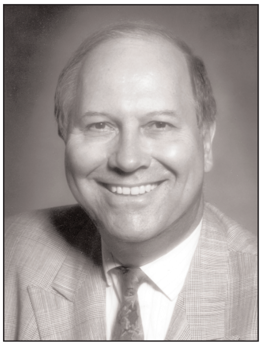
POINT OF VIEW

> *“The Sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of some verbal interpretations, describes observed phenomena. The justification of such construct is solely and precisely that it is expected to work.”—John von Neumann*[1]

> *“Up until now, science has expended its efforts on decoding most of the fundamental natural processes—the dance—of elementary particles deep inside stars and the rhythms of DNA molecules coiling and uncoiling within our bodies. Science’s task now is to cross-pollinate advances thrown up by the study of matter, biology, and the mind-modern science’s three main theaters of endeavor. We are now making the transition from amateur chess players to grand masters, from observers to choreographers of nature.”—Professor Michio Kaku*[2]

A Vision Toward Self-renewing Intelligent Thin Film Media and Modular Storage Systems



By Ed H. Zwaneveld

Scientists in a variety of fields assemble molecules to form new physical structures. Selected molecules can be equipped with memory, responsiveness, and sensory characteristics and designed to engage in constructive pursuits. Investigation and analysis of the potential composition and arrangement of these molecules should reveal their appropriate uses consistent with our understanding of their potential significance. This investigation focuses on storage technologies as they make human knowledge and experience not only accessible, but also repeatable. In the not too distant future, we may employ designer molecules equipped to sense, diagnose, trigger, scavenge, purge, protect, and heal the memory in which they are embedded. We shall briefly consider the enabling technologies and their potential to respond to our growing storage needs while keeping in mind the criteria that inspired current storage system designs, and if they are to be made intelligent, how that might be done.

Recording and storage products are based on non-renewable resources, so we shall challenge some of our assumptions about “fresh until consumed” thinking to “fresh for life” thinking in the design of future media. There is growing frustration with the industrial age mindset, which dictates the linear production flow of extract, produce, sell, use, discard—what *Ecology of Commerce* author Paul Hawken calls “take-make-waste.” Scientists can arrange molecules by design to transform them into lasting storage objects and make today’s temporary media a bad memory.[3]

Theoretically, digital storage systems could use DNA that treats the double-stranded molecule as a kind of biological computer tape, where instead of encoding 0s and 1s in binary, the four nucleic acids, represented by A, T, C, and G, would be used.[4] Molecule-sized carbon nanotube[5] transistors[6] made of plastic will shortly be implanted into a single flexible plastic display. In the future, intelligent molecules may be implanted in thin film media. They would engage in media self-healing to counter degradation processes immediately and stop when sensor and diagnostic molecules determine that a threatening condition has been corrected. They should be smart enough to remain dormant until decay sets in again.

Suitable micro-environment architectures already exist. Optical disc media use thin film layers encapsulated between polymer coatings or substrates and novel magnetic tape recording media. Their recording particles are embedded in polymer thin film and have a layered structure. The design of intelligent thin film storage media systems will require built-in resources to enable reinvigoration or replenishment of depleted molecular building blocks to the originally designed state of the medium. This would enable the preservation of content stored on such media to live on for centuries if desired, or enable re-use of such self-healing media for new recordings as encoding technology advances.

In this age of molecular nanotechnology we should be able to embed molecules in storage media that are capable of preserving recording layer components. This approach can counter degradation as it occurs and renew the recording layer on an ongoing basis. The benefits of this 21st century “tidal approach” where, like the movements of ebb and flood, molecular movements renew our creations, are countless.

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Sustainable Storage Systems

This paper will explore recent discoveries and thinking that may facilitate constructive change. There is a world-wide shortage of energy, yet the coarse engineering approach of the last century has perpetuated the state of mind of the industrial age. It assumed that we need to harvest natural and social capital in order to create financial and productive capital.[7] The resulting technology surge induced "speed greed" and "capacity audacity" and created an imaginary demand at the price of unbelievable waste of energy, resources, and irreplaceable materials. We need to let go of the myth that because the role of humans is supreme, the natural world exists as mere "resources" to serve human "progress" and that accomplishment is measured in "having the goods." Meanwhile, the assault on natural capital continues at an accelerated pace. If we are using up our principal rather than the interest, we become a burden to the generations who follow us.

Following Buckminster Fuller's dictum, companies should "learn how to live on our energy (and resource) income (solar, wind, hydrogen) rather than off our principal (oil and gas)." We should not waste irreplaceable resources for temporary purposes. Are we prepared to confront the anticipated shortages of nonrenewable resources before having to cope with actual shortages? Our industrial progress and addiction for raw materials has a price that is paid by giving up cultural and biological diversity. Having no alternative other than spending resources on replacing products designed to become obsolescent is no option. Nonrenewable materials should be used only in permanent products, or products that can be recycled.

Leading scientists and concerned people agree that we must reduce the impact of human activities on our climate and abodes. This knowledge, fueled by an emerging enlightened way of thinking, leads us to take a closer look at opportunities to reduce waste and develop solutions compatible with economic and ecological realities. *The Emerging Mindset* considers that living systems are inherently order-finding; they self-organize from within, naturally making order out of chaos. Stability is not desirable: growth happens in a living system through disruptions and perturbations of its current reality. The disorder of chaos is the source of renewal; the next order of evolution emerges from the chaos. Incoming information (open systems) is the creative force that transforms them.

Meanwhile, innovation should remain attractive for entrepreneurs and the communities financing their initiatives. Our model for this new way of looking at sustainable and ongoing progress and accomplishment is the example found in living systems. *Life Sciences* writer Janine Benyus calls it "biomimicry—innovation inspired by our understanding of how living systems work. What is consistent with life is sustainable."[8] Peter M. Senge and Goran Carstedt[9] have also pointed out: "All living systems follow cycles: produce, recycle, regenerate. By contrast, industrial-age systems follow a linear flow of extract, produce, sell, use, discard—what *Ecology of Commerce* author Paul Hawken calls "take-make-waste."

And just how wasteful is our current approach?

The Taxco Silver Mines recently reported that their output is 96.4% rock and waste; 2.0% zinc; 0.7% lead, and 0.05% silver. The electronic industry is the biggest user of silver.

