The last book

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In this paper we describe our efforts at the Massachusetts Institute of Technology Media Laboratory toward realizing an electronic book comprised of hundreds of electronically addressable display pages printed on real paper substrates. Such pages may be typeset* in situ, *thus giving such a book the capability to be any book. We outline the technology we are developing to bring this about and describe a number of applications that such a device enables.

A book represents a fundamentally different entity than a computer screen in that it is a physical embodiment of a large number of simultaneous high-resolution displays. When we turn the page, we do not lose the previous page. Through evolution the brain has developed a highly sophisticated spatial map. Persons familiar with a manual or textbook can find information that they are seeking with high specificity, as evidenced by their ability to remember whether something that was seen only briefly was on the right side or left side of a page, for instance.[1] Furthermore their haptic connection with the brain's spatial map comprises a highly natural and effective interface, when such information is embodied on actual multiple physical pages.

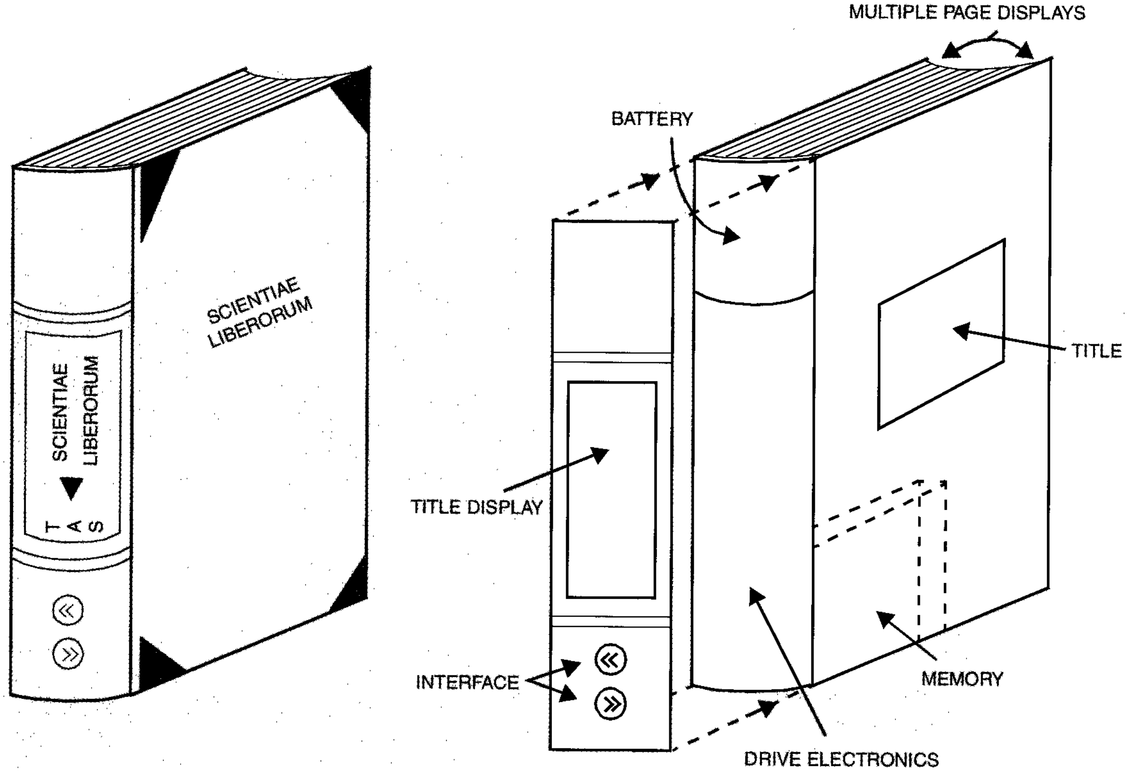
Another aspect of embodying information on multiple, simultaneous pages is that of serendipity and comparison. We may leaf through a large volume of text and graphics, inserting a finger bookmark into those areas of greatest interest. Similarly, we may assemble a large body of similar matter in order to view elements in contrast to one another, such as might be done to determine which of a particular set of graphical designs is most satisfying.

The problem, of course, with traditional books is that they are not changeable. The goal of the electronic book project is to construct a compelling version of the book updated for modern use.

