A sheet of office paper is easy to take for granted, but it's a modern marvel. It's flexible and strong and can take any color of ink, yielding high-resolution printed letters. Yet office paper requires cutting down trees, and manufacturing it requires water and often bleaching chemicals, such as chlorine dioxide, which can produce toxic chlorinated organic compounds as waste.

That's why, two decades ago, when U.S. paper consumption peaked at a staggering 14,073 metric tons per year of uncoated freesheet paper, the category that includes familiar products like notepads and computer paper, researchers began to explore the idea of rewritable paper.

Such a paper, they agreed, would offer all the conveniences of regular paper: it would be smooth, thin, and pliable. The content would appear instantly at high resolution and contrast, and remain visible for long periods. When erased, content would vanish completely and immediately. The optimal rewritable paper would also be able to undergo several cycles of writing and erasing without any loss in the resolution of the printed content, before being recycled. It would hold up to environmental stressors like heat, humidity, and light.

They began to fabricate paper that used heat, light, and even water as ink that they could erase through cooling, evaporation, and other methods over and over again. But even as research groups focused on developing this technology, electronic communication began obviating the need for rewritable paper. Meanwhile, the pulp and paper industry has taken steps to reduce the environmental impact of standard paper production, reducing the drive for an alternative. Practical issues such as the recyclability and cost of rewritable paper have also cast doubt on whether such technology would find any significant market beyond novelty and niche applications. Yet as a matter of basic science, the chemistry being developed for rewritable paper still has value, says Stephen Carr, a materials science and engineering professor at Northwestern University who has researched and engineered polymeric materials for more than 50 years. As in many cases of basic research, the research on rewritable materials may lead to solutions we can't yet foresee. Rewritable paper "is compelling for its novelty right now," Carr says. "It's not practical, but maybe someday it will morph into technologies that are practical."

Now You See It, Now You Don’t

Although early takes on rewritable paper were often difficult and time consuming to produce and use, refined methods have emerged, yielding smart materials that respond to a variety of stimuli and address some of these shortcomings. In one approach, researchers led by Levente Csóka of the University of Sopron are fabricating a colored thermochromic paper consisting of cellulose fibers impregnated with iron-centered transition-metal complexes; people can write on the paper with heat, which turns it white. Heat converts the complexes from a low to a high electron spin state, causing the color change. Cooling to below a certain temperature returns them to their low-spin, colored state, erasing the image. Although Csóka and team have fabricated paper that appears violet before heating, the colored state can vary depending on the complex used. The patterns they drew with heat from a laser remained visible for more than 9 months when stored in an office at room temperature, and they could draw and erase content more than 100 times.

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Meanwhile, researchers led by Luzhuo Chen of Fujian Normal University used organic dyes to create a related heat-based rewritable paper that can also retain content for several months and undergo more than 100 rounds of heating and cooling. Both types of thermochromic paper look and feel like regular paper.

Even so, they still aren’t as convenient as regular paper. They allow people to write or print only colorless content on a background color. Writing on the paper being made at Fujian Normal University requires a heated pen, and erasing it needs about 5 min of refrigeration. “It’s pretty cumbersome,” Carr says.

At the University of California, Riverside, researchers led by Yadong Yin have taken a slightly different approach by using light as ink. They’ve developed a blue film that they coat onto a sheet of paper. Printing with UV light produces colorless content, and erasing, which happens via exposure to oxygen, turns the content back to blue. The thin film consists of titanium dioxide and Prussian blue nanoparticles, creating a blue sheet (although using analogues of Prussian blue creates sheets of different colors). When UV light illuminates the titanium dioxide nanoparticles, they release electrons that reduce the Prussian blue nanoparticles to a colorless state.

Yin’s team prints on the paper by shining UV light over a clear sheet of plastic that is printed with black letters or images and laid atop the film-coated paper. The UV light turns the entire film, except the regions covered by the black letters or images, from blue to colorless. Oxygen in the environment reacts over time with the reduced nanoparticles, turning them blue again after a few hours. Adding a hydroxyethyl cellulose layer onto the film can slow this oxidation, allowing the printed content to last more than a week, while heating above a certain temperature speeds up oxidation and erases content more quickly. Yin notes that the film can be reused at least 80 times.

Like thermochromic paper, though, Yin and colleagues’ photochromic paper isn’t entirely practical. The stencil-based printing method is cumbersome, the printed content can appear only in one color, and erasing it takes 10 min at best.

In yet another approach, chemists led by Sean Xiao-An Zhang of Jilin University have set their sights on paper that can be written on or printed on with water. To fabricate it, they coat filter paper with a dye dissolved in polyethylene glycol sandwiched between layers of polyethylene glycol alone. They synthesized different oxazine, oxazolidine, and spiropyran dyes that convert from colorless, closed-ring isomers to colored, open-ring isomers when they come in contact with water. In a 2014 study, the researchers filled inkjet printer cartridges with water to print text in blue, magenta, gold, or purple, depending on which dye the page contained. Recently, they developed a similar type of paper that allows printing in black.

The color appears as soon as the water hits the paper and fades as the water evaporates, which takes about 15 min at room temperature, although integrating sodium chloride into the paper allows the content to stay visible for a day or so. Integrating poly(vinyl alcohol) into the paper slows evaporation still further—trapping water molecules in the coating even as the sheet feels dry—so marks can remain for more than a year. Heating the paper above a threshold temperature speeds up evaporation, erasing the content faster. Guan Xi, a former doctoral student in Zhang’s lab, says the paper can be reused at least 50 times and that the dyes it contains have low toxicity or are nontoxic. Again, though, it lacks many of the conveniences of regular paper. Erasing takes a few minutes, and each sheet of paper can print in only one color.