"Indeed, the primary output of today's production processes is waste. Across all industries, less than 10% of everything extracted from the earth (by weight) becomes usable products. The remaining 90% to 95% becomes waste from production.[10] Moreover, what is sold creates still more waste—from discard and from use... So, while businesses obsess over labor and financial capital efficiency, we have created possibly the most inefficient system of production in human history. What would industrial systems that conform to natural principles look like? First, they would be circular rather than linear, with significant reductions in all waste flows. This implies three specific waste reduction strategies: resource productivity; clean products; and remanufacturing, recycling, and composting."[11]

Architect William McDonough and chemist Michael Braungart, under the dictum "Waste equals food," define some primary motivators:

- Resource productivity reduces waste from production through ecoefficient production technologies and the design of production processes in which wastes from one process become nutrients for another.
- Clean products (say, hybrid cars) reduce waste from goods in use through nonpolluting product technologies.
- Remanufacturing, recycling (creating "technical nutrients"), and designing more biodegradable products that (creating "natural nutrients") reduce waste from discard.
- Investment in nature's regenerative processes. Companies would do fewer things that compromise regeneration.
- Following Buckminster Fuller's dictum, companies would "learn how to live on our energy income (solar, wind, hydrogen) rather than off our principal (oil and gas)." Living on our income would not only reduce resource extraction, but also eliminate the side effects of using minerals, like auto emissions.
- Growth is sustained only by reducing total material throughput and total accumulated waste. A systematic approach would reduce all sources of waste: from production, use, and discard."

Our industry with its unceasing cycles of new product introductions has a chain effect causing earlier implementations (and their derivative recording products) to become obsolescent. There are many opportunities, here, to increase ecoeffiency. The end of life (EOL) of storage media occurs when an output signal can no longer deliver high enough quality to meet user requirements. The quality of the signal depends on the ability of the storage medium (and the tools required to retrieve and decode it) to remain healthy and not weaken in terms of physical, chemical, magnetic, and/or optical properties and its data recovery capability.

A recent multiyear study, "Future Television Archives," conducted under the auspices of the European Broadcasting Union, brought archivists and engineers from 50+ member countries together. We searched diligently for solutions to manage the sea of tape recordings that overwhelms the ability of archivists to manage them and to defend the production investments they represent. We have concluded that there are actually no options to preserve audiovisual content other than to continuously migrate it as losslessly as possible. We must assure that subsequent transfers of archived content to new media be carried out transparently, in an automated environment, to newer recording flavors. As a consequence, earlier media will end up being discarded over and over again.[12] Whether signal degradation can be avoided in time, in spite of digital technologies, remains in doubt.

> "Discussion on archival matters focused almost exclusively on media decay and recording format obsolescence. Larger investments in this area were confined to the "last minute" transfer of legacy content onto new recording formats before the poor physical state of the carrier and the lack of legacy replay equipment threatened to make the recovery of the original content impossible. The methods currently used for long-term media preservation, storage, and retrieval are rarely in line with existing industry recommendations, due to the lack of manpower and the time and control required for the correct exercise of the prescriptions. The methods used in conventional television program production and archiving for the past decades will definitely prove to be inadequate if broadcasters want to meet the challenges of the future."

It is also useful to note that to avoid future legacy problems, archivists should make collections "automation-ready" in order to save on labor costs. All transfers should be done using a robot, (i.e., automatically, without human intervention, without human quality control, without or with minimal content integrity losses) and plan for continuing transfer from older storage media. All this effort is justified by the assumption that degradation of recording media and obsolescence of recording systems is unavoidable and that the curators of all our legacy recordings have the funds to keep "refreshing" their collections to cope with newer recording technologies. This may not be any more likely than expecting to recreate a single copy reprint of each ancient book and document, just to replace degraded copies. The sole justification for the forced expatriation of our production asset populations just for the sake of resettlement in new and inhospitable territory is increased capacity, greater speed, and constant change.

One assumption is missing: We should not become hostage to the mindset of the industrial age by assuming that the recording medium can be discarded every few years or so, without consequences and without an effect on our resources. There is no agreement that archives are even in a position to afford the necessary resources to happily keep replacing recordings simply because some company decided to pull the plug after sales stagnated! We should at least seriously consider whether a solution can be found that is more in line with the natural life cycle and ask ourselves whether the storage medium itself could already include the "medication" required to regenerate itself indefinitely.

Along with this approach we should take a closer look at the "design for obsolescence" industrial age mindset that pushes customers into buying new recording systems. We have assumed that having, or owning, stuff is the key to prosperity. Maybe it is not such a good idea to own dumb industrial-era systems that die before they reach a ripe old age. If the same manufacturers would adopt a resource-friendly business model that favors selling storage services rather than the hardware and tape, their priorities and strategies would change radically. They would design products for longevity, efficient servicing, and improved functioning; make modular and upgradable products and practice product take-back; and plan to maintain customer relationships by always assuring that products are providing the services required at the lowest cost to the service provider. This model would discourage vendors from implementing marketing strategy dictates for new technology cycles without hearing the voice of the customer about the consequences. This is a shift, as Senge[13] and Carstedt call it, from "value is in the stuff" to "value is in the service the stuff provides."

The recent introduction by Sony of the MPEG IMX VTR permits other Betacam recordings, including Betacam, Betacam SP, Betacam SX, and Digital Betacam tapes, to be played back. This backward compatibility and versatility between recording system generations is also a characteristic of Panasonic multiple DVCPRO-based recording systems that are extensible from NTSC to high definition within the same video format, where each latest VTR also plays back previous recordings.

There are already indications that this more enlightened approach will drive broadcast recording product and systems' designs. Multiple recording systems that are DV and MPEG-compatible are now backward-compatible with earlier systems, thus avoiding instant redundancy of legacy recordings. Another indicator is the IBC2001 announcement by Sony that it will change from being a manufacturer into being a service provider focusing on developing system solutions.[14] The shift in emphasis from "selling stuff" to the "service the stuff provides" will open up enormous new markets—truly a radical shift in the concept of ownership. In the future, the manufacturer of recording technology and media can own what they manufacture forever.

Media manufacturers will have strong incentives to design recording media that heal themselves. Equipment manufacturers will provide modularly designed and backward compatible hardware that can be easily disassembled and upgraded, remanufactured, or recycled, whichever is more economical and in harmony with the natural life cycle and has the least impact on existing collections of recordings. It is with this concept in mind that we could examine the proposed quest for self-renewing intelligent storage media systems. Nanoscale thin film technology, our brightest star enabler, might just make it possible to realize this ideal, not yet today, but this is a vision for the future.

