Data Storage: Retrospective and Prospective

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We study history to learn from its lessons so we don't repeat the mistakes. Ironically, however, as Pat Savage of Shell Development remarked, sometimes it seems that the lesson we learn from history is how to repeat the mistakes more precisely. In this brief talk, I would like to reminisce a bit about the history of magnetic recording, and use the lessons of the past to look into the future.

Magnetic recording is an extraordinary technology. It is so pervasive and so difficult to replace or supplant that it cannot even replace itself. In the beginning of the computer era, peripheral memories and mass storage were dominated by magnetic recording devices and systems. Today, some forty years later, magnetic recording is still the overwhelmingly dominant technology, and will continue to be the dominant technology well into the beginning of the next century. The pace at which this technology has changed is sometimes exasperatingly slow, and sometimes extraordinarily fast. For most implementations of the technology, however, the old concepts continue to exist almost *forever*, with small evolutionary changes along the way. New implementations usually do not replace the old ones, but simply expand the horizon and coexist with the old ones. Because the technology is so deeply and widely embedded, it has acquired enormous inertia to change, and a broadband frontal attack by a new technology is destined to fail. Evolution succeeds, bu revolution does not!

Early tapes and disks utilized primarily particulate γ-Fe_2O_3 (gamma ferric oxide) media. Forty years later, γ-Fe_2O_3 is still widely used in low and high performance applications, including the top-of-the-line IBM 3390 large disk drives, in spite of the tremendous progress in more advanced particulate media (chromium dioxide, Co-modified γ-Fe_2O_3 , metal particles, [illegible] have not been replaced by the newer magnetic recording techniques, what are the chances that a new and totally different technology is going to replace them?

After graduating from college, my first industrial assignment was to develop plated tape - a thin metallic film of Co-P deposited electrolessly onto mylar substrates. It was argued that the old γ-Fe_2O_3 technology was nearing its end, and thin films with their higher coercivity and magnetization would soon replace it. It did not happen then, and it did not happen for the next 25 years. Today we see some metal-evaporated (ME) tapes, but they have inferior wear and corrosion properties. The head-media interface is a very difficult problem for a thin metallic film rubbing against the head, and particulate media will continue to dominate tape technology for the foreseeable future. Evolution works, but revolution does not!

A perennial dream of peripheral storage architects has been to eliminate the famous memory access gap between the sub-microsecond access of main memories and the tens of milliseconds access of disk files. If a technology could be found to close the access gap, it would also eliminate the electromechanical devices inherent in disk and tape systems which tend to be bulkier, power inefficient, and less reliable than totally electronic systems. Of course, cost must always be a primary consideration. Per-bit costs of main memories are relatively high because of the discreteness of the bits, and of the wired access paths to the bits. On the other hand, magnetic recording systems offer low per-bit costs because the storage media do not require bit discreteness, and many millions or billions of bits share a common write/read sensor by moving the bits to the sensor, or the sensor to the bits, or a combination of both. The non-discreteness of the storage media and the sharing of a large number of bits by a single sensor, seem to be prerequisites in order to achieve low per-bit costs. Essentially inertialess beams of photons or electrons can be used to electronically address large numbers of bits in otherwise homogeneous media. The interaction of the beam with the media is used to write and read the bits. Absolute positioning of the beam is not necessary, but repeatability is. By the middle 60's the newly developed laser had caught the imagination of the memory architects, who believed that beam-addressable memories would soon replace the "old" electromechanical magnetic recording storage devices. Everybody climbed on the laser bandwagon, and basic work on magnetic recording stopped. Why spend any effort and money on the old horse if it was to die soon? How wrong can one be? Laser beam memories faced a host of problems ranging from deflection to storage materials, and did not succeed - at least not at that time.

Some of the problems and limitations facing laser-beam memories derive from fundamental diffraction limits and from the limited types of interactions of photons with materials. Electron beams are much less limited by these constraints. They have no practical diffraction limits, they are very easy to deflect - in fact, they are too easy to deflect, which becomes a liability - and they interact strongly with all materials (ferromagnetic, ferroelectric, semiconductor, etc). The main drawbacks are that they require a vacuum, and they lack electron emitter sources that provide high current density, mono-energetic, collimated beams. Consequently, the depth of focus and the depth of field are limited by aberrations. To circumvent these problems, it is necessary to employ very precise and expensive focusing and deflection systems, which raise the entry price and the physical size of economically feasible memory modules. Therefore, even though the basic reasons were quite different than those facing the laser, several valiant attempts to develop electron-beam addressable memories in the late 60's and through the 70's failed, much like the laser-beam addressable memories had failed before them. The great memory-access gap was still wide open, and in fact getting wider, as the integrated semiconductor memories began to replace the ferrite core and to dominate main memory technology.