The electronic book that we are developing is shown schematically in Figure 1. Such a book has hundreds of electronic page displays formed on real paper. On the spine are a small display and several buttons. The user may leaf through several thousand titles, select one he or she likes, wait a fraction of a second and open the book to read *King Lear*. When done with *King Lear*, another title may be selected; after the same waiting period, the user opens Steve Weinberg's *General Relativity*. As the reader might suspect, we need to completely reinvent the electronic display before considering such an endeavor.

The current standard for flat panel displays familiar to notebook computer users is a 12.1-inch active matrix, thin-film transistor (TFT) display. Such screens can now have both high resolution and contrast. Unfortunately for an electronic book (or even for a notebook computer), they have a number of serious deficiencies. The current original equipment manufacturer (OEM) price for such a display is approximately \$1000.[2] As larger substrate manufacturing technology is placed on line, this price will come down, but the asymptote price is still projected to be above \$300. If integrated metal insulator metal (MIM) drivers become available, probably around the year 2000, this price may halve again.[3] One reason

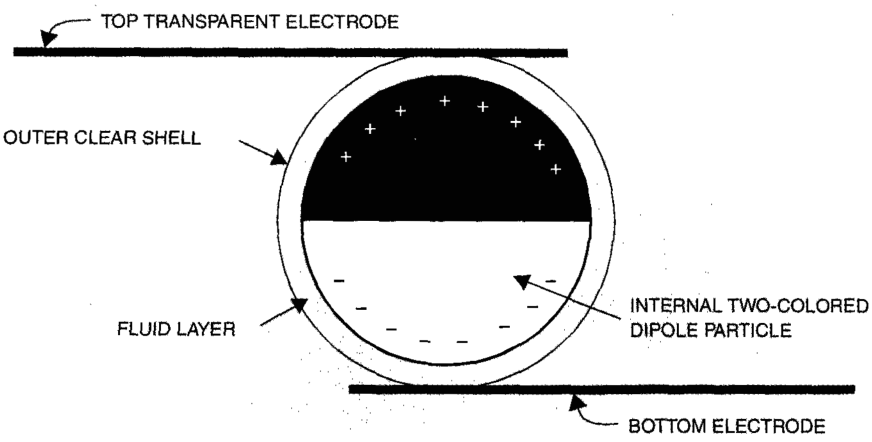
Figure 1 Schematic of the electronic book



for the high price is that, in an active matrix (TFT) liquid crystal display (LCD), each pixel requires its own transistor latch to keep its state (black or white) fixed while other pixels are addrssed. Further, since the display is transmissive, each transistor must be made as small as possible in order to let as much of the back light through as feasible. Manufacturing 10^6 such transistors to address a 1000×1000 display over a large substrate means that yields are poor.[4] Another deficiency is power consumption. Typical power consumption for a 12.1-inch display is 2.5 watts split nearly evenly between the back light and the display drivers. Finally, such displays—which are built on glass substrates—are far from flexible and they are heavy.

There is much recent advancement in the area of organic light emitters that have the ability to be printed or spin-coated onto flexible substrates.[5] Unfortunately, such displays, with fundamental input power to output optical power efficiencies of less than

Figure 2 Schematic of an electronic ink particle



5 percent, are power-intensive and, further, do not have the archival properties desired in a book.

Recent nonemissive flat panel research at companies such as Sharp Electronics Corporation, Minolta Co., Ltd., Kent Display Systems (KDS), and others has attempted to rectify some of these deficiencies. Sharp, among others, has developed what can be called guest host liquid crystal (LC) displays that do not require a back light.[6] In a standard liquid crystal display, liquid crystal molecules are rotated in an electric field that in turn rotates the polarization of light. Only when a top polarizer is put into place does the display actually turn into a black and white display (adding color filters yields color). The problem is that such polarizers have a very low coefficient of transmission for light (typically 20 percent transmission or less), thus requiring backlighting that consumes power. The guest host LC works without a top polarizer. It does this by linking a dichroic dye to the rotation axis of the LC molecule. The dichroic dye can be thought of as a cigar-shaped molecule. When viewed head-on, its cross-section to light is small and thus not visible, but if rotated it becomes highly visible. Such displays can be viewed fairly well in ambient light. However, they still require an active matrix to drive them, so there are still issues of cost and the power needed for the active matrix.