The Era of Nanoscale Technology

A nanometer is a unit of measurement one-billionth of a meter long (10^{-9} m), roughly ten times the size of an individual atom. 10 nm is 1000 times smaller than the diameter of a human hair. There are as many nanometers in an inch as there are inches in 400 miles. The building block of nanomechanics is the molecule found in every physical object. Material properties and behavior can now be systematically and significantly engineered by tailoring the structure of materials in the range of about 10^{-9} to 10^{-7} m. The importance of this length scale is explained by the Los Alamos National Laboratory:[15]

> "The wavelike properties of electrons inside matter are influenced by variations on the nanometer scale. By patterning matter on this scale, it is possible to vary fundamental properties of materials (for instance, melting temperature, magnetization, charge capacity) without changing the chemical composition of the material.
>
> The systematic organization of matter on the nanometer length scale is the key feature of biological systems. Nanotechnology therefore promises to allow us to place artificial components and assemblies inside cells and make new materials using the self-assembly methods of nature. This demonstrates a powerful new combination of materials' science and biotechnology.
>
> The finite size of material entities, as compared to the molecular scale, determine an increase of the relative importance of surface tension and local electromagnetic effects, making nanostructured materials harder and less brittle.
>
> Nanoscale components have very high surface areas, making them ideal for use in composite materials, reacting systems, drug delivery, and energy storage.
>
> Finally, the interaction wavelength scales of various external wave phenomena become comparable to the material entity size, making materials suitable for various opto-electronic applications."

In 1959, theoretical physicist Richard Feynman described opportunities for innovation on a nanoscale. In a lecture delivered at the California Institute of Technology, "There's Plenty of Room at the Bottom," he noted:

> "A biological system can be exceedingly small. Many of the cells are very tiny, but they are active; they manufacture substances; they walk around; they wiggle; and do all kinds of marvelous things—all on a very small scale. They also store information. Consider the possibility that we, too, can make a thing very small, which does what we want—that we can make an object that maneuvers at that level. I can hardly doubt that when we have some control of the arrangement of things on a small scale, we will get an enormous greater range of possible properties that substances can have, and of different things we can do."

He also suggested that one day it would be possible to build machines so tiny that they would measure just a few thousand atoms. The construction projects of such machines, on the tiniest scale, would use molecules from any physical object and even individual atoms as their building blocks. In chemistry and biology, it is possible to construct literally anything at all from scratch, or alter and rearrange molecules, as has already been demonstrated by using a scanning tuneling microscope to move individual atoms into arrangements that they would never assume in nature. Nanotechnology is largely made possible by the refinement of the atomic force microscope, near-field microscope, and the scanning tunneling microscope. These enabling technologies are said to have given scientists the "fingers" necessary to manipulate atoms and the "eyes" to observe the results.[16]

Feynman suggested that by reversing the lenses of an electron microscope, one can demagnify as well. A source of ions sent through the lenses in reverse, could be focused to a very small spot. We could write with that spot like we write in a TV cathode ray oscilloscope by going across in lines. This would provide the means to etch directly onto a metal surface. All the 24 million books published in the world's history could be written on 35 metal thin film pages, using 100 atoms for each bit of information. That sure beats microfilm. We see the beginnings of this permanent storage technology in the work of Norsam.
(See: http:www.norsam.com/hdrosetta.htm).

Recent observations made by using a low-energy electron microscope showed how nanometer atomic or molecular-scale systems of lead deposited onto a copper substrate self-assembled and transformed as a function of temperature and the amount of added material.[17] New work has also revealed how absolutely perfect films can be created by simply increasing the pH of the monolayer. The higher pH has the effect of increasing the concentration of the molecules so they have less freedom of movement during the transfer to the substrate.[18]

But such observations have already included the study of ultrahigh-density molecular storage of audiovisual content. The Open Lab of Beijing Vacuum Physics, Condensed Physics Center, reported recently the recording and erasure of ultrahigh-density data marks on 3-NitroBenzal MalonoNitrile (NBMN) and 1,4-PhenyleneDiamine (pDA) organic composite films and on 3-Phenyl-1-UreidoNitrile (PUN) organic films[19]:

> "The rapid development of information science motivates us to pursue higher storage density and more compact ultrahigh-density data storage. When the size of the storage marks reach nanoscale dimensions, traditional materials and technologies will face drastic challenges. Thus the study of nanoscale thin films and relatively new storage technologies on which prospective ultrahigh-density data storage will be based, is the focus for research in information science. Organic materials are widely used, because of their low cost, convenient synthesis, controlled properties and suitable film formation."

The study of metals has resulted in basic knowledge about some natural laws, which has been applied to create new materials (the dance referred to by Kaku). Traditionally, metallurgy, which includes chemical metallurgy and physical metallurgy, was the science guarding the resource warehouses of nature waiting to be mined. Chemical metallurgy involves the separation of individual metals from ore and the mixture of metals to form alloys. Physical metallurgy occupies itself with the study of how the atomic structure of a metal affects its mechanical properties. The descriptors used for various physical properties of metals include strength, malleability, toughness, elasticity, and ductility. There are other properties such as the ability to give off electrons or electrically charged particles when heated, which are important in electronics. The characteristics of metals as with all other physical substances, depend on the nature of the atoms that make up the metal or material. The basic approach for the arrangement of the atoms was to control them by heat treatment or alloying them with other metals. We are now reaching way beyond that.

Now we witness the birth and blossoming of a new nanoscience and technology that produces profound changes in the manner in which we store and display images and read sound, and many potentials of this new science are waiting to be explored. Thin films are already used for dichroic mirrors in film printers, micromirrors in video projectors, anti-reflection coatings for lenses, transparent conducting coatings for flat-panel displays, and low-friction coatings for bearings. Thin films are also found in Hall elements, magnetic sensors that convert magnetic signals into electrical signals, and are an indispensable component in the control of the precision motors that drive CD-ROM and floppy disk drives. Thin film polymers used as oxygen and moisture barriers in the packaging of foodstuffs to prolong shelf life more or less protect the label side of optical compact discs and the metal particles in magnetic tape media.

Thin film coatings also have unique properties that may be used in the polarization, reflection, transmission, and absorption of light. They are used as the recording, reflective, and buffer layers in compact (CD), digital versatile (DVD), and magneto-optical (MO) disks; and in microelectronics, magnetic hard disk, optical and magnetic tape and disc recording. Thin film technology therefore is of significant importance in current as well as future magnetic and optical recording systems.

In the study of polymers we encounter macromolecules,[20] giant molecules in which at least a thousand atoms are linked together by covalent bonds. Many natural substances, especially biological construction materials, are macromolecules. Of these, proteins and cellulose are the most important. Other than these complex natural macromolecules, many synthetic macromolecules or polymers, have a rather simple structure as they consist of identical constitutional repeating units (structural units). There are only two really fundamental characteristics of polymers: chemical structure (CS) and molecular mass distribution (MMD). These fundamental characteristics determine all the properties of the polymer, directing the cohesive forces, packing density (and potential crystallinity), and molecular mobility (with phase transitions). In a more indirect way they determine the way the morphology and the relaxation phenomena, i.e., the total behavior of the polymer are controlled.

