleons and bobtail squid is biologically complex. But optically, it's easy to understand. The skin contains pigments that concentrate into small dots when the muscle relaxes. Transparent muscle fibers stretch out the skin, thereby enlarging the pigments so that their color becomes visible. When the muscle fibers relax, the pigments spring back into small, barely visible dots.

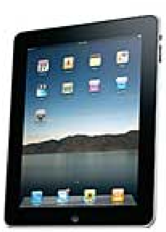
*To Market, to Market*

READIUS

DISPLAY
*Electrophoretic pixel with plastic electronics*
RELEASED
*Announced 2008; has yet to ship*

SONY READER

DISPLAY
*Electrophoretic pixel from E Ink*
RELEASED
*2006*



APPLE iPAD

DISPLAY
*LCD*
RELEASED
*2010 (planned)*

Conventional printed media exploit a similar principle to mix colors. In theory, a printed image can be made from dots of cyan, yellow, and magenta that overlap to create the full spectrum of color. Using smaller dots, wider spacing between dots, or no dots at all simply permits a brighter, whiter reflection from the paper underneath. (In the real world, black is added in many cases for certain practical reasons.)

In 2006, my team of display researchers began trying to combine those two concepts—the millions-of-years-old biological method of switching pigment and the centuries-old brilliant color capability of printing pigments. Our lab, the Novel Devices Laboratory (http://www.ece.uc.edu/devices/) at the University of Cincinnati, began collaborating with pigment supplier Sun Chemical to try to put modern printing pigments into electrically switchable pixels. We worked at first in electrowetting pixels, a dyed-oil technology now nearing commercialization at Liquavista (http://www.liquavista.com/technology/default.aspx), a start-up in Eindhoven, Netherlands, backed by venture capital and spun out of Philips Research Labs in 2006. Back at the University of Cincinnati, in 2007 we discovered a new way of building a pixel that uses pigments in water instead of dyes in oil, initially using the same colored fluids found in the cartridges of an inkjet printer. The images produced by this technology look remarkably like printed media.

We called the resulting technology electrofluidic, because the device electrically pulls pigment fluid through microfluidic cavities. The back plate of the display is highly reflective and patterned with an array of tiny holes about 30 µm deep. The holes make up only 5 to 10 percent of the area of the reflective back of the display, so most of the light falling on the display reflects back to the viewer. The front panel of the display is transparent and pressed against the back plate within a space of only about 3 µm. With no voltage, surface tension acts on the pigment fluid to minimize its exposed area, similar to the way a droplet of water favors a spherical geometry. In that state, the pigment fluid rests inside the microscopic holes.

The front and back of the display also include electrodes. Voltage between these electrodes attracts the pigment fluid from the holes and spreads it into the space between the plates. Now most of the colored pigment is visible, filters reflected light, and creates color. Pulling the pigment out of the holes and releasing it back takes only tens of milliseconds, fast enough for video.

In May 2009, the University of Cincinnati spun out a start-up company, Gamma-Dynamics (http://gammadynamics.net/technology/), to bring electrofluidic technology to market; I am the principal scientist. It has several years to go until commercialization. To date, we have demonstrated 1-inch-diagonal arrays of pixels with about 55 percent reflectance. The first commercial electrofluidic displays will likely use a simple pixel filled with black pigment fluid, which can switch the pixel from black to white, overlaid by either a red, green, or blue filter for three out of four subpixels. The fourth subpixel is unfiltered; when it switches to white it simply boosts brightness to about 40 percent.

Even so, this is still only half as bright as the envisioned 2020 e-reader. Electrofluidic technology could potentially allow highly saturated colors and up to 70 percent reflectance if, instead of color filters, the display incorporated multiple holes per pixel, each hole containing a different color fluid. Eventually, they may be bistable and rollable and display video. Electrofluidic displays are the newest player in the color e-reader race, but it typically takes 5 to 10 years to turn a new discovery into a commercial product.

Electrofluidic displays aren't the only latecomer that might make the leap to commercialization before 2020. Consider another: photonic ink. Developed by the University of Toronto spin-out company Opalux, photonic ink creates colorful interference with a stack of precisely spaced nanobeads. A polymer between the beads swells when exposed to electrolytic fluid, altering the optical cavity between the beads and allowing tuning of any color at any pixel in a single layer. It's a very intriguing idea. But the displays built so far aren't very bright, and like many rechargeable batteries, they have limited lifetimes.

**When the ultimate** display arrives, the e-reader or roll-up computer will be only one of its many applications. Besides the Kent State technology, which could make the entire casing of an electronic device a reconfigurable display, we'll also see a boom in electronic supermarket shelf labeling. Electronic shelf labels have started to appear in Europe and a few other markets. These labels can reduce a full day's chore of relabeling grocery store shelves into an instant, downloadable activity. It also lets stores adapt pricing to consumer habits in real time—a senior citizen shopping midmorning may get different bargains than those picked up by a professional stopping on the way home from work.

Some of these display technologies may make their way into buildings. E-paper technologies like polymer-dispersed liquid crystals and electrochromic displays are beginning to cross over into "smart" window applications. Windows that shade themselves electronically are already on the market, but smart windows could reflect the infrared portion of the sun in summer and transmit it in winter. This technology may first appear in switchable opaque/transparent glass refrigerator doors, which won't face the potential UV degradation of windows. You'll also see these low-power, high-visibility displays coming into signage and billboards; today's LED billboards use lots of energy. Companies like Israel's Magink (http://www.magink.com/page.php?id=38 ) are applying cholesteric liquid crystal technology like that used at Kent to large billboards and already have a few in use.

Finally, one more science-fiction fantasy may become reality. Think back to the 1987 movie *Predator*, in which the alien being sweeps through the jungle with perfect color-changing adaptive camouflage armor. The appeal of invisibility, adaptive camouflage, or cloaking never seems to fade. For military applications, the requirements are tough: The green found in plants—chlorophyll—has a complex spectrum that's particularly challenging to reproduce. But there may be a simple answer: Take the complex pigments used in military camouflage and disperse them in the fluid used in an electrofluidic display, and you could create the perfect adaptive camouflage. The truly ultimate display's perfect visibility might have a side benefit—perfect invisibility.

*This article originally appeared in print as "Lite, Brite Displays."*

## About the Author

Jason Heikenfeld, an IEEE Senior Member, doesn't own an electronic reader, even though he and his colleagues in the University of Cincinnati's Novel Devices Laboratory are working to develop the ultimate e-paper technology. Meanwhile, he's got his eye on Plastic Logic's new Que, which can display newspaper layouts with photos and headlines in addition to straight text. "I am an avid reader of The Wall Street Journal," Heikenfeld says, "but I hate all the paper and the fossil fuels used to ship it."