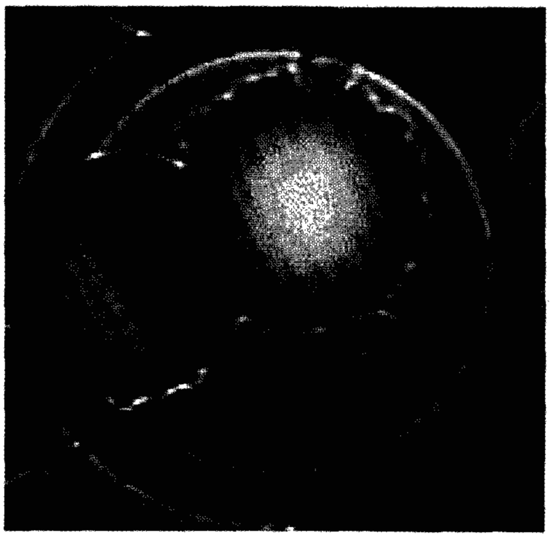
Other companies are pursuing displays that do not need an active matrix (thin-film transistor backplane). Such displays are possible if the pixel is "bistable," meaning that after the pixel is addressed, it stays in the same state without a further field being applied. KDS and Minolta,[7] among others, have developed special textures of liquid crystal that, when doped with a polymer, perform this function. To date, these approaches have suffered from high power consumption requirements or slow address times.

Electronic ink

At the MIT Media Laboratory in Cambridge, Massachusetts, in order to construct a book that actually comprises several hundred electronic displays on real paper pages, we needed to conceive of a display technology that would "push the envelope" on power and cost and be inherently amenable to the integration of a large number of displays. The approach that we have taken is to invent a new microfabricated material that we call electronic ink or *e-ink*. E-ink is an ink-like material that may be printed by screen print or other standard printing processes, but which undergoes a reversible bistable color change under the influence of an electric field.

The e-ink that we have developed consists of a microparticle system, susceptible to an electric field, which is then further microencapsulated in an outer clear shell that may be glued or printed onto an arbitrary surface.[8] One such possible system that we have fabricated is shown schematically in Figure 2 and as a micrograph in Figure 3. In this system a two-colored dipolar particle[9] has a dipole moment associated with it along the color axis, as indicated by

Figure 3 Photomicrograph of electronic ink

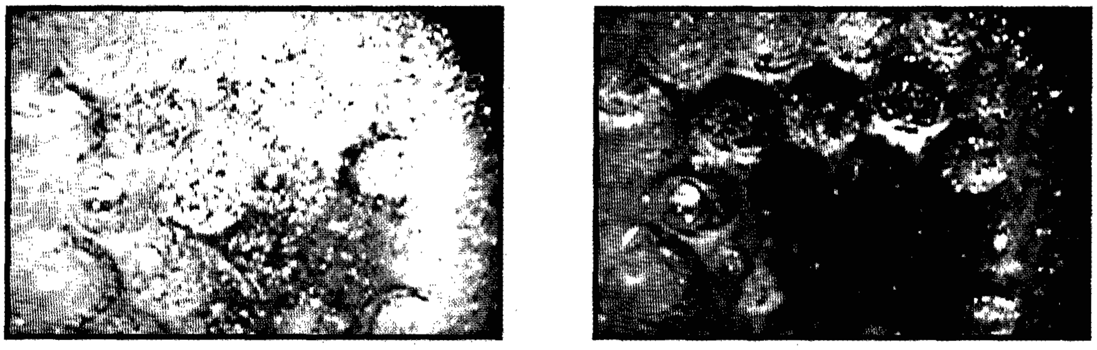


the plus and minus charges in Figure 2. A potential across the address electrodes serves to translate and rotate the two-color particle so that its top half or bottom half is made visible to the reader. An interaction between the particle and the inner wall of the clear shell makes the system bistable.

A convenient feature of such a system is that the technology already exists for high-quality coating and printing of not only paper, but also of a large range of plastics and other materials. The technology allows us to fabricate thin, low-power, and low-cost displays on a wide variety of substrates. Furthermore, such material may be curved, and so we may think of imbuing a large class of objects with electronic display characteristics. The overall display thickness may be eventually on the order of 200 microns, corresponding to about two and a half times the thickness of an uncoated sheet of paper (approximately 80 microns). The cost of a piece of 8.5×11-inch electronic paper is expected to be in the \$1 to \$10 range, with printing technology well suited for scaling up to larger sizes.