Applications of Nanoscale Thin Film[21]

We shall now examine the degree of cross-pollinating advances raised by the study and interactions of matter, biology, and the mind—modern science's three main theaters of endeavor. We should be "making the transition from amateur chess players to grand masters, from observers to choreographers of nature," as Kaku observed.

Thin films consist of nanoscale layers in a wide array of materials such as metals, insulators, and semi-conductors applied to a variety of surfaces by sputtering or spin coating. They are also used to modify the surface properties of solid materials. They can transform the electrical, mechanical, and/or optical properties of solid base materials in a cost-effective way. Individual films may be electrically conductive or nonconducting, hard or soft, thermally conducting or insulating, optically transparent or opaque.

The nanoelectronic circuits industry is investing considerable research effort in atomic-level electronic devices. It has already produced transistors that were built in carbon-based nanotubes, the so-called top-gate carbon nanotube field-effect transistor. On August 28, 2001, IBM scientists announced[22] that they had successfully created the first logic circuit within a single carbon molecule. Building a logical circuit within a single carbon nanotube molecule forms the basis of the successor technology needed in 10 to 15 years time to replace silicon in electronic circuits. If implemented as planned, researchers will have enabled the building of switches measuring only 5 nm across, about 100 times smaller than today's silicon switches. One of the benefits will be that higher density electronic devices could then be built that consume less electricity and dissipate less heat.

Another example of advanced research on the storage of bits of information on individual atoms is reported by the Georgia Institute of Technology.[23] Chemist Robert M. Dickson and his colleagues have demonstrated the storage of bits in nanoclusters[24] of two to six silver atoms.[25] The nanoclusters exhibit "caged" fluorescence, in which the clusters fluoresce only after they have been photoactivated or "uncaged" with blue light. This information can be read out nondestructively by exposing the particles to green light, which causes them to emit red light. These silver nanoclusters are produced by a modification of a photographic emulsion where silver halide grains absorb light energy, which converts them into silver. The Georgia Tech experiments used a thin film of silver less than 20 nm thick that was deposited on a glass plate in total darkness. Such thin films break up into islands, which rapidly oxidize to silver oxide when exposed to air, producing particles of 10 to 30 nm across. When these particles are exposed to continuous blue light (450 to 480 nm wavelength), they start to fluoresce intermittently, blinking and shifting their emitted light in a seemingly random fashion from red to green to yellow. Dickson says:

> "This is a clear indication that we are observing nanoclusters. As the silver oxide molecules absorb energy, they break up and form

silver nanoclusters of a few atoms, which fluoresce collectively in the same way a molecule would."

To demonstrate that information could be stored and read nondestructively, the researchers exposed the particles in the pattern "L". They then were able to read the image out by exposing it to green light for up to two days afterward, which is as long as they tried to read it.

Other scientists at the Joint Center for Atomic Research in Tsukuba, Japan,[26] are developing the capabilities of silicon cage clusters instead of caged fluorescence. They have created a spherical compound of silicon around a caged metal atom. Called a silicon cage cluster, it could have application as a basis for quantum computing, in new catalysts, and possibly even as a super conductor. With different metals in the cage, such as cobalt, nickel, or niobium, the chemical properties of the cluster can be tuned for many applications. Potentially, nanoclusters could form the basis for ultradense energy-storage systems. But much work remains to show that the particles can be arranged into very compact arrays and that reading and writing information can be done at the extremely high speeds required by computer technology.

Our industry is an early beneficiary of nanoscience and technology, which not only generates enormous amounts of information, but also faces the challenge of packaging it efficiently and affordably and preserving it for as long as required without wasting valuable and costly resources. We can already witness several early applications in highly efficient storage and display systems.

Holographic recording[27] can support storage densities that surpass super-paramagnetic and diffraction limits and provides data-transfer rates of billions of bits per second. This is possible because it enables massively parallel recording and reading of data instead of the serial approach of traditional methods. It also exploits the entire thickness of the recording medium, rather than just its surface. At Lucent Technologies' Bell Labs,[28] new photopolymers (claimed to have more sensitivity and better dynamic range than lithium niobate) have recently been designed that yield high response, high sensitivity, dimensionally stable, and environmentally robust storage media in millimeter thick optically flat formats, i.e., polymer thin films.[29] This holographic recording technology is currently being developed further.[30]

An indication that scientists are taking a much closer look at the physics of the recording process, something of which we need a great deal more, is illustrated by an account from H. Neil Bertram at the University of California San Diego's Center for Magnetic Recording Research (CMRR).[31] Research by this group resulted in a 30-fold increase in data density on disks. Now they are determined to have a greater impact on data rates from the work they are doing on magneto-resistive (MR) heads and in particular on the rise times. Bertram is concerned that the speed of computers is limited by the rates at which they can interact with the disk drive, reading data from and writing data to disks.

"Five years ago, the major advance in magnetic recording was the beginning of widespread use of thin film media, which enabled enormous increases in data density. The next decade will see the major advance in data rates coming from new disk drive heads, which will work not by induction, as they do today, but via the magneto-resistive (MR) effect. Instead of reading magnetic flux directly (by induction), MR heads detect a change in electrical resistance modulated by changes in magnetic flux. What we're doing when we write or read a single bit is simply changing the direction of spin of the atoms in the medium. Bit recording and detection in bulk materials (including best thin film media) occur at a slower rate than the speed of the spin of a single atom can change. This is due to two phenomena. One is the presence of magnetic domain walls in thin film media, which move at rates only on the order of 30 MHz. Second is the fact that the thin materials are very conductive, so eddy-current damping of domain wall motion reduces the dynamic rate even further. We want to know exactly how these phenomena, coupled with the geometry of the devices, reduce the rise time of a recording signal in the inductive recording-head and also reduce the response time of the playback MR head."

Recording Media Applications for Thin Film

Magnetic Thin Film

In August 2000, a comprehensive evaluation was completed of the state of the art in recording media and systems. Various current recording systems are described in considerable depth in the report by Koichi Sadashige,[32] Past-Chairman of SMPTE's V16 Television Recording and Reproduction Technology Committee. (Free copies may be requested from the National Media Laboratory (NML).

Magnetic media recording system component failure becomes evident upon aging of tape media and will occur at different rates. Eventually the decay of the weakest component determines the limits of media life, when it causes the medium to fail in the delivery of the required performance. The components affected include the base film, binders (not used in ME tape), magnetic particle or metal-evaporated layer and coating, lubricants, protective layer over the metal-evaporated layer, and back coating. Initial design, temperature, humidity, and tension are the main causes of premature decay.