The attacks of the beam technologies on fortress ***Magnetic Recording*** were fueled to a large extent by the hope of achieving electronic access at low cost by *bringing the sensor to the bits* and sharing its relatively high cost among millions or billions of bits. But what about reversing the strategy, and bringing the bits to the sensor electronically? This approach gave rise to the *bucket brigade* technologies of magnetic bubbles and charge-coupled semiconductor devices (CCD's). These approaches would not actually eliminate the access gap, but they would shorten it significantly, while eliminating electromechanical systems. In spite of great investment and effort, bubbles and CCD's attained very limited success, and the fortress ***Magnetic Recording*** was still intact and looming more unassailable than ever before. The challenges presented by the new technologies and general market demands had, in fact, contributed to strengthen the fortifications and to raise the walls of the fortress, thus rendering it more impregnable. The lessons for new technologies trying to gain market in an area dominated by a firmly established and broadly based technology are:

(i) Frontal attacks across the entire market area are prone to failure, while selective attacks in specific sectors may have a better chance of success.

(ii) It takes a very long time to develop a new technology, particularly if it requires the synthesis of new materials.

(iii) Do not be so absorbed in developing the components of a new technology that you forget to consider their integration and how they interface in a total system.

(iv) A lonely technology has a much lower chance of success than a technology with broad industrial interest.

(v) Never underestimate the opposition by assuming it will stand still during the time you are developing your new technology and thereafter.

There is little doubt that magnetic recording is a mature technology. Consequently, we might expect that making large strides and fast progress would be more difficult. In fact, however, the strides being made today are bigger and bolder than they have ever been in the past:

Very thin film media
Extremely high coercivities
Multilayer film and particulate media
Magneto-resistive heads
1-, 2- and perhaps 10-Gbit/in^2 areal densities
Contact recording on rigid disks
Superfine metal and oxide particulate media
Perpendicular and quasi-perpendicular recording systems

Yes, the technology is mature on account of its longevity, and the breadth and depth of its accomplishments. But it is not getting old, slowing down, or about to disappear or be replaced by a new technology any time soon. It is more vibrant and more vigorous today than ever before in the last forty years that I remember. We have much greater rate of advancement, more new products, new developments, new expectations, and more things happening more quickly today than ever before. And, all along, the old products coexist with the new and hardly anything gets replaced. But there seems to be a distinct evolutionary trend in magnetic recording media

- from low coercivity to high coercivity
- from particulate to thin film
- from oxide to metal
- from thick to thin

and a corresponding rapid change in heads from ferrite and MIG to thin film and MR. This evolution, in the case of the media, has brought about a whole set of problems relating to noise and corrosion which are inherent to the metals. It would seem that, ultimately, the oxides offer more advantages compared with the metals (easier coercivity and anisotropy control, immunity to corrosion, and low noise), and I would predict that the oxides will dominate the future media. On the other hand, longitudinal recording, which requires ever-increasing coercivity and decreasing media thickness in order to achieve optimization, will gradually be replaced by perpendicular recording, which does not require extreme optimization of the magnetic parameters and of the thickness of the magnetic media.

The longevity, the dominance, and the vigor of magnetic recording, simply demonstrate the extraordinary power of the technology, which has sufficient base and momentum to carry it well into the next century. This is not to say that other technologies, such as magneto-optics and semiconductors, will not have an impact. But that impact will be felt primarily in certain areas and will not be an across-the-board displacement. Floppy disks, for example, may be impacted by magneto-optics, and very small rigid disk systems may be replaced by flash memories, but regular rigid disk and tape will probably not be affected in the foreseeable future. In the future (one to two decades), it is probable that some new technology will emerge which will challenge the main stream of magnetic recording. My opinion is that such a technology will have to be electronic (not electromechanical), and the storage media will be three-dimensional as compared to the two-dimensional technologies currently in existence.