Nonetheless, Xi and others at work on rewritable paper believe that once they smooth out the wrinkles in their technologies, such paper could have several practical uses, such as in notepaper, sticky notes, and labels. Photochromic and hydrochromic approaches in which the content disappears on its own over time could be used for time-sensitive or confidential material that people typically
Inkjet cartridges filled with water print pandas on this sheet of paper, which contains a dye that turns black when exposed to water. Heating the white paper above a certain temperature accelerates evaporation of the water ink, erasing the image in a few minutes. Credit: Nat. Commun.

discard soon after reading, such as meeting documents or newspapers so the next week’s news can be printed on it, their developers say. The paper market, though shrinking, has far from vanished, Yin says, so there is still an opportunity to reduce paper’s environmental toll. “At least in my office, I have zero possibility to rule out the use of paper.”

Paper Tear Down
Any introduction of a new product—like rewritable paper—fights against that shrinking market, says Bill Moore, president of Moore & Associates, a paper recycling consulting firm. From 2000 onward, uncoated freesheet paper use in the United States began a steady decline. By 2018, it had dropped by about 50% to 6,966 metric tons. Paper consumption in the rest of the world has also slowed, but by a lesser degree, decreasing from a peak of 55,042 metric tons in 2007 to 52,834 metric tons in 2018.

The culprit, of course, is the rise in electronic communication. Screens have largely negated the need for rewritable paper, its function “more or less included in something like a tablet,” which lets us record and erase content countless times over, Carr says.

While Steven Keller, a professor of chemical, paper, and biomedical engineering at Miami University, acknowledges that regular paper isn’t going anywhere anytime soon, he also doesn’t see rewritable paper as a competitive substitute for it. Erasers and word processors already enable easy writability, and realistically, most people would probably want to use a fresh sheet of paper for their writing needs, not reuse sheets, which can wrinkle and show wear. “You know as well as I do...that that’s not going to happen,” Keller says. Carr says rewritable paper is “an academic solution to an academic problem.”

Rewritable paper faces stiff pricing competition from regular paper, which can cost less than a cent per sheet and be recycled. Researchers’ estimates of the cost of rewritable paper range from a fraction of to double the cost of regular paper; it’s too early to tell where final prices might land. But if rewritable paper costs more than regular paper, it’s not clear how much more consumers would be willing to pay for the privilege of reuse.

Researchers developing rewritable paper frequently claim that replacing paper products with their technology could reduce paper use, which they say contributes to deforestation. But paper use is not a major environmental problem, Keller says. In fact, most new paper products—64% in the United States and 57.9% globally in 2013, according to an International Council of Forest & Paper Associations report—are now recycled. Specifically, they’re downcycled, meaning the lignocellulosic fibers recovered from high-quality paper products, like photocopy paper, go into lower-quality products, like cardboard. And the trees used to make paper can be regrown in a sustainable manner, Keller says.

While proponents of rewritable paper see it as a more sustainable alternative to regular paper, rewritable paper may in fact create environmental problems. Many approaches involve using pigment and other compounds to coat an entire sheet of paper, only a small portion of which people actually write or print on. In contrast, small volumes of ink are sufficient for writing or printing on regular paper. Plus, the safety and recyclability of the materials in rewritable paper aren’t entirely clear, Keller says. He adds that these materials could interfere with the existing paper recycling process and may even necessitate a separate recycling infrastructure.

Yet many researchers working on rewritable paper maintain that their approaches use safe, recyclable materials. Yin says Prussian blue, found in the photochromic film his lab has developed, is a safe, widely used pigment found in printer ink. Likewise, the titanium dioxide in the film is already added to regular paper to make it whiter and brighter. Csóka says his group’s thermochromic paper consists almost entirely of recyclable, biodegradable cellulose, while the transition-metal complexes contain iron, which will most likely have minimal health or environmental impact.

Despite all these challenges, these rewritable materials may still have practical use. For instance, Keller proposes using thermochromic paper as a sensor to detect heat in circuit boards, which could indicate a defective electronic circuit or component. He envisions laying the paper onto the circuit board and seeing if the paper changes color in response to the components generating heat above a certain temperature. (Temperatures would remain below paper’s combustion temperature, Keller says.) Csóka similarly envisions the thermochromic paper he and his colleagues developed being used in temperature- or gas-sensing
applications in which the sheets would change color in the presence of a gas leak, for instance. In other words, maybe the materials under study do provide a solution, but to a problem other than paper waste.

In the 1980s, Carr worked on conductive polymers and says he couldn’t have predicted that they would later inform the development of polymer light-emitting diodes, now used for color displays on mobile phones and computers. Similarly, rewritable paper could wind up in all sorts of products, such as Etch A Sketch-like toys or cell phone cases, which Chen’s team already created with their thermochromic paper. “I think the only way rewritable paper can be successful is in some kind of niche market,” says the paper recycling consultant Moore.

But practicality may even be beside the point. Whatever the outcome of the research on rewritable paper, chemists are learning how to create new substances that have new uses, practical or not, Carr says. The compounds being developed for rewritable paper “do things that are pretty dazzling, and there’s nothing wrong with that.”

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Shining infrared light on a stencil printed this image of a basketball player on a cell phone case with rewritable paper affixed inside it. Credit: ACS Appl. Mater. Interfaces.

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