Optical Thin Film on Disk Media

All optical disc media consist of thin film layers encapsulated between polymer substrates and in some applications coated by a thin film polymer protective layer. Optical Write-Once-Read-Many (WORM) recording in the form of a 12-in. disk was first demonstrated by Philips at Briar Cliff Lab in 1979,[33] and entered the marketplace in 1985 with 2-GByte capacity. WORM recording in both its ablative and phase-change forms, uses the principle of writing data by changing the characteristics of an organic dye. To record, laser heat is used to alter the optical characteristics of the dye. To play the signals back, a lower power laser beam is used to pick up the changes of light-intensity reflectance of a recording layer of thin film alloy, or a stack of several thin film alloys deposited on top of each other. The data can be made unreadable by writing additional marks in the spaces between the original marks. Most phase-change media are estimated to provide stability, durability, and longevity, resisting corrosion for hundreds of years. Ablative media are estimated to remain stable for less than 30 years with an irreversible increase in hole size after aging. Examples are the CD-R, and DVD-R.

Another thin film system for recording marks and spaces and their subsequent playback uses amorphous crystalline phase change recording technology. To record, the medium is heated and cooled, which produces amorphous and crystalline phases; for playback, the intensity change of the reflected light is detected. One example of this technology is the DVD-RAM. And yet another recording system is based on magnetization reversal. To record, the medium is brought to the Curie point that reverses polarity by magnetic field; To read the signals back, Kerr Angle rotation detection is used. MO products are examples of this approach, which is popular for audio archiving. Finally, there are playback-only optical compact discs that are mass replicated by injection molding techniques. The mark and space have a 1/4 wavelength elevation difference. To play the signals back, reflected light intensity changes are detected. Examples are CD-Audio, CD-ROM, DVD-Video and DVD-ROM.

For the next generation of recordable super-resolution blue laser DVD media, a variety of thin film approaches are being considered. They include a metal polymer deformation (MPD) DVD-R, which has a thin nickel film between the polycarbonate (PC) substrate and the dye layer. It extends the light stability of the dye layer and widens the window of dye selection criteria for DVD-R technology. It also improves the recording sensitivity, and the modulated amplitude.[34] Another approach uses cobalt oxide (CO), silicon (Si), calcium (Ca), sodium (Na), and oxygen (O) as components sputtered onto the substrate and shows a refractive index change upon irradiation by a laser beam. It is durable against high-power laser irradiation (durability against continuous read-outs of up to 70,000 times was confirmed) and can be used in rewritable optical discs as well as in read-only (ROM) disks. These phase change disks are more durable against continuous many-time readout. C/N improvement with a 3 to 4-mW readout power, depending on the disk velocity, is estimated to achieve 1.4 times linear data density.[35]

Other than increasing disk capacity, research also focuses on dye enhancement, particularly cyanine dye, by improving its light fastness by doping with singlet oxygen quenchers such as dithiolato-metal complexes or diimmodium salts.[36] Another refinement to enable two or more 25-GByte capacity recording layers on a next generation DVD disc is the recent synergy of know-how at Hitachi/Asahi Optical.[37] The latter has developed an optical-head technology using a single objective lens, which requires a precision level of nearly ten times that of DVD product lenses today. Asahi Optical has developed precision glass-molding technology to manufacture a single objective lens with a numerical aperture of 0.85, the spot where most prototypes of next-generation optical disc systems are converging. The result is the ability to store more than eight hours of high-definition video content.

Nanochips require very low power when not in use (power down to 1 millisecond). Nanochip media is anticipated to provide replacements for hard disk drives with a capacity of 200 Gbytes, using packaged nanochips, and 1.4- Terabyte drivers, using flip chip packaged nanochips in a standard 3.5 in. form factor. The technology is projected to offer 10 times faster access speed (i.e., 500 microsec average latency). Nanochips are fabricated using primarily standard semiconductor fabrication techniques and are packaged as die-on-silicon wafers. The development strategy of the nanochip seeks to enhance the storage capacity of portable devices and to be the next generation replacement for the magnetic hard disk. It also seeks to replace flash chips and micro-drives in the memory component markets for web phones, digital cameras, MP-3 players, PDA devices, microcomputers, and related wireless and remote storage devices.

Optical Thin Film on Tape Media

Digital optical tape systems are another class of next-generation phase-change write-once-read-many (WORM) storage media. They offer the potential for high areal density, high transfer rates, and a long archival life because of a high resistance to corrosion.[38] This emerging technology has already faced many challenges, including the competition with magnetic tape recording the performance of which is a moving target, and the need to develop open standards.

At Philips Research Laboratories, The Netherlands, a compact optical tape recorder has been described with 80-GByte capacity in a 8-mm cassette at approximately 30 Mbits/sec transfer rate, and 15-sec access time.[39] For the first generation of the drive, a transfer rate of 15 Mbits/sec is envisioned.[40] Nanochip Nano Media technology,[41] is defined as micro-electro-mechanical systems (MEMS) silicon memory-based mass storage devices of high density, great speed, and low cost, based on molecular scale technology.[42] It is a molecular memory medium integrated circuit (IC).

IBM has also developed and, in fact, has started to use in some laptop computers, a breakthrough recording technology, known as antiferro-magnetically coupled (AFC) media. It delays the impact of the critical super-paramagnetism barrier that limits further areal density increases. Conventional magnetic disk media stores data in only one magnetic layer, typically of a complex magnetic alloy such as cobalt-platinum-chromium-boron (CoPtCrB). AFC media has a multilayer structure in which two magnetic layers are separated by an extraordinarily thin—just three atoms thick—layer of the nonmagnetic material ruthenium. It causes the magnetization in each magnetic layer to be coupled in opposite directions—anti-parallel—which describes antiferro-magnetic coupling.[43]

Yet another early application of nanoscale thin film technology is encountered in the recently announced breakthrough by Fuji, Nano Cubic tape recording technology.[44] It is intended for both helical and linear recording formats; high-capacity floppy disks; high-definition, long duration digital videotape for broadcast and home use; and data and video storage tape for home network servers. It makes 1 TByte uncompressed video recording viable and increases the capacity of a floppy diskette to 3 GBytes.

Nano Cubic thin film tape represents an advanced precision coating process that can control the thickness of the magnetic layer on a nanometer scale. Two types of magnetic particles were developed for the technology, both tens of nanometers in size: acicular ferromagnetic alloy particle and tabular ferromagnetic hexagonal barium ferrite particle. For dispersion, it uses a special organic binder material that has the ability to thoroughly disperse the particles in the coating solution so that a uniform packed structure of the layer is realized. This development is an advancement on the earlier Fuji ATOMM (advanced super-thin layer and high Output metal Material) technology, which is used for DVCPRO and D-9 (Digital-S) professional videotape cassettes.