We have fabricated both single-pixel and multiple-pixel displays with this material. The device is capacitive, and thus the only current draw is from displacement current. The current draw is about 500 nanoamps (nA). A 12.1-inch electronic ink display would draw only about 12 milliwatts (mW). Although the switching time is dependent on the voltage, we have created pixels suitable for electronic book applications with switching voltages below 10 volts. Pixels in the *on* state and the *off* state are shown in Figure 4. Current particle size is approximately 250 microns, which corresponds to an addressable resolution of 100 dpi. We are currently working toward reducing this particle size by a factor of five. Currently we are also further developing the technology to allow paper sheet displays that may be integrated into a book.

Figure 4 Pixel in the ON state and OFF state



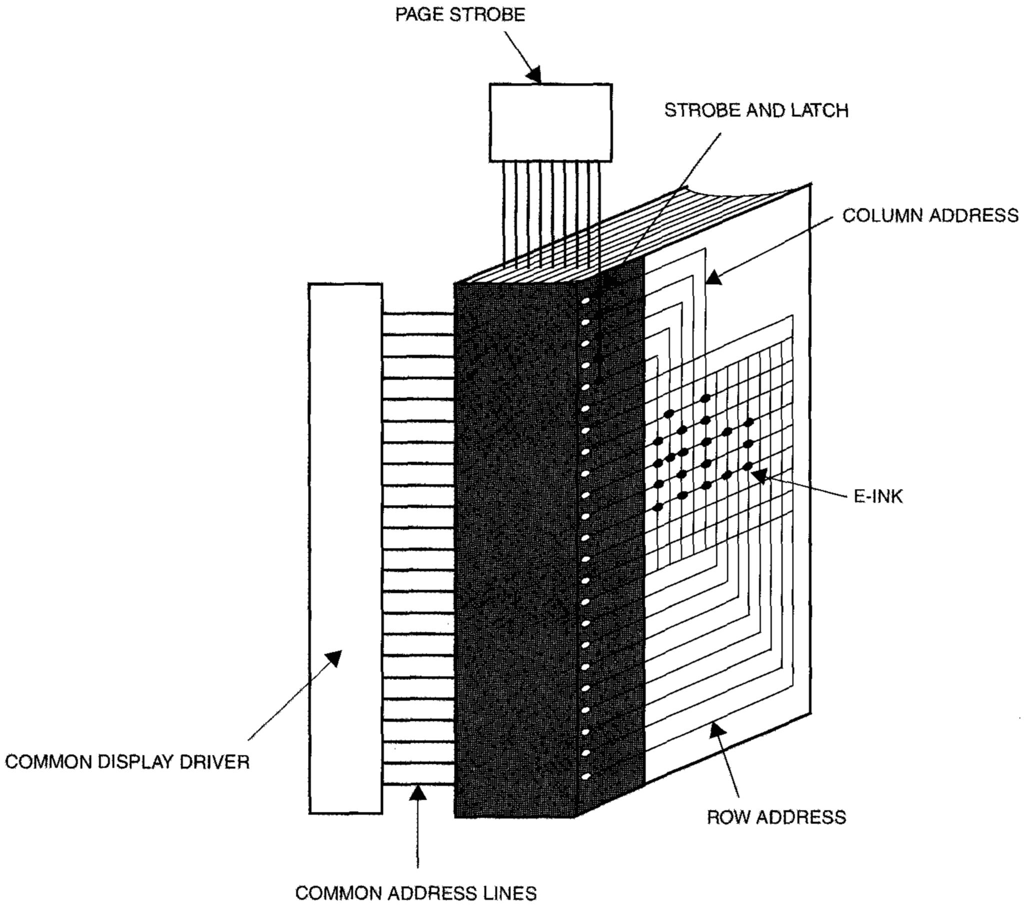
The construction of the electronic book from printed electronic displays is shown schematically in Figure 5. In order to keep fabrication costs to a minimum and fabrication technology tractable, each page has a common set of address electrodes connected to a single, chip-based display driver in the spine of the book. Such connections may be made by means of anisotropic conducting adhesives, as is prevalent in liquid crystal display technology. We have developed a printer that is capable of printing, not only conducting lines, but n-type and p-type (transistor) materials, suitable for switching, directly onto the page display. Thus each page has a unique strobe address line making that page active. Alternatively each page may be given a unique page address. Data can be "typeset" quickly by means of on-board latches with a response time much faster than the display response. Thus, although data are sent to the pages serially, the data are typeset effectively in parallel. This design allows for inexpensive integration of a large number of displays. It is also flexible enough to allow a damaged page to be bypassed and have data sent solely to active pages, thus extending the life of the book. Provisions are also made to allow the display address matrix to sense the presence of a stylus directly, thus acting as a pen input. Such a provision may be used, for instance, to resize text on a page, insert a larger margin space, or add handwritten annotations.