How to Implement Self-Renewing Storage Media?

Our understanding of the ability of molecules to rearrange and propel themselves, in different configurations than appear in nature (or in the conventional design of storage media), is increasing. This knowledge is fundamental in realizing our vision to meet the requirements for intermediate and long-term generations of storage media. We should also be assured that molecules can have both intelligence and the ability to displace themselves. For a model of the architecture of self-renewing media, the following examples will suffice. Note the description by scientists[45] of the observed behavior of DNA molecules:

> "The DNA inside some viruses is packed so tightly that the internal pressure reaches ten times that in a champagne bottle, according to new measurements by biophysicists at the University of California, Berkeley, and the University of Minnesota… The researchers suspect that this high pressure helps the virus spurt its DNA into a cell once it has latched onto the surface. Such tight packing is achieved by one of the most powerful molecular motors ever observed, stronger than the motors that move our muscles or the nanoscale molecular motors that duplicate DNA or transcribe it into RNA. …Pound for pound, this is stronger than any known molecular motor, and can pack DNA to a pressure of about 60 atmospheres.[46] A bottle of champagne typically is under pressure of five or six atmospheres, the equivalent of nearly one hundred pounds per square inch."

The above example refers to the molecular motor as a device to transport a virus, but molecular motors are also the vehicles that transport medication into a body, that could also replenish the building blocks required for the renewal of future storage media. For example:

> "For millions of consumers who must regularly take medication using pills or needles, there may be another option that offers unique advantages. A patch, which delivers medication through the skin and into the bloodstream, is becoming an increasingly popular alternative. Known as transdermal (through-the-skin) drug delivery systems, patches are available to treat or manage a number of health conditions, including chronic pain, heart disease, high blood pressure, menopause, motion sickness and nicotine addiction. And more uses for patch technology are in development-including birth control and treatment of asthma and diabetes...Patches can deliver medication into the body at a consistent level over an extended period of time, minimizing the need to take pills on a frequent basis.… Transdermal delivery systems compared to pills is consistent medication release for an extended period of time… The skin-particularly the outermost layer, known as the stratum corneum-acts as a barrier designed to prevent foreign molecules from entering the body. For a medication to reach the bloodstream, its molecules must be small enough and durable enough to pass through this outermost layer as well as the more watery layers below. The medication also must be potent enough to retain its efficacy after its "trip" through the skin, into the bloodstream and to its therapeutic target. And finally, the medication—and the other patch components—must be compatible with the skin's chemistry to avoid significant irritation or allergic reaction."[47]

Closer to home, for photographic emulsions coated on polymer supports, the nature of the emulsion is modified to achieve projectable images through its interaction with chemical solutions. The depletion of chemical ingredients in motion picture film processes is avoided, using a highly refined process design. This is accomplished by means of a continuous dosage of higher than tank solution concentration replenishment into each solution tank in which the film is successively immersed during processing.

Good processing requires that the designed ecology balance for the film continues to be respected even though the chemistry is being depleted. As film moves through a succession of solutions, carryover from the previous step unavoidably dilutes the next stage, modifying the chemical balance of successive solutions. Quality assurance and control requires the precise balancing of the active chemicals suspended in each solution that affect the end-quality of the processed film.

Unfortunately, the designers of these now highly refined processes carefully protect the film ecology system right up to the moment it is processed. The subsequent natural chemical interactions the film would encounter with humid and warm polluted air, or its self-destruction from chemical processes from within has not been a design issue and should have been, assuming that we knew what to expect. That was again, as described by Professor Michio Kaku, our primitive state of "the dance."

Hence the array of coping mechanisms, with costly premature loss or degradation of our production investment, is now limited to making the film somewhat more comfortable in its old age by external treatments, i.e., keeping it cold and dry, enclosing molecular sieve[48] mini-pillows inside the containers, and replacing rusted tin-coated metal containers with inert containers.[49]

If the published Recommended Practices are taken seriously, it would seem that the degradation processes are the full responsibility of the user of the materials. Actually, these are coping mechanisms; the problem was in the short-sightedness caused by an industrial mindset that assumed that there would always be sufficient resources to replace degraded media. Truth is, there are limits, just ask archivists who try to juggle with the unavoidability of media degradation. As we seek sustainable eco-engineering methods, and consider the entire life cycle of the film and its content, we see that the technology life cycle of film, tape, and disk media is not nearly as mature as popularly assumed. Various recording systems are ripe for re-engineering on a nanoscale. Intelligent molecules can do the detailed work that scientists and engineers living in the last century could not dream of. Smart design can keep audiovisual treasures and the containers on which they are stored alive, long after the media were considered to be "new" and finished.

Setting a Storage Technology Agenda

Sustainability of our storage media systems requires reinvigoration or replenishment of the storage medium to its original state. It also means constant upgrading of the basic equipment to accommodate recording technology improvements, without throwing it out at any time. It implies providing the equipment with an ever-growing array of modular retrofit units, that accommodate the unavoidable generations of technology refreshment. This will enable preserving the content stored on recording media for centuries if desired, or permit the re-use of self-healing intelligent media for new recordings. It eliminates the painful transfer of all the output of aging obsolescent machines just to cope with technology refreshment, which for users requires perpetual rescue and revival missions, in spite of the promises of lossless digital content encoding.

In this age of nanotechnology, we should be able to embed molecules in our storage media that are capable of sensing, diagnosing, triggering, scavenging, purging, and healing, using implanted resources that counter degradation as it occurs and renews the material on an ongoing basis. We should not make the mistake again of waiting for human intervention. By the time we notice that there is degradation, it is usually too late to bring the medium back to its original condition and to recover the valuable information on it. Our human sensor mechanisms and memories are ill-equipped to diagnose the indicators of media and signal degradation. In these dark ages of dumb storage media and throw-away recording and playback devices, we allow degradation not only to take place, but to do serious harm to the weakest links in our storage media. Thus, sick media suffer from nitrate film support degradation; triacetate film deacidification, i.e., the vinegar syndrome; color dye fading; reflective layer oxidation; film splice drying; tape binder breakdown; etc. We try to slow down or delay the onset of such degradation and failure mechanisms when death is already assured, calling it rejuvenation and restoration treatment!