The single-volume library

A number of interesting applications are possible with such enabling technology. The simplest and least expensive form of the book is basically that of a reversible hardcopy medium. In this scenario no memory, battery, or input is present. In order to download a book, a connection is made to an external computer. A transaction takes place and a book of interest is downloaded to be read as we might read any other book.

More intriguing is the addition of memory and the idea of a single-volume library in which a vast number of books may be called forth by the user. It is interesting to look at what storage capabilities are required for such a universal library. Taking as an average book the classic edition of *Plato's Laws*, we can assume approximately one megabyte (MB) per uncompressed book. Reasonable amounts of flash memory could store perhaps one hundred books. A current PCMCIA (Personal Computer Memory Card International Association) disk drive stores about 350 MB, or 350 books. On the horizon is the advent of giant and colossal magnetoresistance (GMR and CMR),[10] soon to be commercialized, which holds the prospect for extremely dense magnetic media. GMR should realize between 3.5 and 35 gigabytes (GB) in a PCMCIA format—already more books than the average individual reads in a lifetime. CMR holds the prospect of 10 times this capacity, or 350 GB in the same format. In the longer term, atomic force microscope drives hold the prospect of truly gargantuan storage. To date such a drive has been demonstrated with an information density capable of holding 10 terabytes (TB) in a PCMCIA-size device with data rates of 1.2 megabits per second (Mb/s).[11] Such a capacity is able to hold (using only modest compression) the entire United States Library of Congress, whose holdings number some 20 million

Figure 5 Schematic of drive logic and page layout for electronic book



volumes. Such a device is in effect a *single-volume library*. A simple system of royalties may be set up in which texts are encoded in encrypted form, allowing the reader to purchase the proper access code by internet access, phone, or wireless transaction.

Of course there are more books than this—books, for instance, that do not yet exist. Consider, for instance, if we were interested in mitochondrial DNA studies of Arabian horse heredity. The Library of Congress, Royal Library, and the Bibliotheque Nationale are not likely to have such a book. There may, however, be a number of research articles on the subject, as well as book chapters and other related material on the internet or other databases. A popular notion is the self-assembled book that draws on all of these sources to create such an entity, that previously did not exist, into existence for a readership of one. The electronic book is the medium that serves to make this idea engaging.

From the illuminated manuscript to the animated manuscript

Finally, a remark should be made about the changing entity of the book itself. A medieval religious book, for instance, is immediately identified from the thick, black, Gothic lettering invented during the time of Charlemagne. Similarly, the richly drawn first letter of the Beatus page or the poetic layout of almost any book typeset by the inventor of the modern portable book, Aldus Manutius, is easily identified. We have recently shown that e-ink may be addressed at frequencies as high as 20 Hertz (Hz), setting forth the prospect of going from the illuminated page to the animated page. Thus the book on Arabian horse genetics may have video clips showing the performance of certain classes of horses. The key is that the video clip resides, spatially mapped, to a particular page in a particular book sitting on our shelf. It has a particular spatial place where we know we can find it. Contrast this with the single monitor we now have on the desktop, through which all changeable images must come, and the idea of the animated manuscript is clear.

Conclusion

In conclusion, we have described our efforts at MIT to develop an electronic ink material capable of imbuing a standard piece of paper with electronically addressable information display capabilities. Such paper coated with electronic ink may allow a new class of information appliances to exist, ones that have a very similar look and feel to those we have now, such as books, but with vastly expanded capabilities more suitable to the information age in which we now live.

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