Molecules should be enclosed in new intelligent thin film storage media that have the self-healing abilities required to counter degradation processes immediately and stop only when the sensor and diagnostic molecules determine that it has been renewed. Then those molecules should remain dormant until decay sets in again. To find enabling technologies to accomplish such feats we turn to molecular nanoscience, which is an emerging interdisciplinary field that combines the study of molecular/biomolecular systems with the science and technology of nanoscale structures.[50]

Ghadiri's peptide rings, composed of a novel alternating pattern of naturally occurring and synthetic amino acids, have amino acid side chains that face outward from the "donut" and react to the environment. These "sensor" molecules have been shown to be reconfigurable, a flexibility characteristic that enables the targeting of bacteria and to control how peptides insert themselves into the membrane and self-assemble.[51] Molecular behavior in thin film structures, approximately 200 nm thick, resembles a forest of preposterous cookie-cutter trees. These structures are the result of the patented deposition technique used to lay down the film. It is known as glancing angle deposition (GLAD), a technique developed by Brett and Robbie in 1994, at the University of Alberta.[52] GLAD films have an inherently high porosity and therefore a large surface area, making them highly suitable for sensing materials. Andy Wu, a research associate in Brett's lab, has already developed humidity sensing devices that incorporate GLAD structures. Because these structures are able to respond very quickly and over a wide dynamic range, they show a potential to be superior to any humidity sensors now available commercially.

The benefits of the proposed 21st-century "tidal approach" where, like the movements of ebb and flood, the molecular tides renew our creations are countless. We may expect intelligent magnetic and optical recording media developments that through the use of self-healing mechanisms extend lubricant life, preserve binders, counter hydrolysis, avoid staining of mirror surfaces, and prevent magnetic particles from ever shedding, becoming sticky, or losing magnetism. In motion picture media, we should expect the inclusion in the film of intelligent zeolite molecules to apply their molecular sieve healing capacity, when storage conditions cause relative humidities and pollutants to attack the triacetate stock and color dyes.

The exchange of healing molecules does not occur by coincidence but by design. It requires embedded resource molecules that permit the healer molecules to do their renewal work. Just as we embed with our encapsulated thin film layers a dye recording layer, a reflective layer, or a heat absorbing layer, and, above it, a protective thin film polymer hard coat stacked on the polycarbonate substrate of the CD or DVD, we should expect to include healing resource layers as well. The principle of self-healing molecules is already used for the preservation of paper documents, such as when lignin-free or low-lignin and high-pH paper[53] is made or lignin-containing wood pulp paper is preserved by the addition of high-pH buffers.

Molecular level nanotechnology could become the major enabler of this information age. Nanoengineering and nanotechnology are concerned with development of structures and systems that use and enhance the significantly improved properties of their nanoscale components.[54] This will result in more efficient and creative use of our natural resources, designing intelligent media systems that adapt and maintain themselves in the new condition for as long as required. Its impact: serious miniaturization of many in the long run unsustainable space and energy wasting systems. Its importance to the development of equitable wealth for the world's people could surpass the significance of the computer and genetic medicine.

Conclusion

This technology assessment (TA) has explored and assessed potentials of nanoscience and technology for the development of breakthrough-caliber new intelligent thin film materials. It is a high-level vision map of the technological landscape of our time, beckoning us to look ahead. Important questions remain to be asked in developing a TA that answers relevant questions relating to feasibility and maturity, implementability, market potential, and competitive advantage for the investors who will enable the goals to be met. TAs also include critical analysis of claims; facts that may not exist in published form assumptions that may be opinions, guesstimates, and best judgments. An important evaluation aid is to look at and describe the enabling technologies in functional terms: customers value functionality. It also enables comparison against the relevant competing technologies and should reveal categories of opportunities.

The TA process should also address whether a change from our "fresh until consumed" mindset into "fresh for life" thinking is viable. This paper argues that the approach of the industrial age, summarized as take-make-waste should be replaced by biomimicry thinking for all products based on nonrenewable materials.

Storage technology refreshment and overcoming obsolescence implies the disposal of degraded storage media and obsolescent playback hardware, and continuous periodical migration of storage media content. It is argued that this is not an acceptable solution. Opportunities for self-renewing intelligent media and modular storage systems were explored, using examples from state-of-the-art nanoscale technology and applications in our industry already taking advantage of it.

A proposed Storage Technology Agenda calls for the development and implementation of recording technologies that reach beyond the moment of recording or processing of film. It urges that content production investments should be protected with responsive media-embedded molecules that counter media degradation as it occurs on an ongoing basis.

Innovative contributions from around the world make for exciting and inspiring virtual tours of new industries in the making. But more interdisciplinary work teams must take a closer look at the opportunities for more efficient storage solutions. Needed is input from physicists, chemists, biologists, and engineers to explore the opportunities and overcome the challenges. Manufacturers of media recording systems and their informed customers can benefit from increased dialogue, as customers with a long view are bellwethers of challenges and opportunities. The author hopes that this paper will assist in motivating us to undertake or continue such cooperative efforts, to change the nature of these human-made objects in order to meet the resource requirements that will renew our industry in a sustainable manner.

Endnotes

1. As quoted in D. W. van Krevelen, *Properties of Polymers,* Elsevier, 1997, p. v.
2. Michio Kaku, *Visions: How Science Will Revolutionize the 21st Century,* www.amazon.com.
3. Michael D. Lemonick, "Will Tiny Robots Build Diamonds One Atom at a Time?" June 19, 2000, pp. 94-95.
4. Michio Kaku, *Visions: How Science Will Revolutionize the 21st Century,* Bantam Books, 1998.
5. The nanotube was discovered by the NEC scientist Sumio Iijima in Oct. 1991.
6. John G. Spooner, "Bell Labs Makes Molecule-Size Transistor," C/Net.com Tech News First," www.news.cnet.com/news/0-1003-200-7570458.html? tag=dd.ne.dht.nl-sty.0.
7. Peter M. Senge and Goran Carstedt, "Innovating Our Way to the Next Industrial Revolution," *MIT Sloan Management Rev.,* Winter 2001, p. 24.
8. Ibid, p. 28.
9. Ibid, p. 28-29.
10. See P. Hawken, A. B. Lovins, and L. H. Lovins, *Natural Capitalism,* New York: Little Brown and Co., 1999, p.14; R. U. Ayers, "Industrial Metabolism," *Tech. and Environ.,* Washington, DC: National Academy Press, 1989; and A. B. Lovins and P. Hawken, "A Road Map for Natural Capitalism," *Harvard Business Rev., 77:*145-158, May-June 1999.
11. These three strategies relate closely to the four strategies of "natural capitalism," and three of the four "system conditions" of "the natural step," described in J. Holmberg and K. H. Robert, "Backcasting From Nonoverlapping Sustainability Principles—A Framework for Strategic Planning," *Intl. J. of Sustainable Development and World Ecology, 8:*1-18, 2000; and William McDonough Architects, 1992. Available through McDonough Braungart Design Chemistry, Charlottesville, VA (info@mbdc.com) or downloadable from www.mcdonough.com/principles.pdf.
12. Draft EBU P/FTA Report, "Future Television Archives—Content Management, Architecture, Services and Functionalities," (to be published soon).
13. Peter Senge introduced "systems thinking" in his book *The Fifth Discipline.* From it emerged "conscious process thinking," which means seeing reality as a multidimensional process, part/wholes connected across space, continuously unfolding through time, conscious living systems in constant and perpetual motion. It is implemented as "conscious transformation" by Dean Anderson and Linda Ackerman Anderson, *Beyond Change Management,* publ. Jossey-Bass/Pfeiffer-A Wiley Co., 2001, ISBN: 0-7879-5645-7.
14. "Wohin geht die Reise?" (Where are we going?), Technik & Gestaltung, *Film & TV Kameramann*, *50:*20, Jahrgang, 10/2001.
15. For a discussion about this importance, see: www.lanl.gov/mst/nano/definition.html.
16. Richard P. Feynman, *The Pleasure of Finding Things Out,* Perseus Books, Cambridge, MA, ISBN: 0-7382-0108-1.
17. R. Colin Johnson, "Experiments refine self-organizing principles," *Elect. Eng. Times,* Sept. 24, 2001, p. 63.

18. Ibid, p. 64.
19. Hongjun Gao et al., "The Study on Ultrahigh Density Data Storage and Molecular Storage," www.casnano.ac.cn/english%20web/news/jindu/jd014.html.
20. D. W. Van Krevelen, *Properties of Polymers,* Elsevier, Amsterdam, 1997, p. 7.
21. University of Paisley, *Thin Film Centre Definition of Thin Films and Applications,* www.eep.paisley.ac.uk/ tfc/info.html.
22. Charles J. Murray, "Nanocircuits ride U.S., Japan advances," *Elect. Eng. Times,* Aug. 27, 2001, pp. 1, 98.
23. Eric Lerner, "Fluorescing nanoclusters," *The Industrial Physicist,* June/July 2001, pp. 8, 10.
24. A nanocluster or nanocrystal is a fragment of solid comprising somewhere between a few atoms to a few tens of thousands of atoms. See: www.genomicglossaries.com/content/miniaturization_glossary.asp.
25. *Science 2001*, *291*:103.
26. Hidefumi Hiura, *Physics Review Letters, 86:*1733, 2001; *The Industrial Physicist,* June/July 2001, p. 10.
27. "Holographic Storage Nears Debut," *Electronic Engineering Times,* Apr. 30, 2001, pp. 46, 78, 80.
28. H. J. Coufal, D. Psaltis, and G. T. Sincerbox, eds, *Holographic Data Storage,* Springer-Verlag, New York, 2000, p. 469.
29. Lisa Dhar, "A new venture in holographic storage," *The Industrial Physicist,* June/July 2001, pp. 26-27.
30. See: www.inphase-technologies.com.
31. N. Bertram, "UCSD Center for Magnetic Recording Research Investigates Data Rates," www.sdsc.edu/SDSCwire/v1.14/1051.bertram.html.
32. Koichi Sadashige, "Data Storage Technology Assessment 2000—Storage Media Environmental Durability and Stability," National Media Laboratory/3M, A National Technology Alliance Host, August 2000. Request a free CD-ROM copy by contacting George Sundem at NML e-mail: gesundem@mmm.com, or tel: +1-651-736-1542.
33. www.plasmon.com/news/phase.html.
34. K. S. Min, Y. J. Huh, and H. K. Shim, "New (MPD) Digital Versatile Disc Recordable (DVD-R) with Metal Thin Film and Organic Film on Polycarbonate," *J. of Appl. Physics, 38:*1675-1678, 1999, Japan; see also K. S. Min et al., "New Recordable Optical Discs with Metal Thin Film and Organic Film on Polycarbonate," *J. Appl. Physics, 37:*2089-2093, 1998, Japan.
35. T. Shintani et al., "A New Super-Resolution Film Applicable to Read-Only and Rewritable Optical Disks," *J. Appl. Physics,* 38:1656-1660, 1999, Japan.
36. Shin-ichi Morishima et al., "A New Type of Light Stabilizer for Dye Layers of Optical Disks: Tetracyano-quinodimethane Derivatives," *J. Appl. Physics, 38:*1634-1637, 1999, Japan.
37. Yoshiko Hara, "Hitachi clicks with camera maker on 100 Gbyte optical-disk system," *Electronic Engineering Times,* Oct. 15, 2001, p. 18.
38. Plasmon: www.plasmon.com/news/phase.html.
39. G.E. van Rosmalen et al., *SPIE,* Vol. 2338, 1994.
40. Chester W. Newell, "Petabyte Mass Storage Memory System Using the Newell Opticell," 4th NASA Goddard Conference on Mass Storage Systems and Technologies, March 1995, *NASA Conf. Publication CP-3295.*
41. www.nanochip.com.
42. Characterization is based on Tod Maffin's Future File, "Computing Beyond the Hard Disk."
43. See: IBM Research News "IBM's New Magnetic Hard Disk-Drive Media Delays Super-paramagnetic Effects," www.research.ibm.com/resources/news/20010518_white paper.shtml.
44. Storage: "Fuji 'Nano Cubic' Tech Will Take Tape to Terabytes," www.medialinenews.com/issues/2001/december/news1201_s3.shtml.
45. EurekAlert, "Molecular motor packs DNA into viruses at greater than champagne pressures, researchers report."
46. Carlos Bustamante et al., Professor of Physics and of Molecular and Cell Biology in the College of Letters & Science at UC Berkeley.
47. Janssen Pharmaceutical Research Foundation, "Transdermal Patches—Using Your Own Skin to Get the Medicine You Need," www.us.janssen.com/feature_articles/feature05122000.html.
48. "Molecular Sieves and the Prevention of the 'Vinegar Syndrome,'" www.kodak.com/country/US/en/motion/support/technical/vinegar.shtml and www.fpcfilm.com/US/en/motion/FPC/fpc/mole.html.
49. For a discussion on inert archival film containers, see: www.stildesign.com.
50. The definitions of many terms used can be found at: www.genomicglossaries.com/content/miniaturization_glossary.asp.
51. Jack Mason, "Nanobiotic Lifesavers," *MIT Tech. Review*," www.technologyreview.com/web/mason/mason102301.asp?nt=m1023h.
52. Rick Pilger, "The Big, Big Future of Tiny," www.ualberta.ca/ALUMNI/newtrail/01-2/nanotech.html.
53. For discussion of low lignin paper boxes, see: www.nara.gov/arch/techinfo/preserva/specs/lowlig.html.
54. Oak Ridge National Laboratory (U.S.) Institutional Plan FY 2001-FY 2005 Internal Review draft, May 31, 2000, www.er.doe.gov/dip/ORNL2000/ORNLird.pdf.

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