

INTRODUCTION

Since the dawn of time, man has tried to record important events and techniques for everyday life. At first, it was sufficient to paint on the family cave wall how one hunted. Then came the people who invented spoken languages and the need arose to record what one was saying without hearing it firsthand. Therefore, years later, earlier scholars invented writing to convey what was being said. Pictures gave way to letters which represented spoken sounds. Eventually clay tablets gave way to parchment, which gave way to paper. Paper was, and still is, the main way people convey information. However, in the mid twentieth century computers began to come into general use . . .

Computers have gone through their own evolution in storage media. In the forties, fifties, and sixties, everyone who took a computer course used punched cards to give the computer information and store data. In 1956, researchers at IBM developed the first disk storage system. This was called RAMAC (Random Access Method of Accounting and Control)

Since the days of punch cards, computer manufacturers have strived to squeeze more data into smaller spaces. That mission has produced both competing and complementary data storage technology including electronic circuits, magnetic media like hard disks and tape, and optical media such as compact disks.

Today, companies constantly push the limits of these technologies to improve their speed, reliability, and throughput -- all while reducing cost. The fastest and most expensive storage technology today is based on electronic storage in a circuit such as a solid state "disk drive" or flash RAM. This technology is getting faster and is able to store more information thanks to improved circuit manufacturing techniques that shrink the sizes of the chip features. Plans are underway for putting up to a gigabyte of data onto a single chip.

Magnetic storage technologies used for most computer hard disks are the most common and provide the best value for fast access to a large storage space. At the low end, disk drives cost as little as 25 cents per megabyte and provide access time to data in

Computer memory based on the protein bacterio-rhodopsin www.bestneo.com ten milliseconds. Drives can be ganged to improve reliability or throughput in a Redundant Array of Inexpensive Disks (RAID). Magnetic tape is somewhat slower than disk, but it is significantly cheaper per megabyte. At the high end, manufacturers are starting to ship tapes that hold 40 gigabytes of data. These can be arrayed together into a Redundant Array of Inexpensive Tapes (RAIT), if the throughput needs to be increased beyond the capability of one drive.

For randomly accessible removable storage, manufacturers are beginning to ship low-cost cartridges that combine the speed and random access of a hard drive with the low cost of tape. These drives can store from 100 megabytes to more than one gigabyte per cartridge.

Standard compact disks are also gaining a reputation as an incredibly cheap way of delivering data to desktops. They are the cheapest distribution medium around when purchased in large quantities (\$1 per 650 megabyte disk). This explains why so much software is sold on CD-ROM today. With desktop CD-ROM recorders, individuals are able to publish their own CD-ROMs.

With existing methods fast approaching their limits, it is no wonder that a number of new storage technologies are developing. Currently, researches are looking at protein-based memory to compete with the speed of electronic memory, the reliability of magnetic hard-disks, and the capacities of optical/magnetic storage. We contend that three-dimensional optical memory devices made from bacteriorhodopsin utilizing the two photon read and write-method is such a technology with which the future of memory lies.

In a prototype memory system, bacteriorhodopsin stores data in a 3-D matrix. The matrix can be build by placing the protein into a cuvette (a transparent vessel) filled with a polyacrylamide gel. The protein, which is in the bR state, gets fixed in by the polymerization of the gel. A battery of Krypton lasers and a charge-injection device (CID) array surround the cuvette and are used to write and read data.

While a molecule changes states within microseconds, the combined steps to read or write operation take about 10 milliseconds. However like the holographic storage, this

Computer memory based on the protein bacterio-rhodopsin www.bestneo.com device obtains data pages in parallel, so a 10 Mbps is possible. This speed is similar to that of slow semiconductor memory.

SEMICONDUCTOR MEMORY DEVELOPMENTS

The demands made upon computers and computing devices are increasing each year. Processor speeds are increasing at an extremely fast clip. However, the RAM used in most computers is the same type of memory used several years ago. The limits of making RAM denser are being reached. Surprisingly, these limits may be economical rather than physical. A decrease by a factor of two in size will increase the cost of manufacturing of semiconductor pieces by a factor of 5.

Currently, RAM is available in modules called SIMMs or DIMMS. These modules can be bought in various capacities from a few hundred kilobytes of RAM to about 64 megabytes. Anything more is both expensive and rare. These modules are generally 70ns; however 60ns and 100ns modules are available. The lower the nanosecond rating, the more the module will cost. Currently, a 64MB DIMM costs over \$400. All Dimms are 12cm by 3cm by 1cm or about 36 cubic centimeters. Whereas a 5 cubic centimeter block of bacteriorhodopsin studded polymer could theoretically store 512 gigabytes of information. When this comparison is made, the advantage becomes quite clear. Also, these bacteriorhodopsin modules could also theoretically run 1000 times faster.

In response to the demand for faster, more compact, and more affordable memory storage devices, several viable alternatives have appeared in recent years. Among the most promising approaches include memory storage using holography, polymer-based memory, and our focus, protein-based memory.

MEMORY RESEARCH AND DEVELOPMENT

Semiconductor memories were first developed in 1958 by Jack St. Clair Kilby was revolutionary for that era but this technology is already showing its age. As the millennium nears, research into memory technologies is expanding into new previously unexplored areas for digital storage solutions. These new fields promise to fulfill the data processing and computational needs of the 21st century. The primary forms of memory which are currently being explored are optical memory and molecular memory. One of the reasons why the need for new technologies has arisen is that the design and construction of smaller and smaller chips is becoming increasingly difficult. Manufacturers are working with dies in the .18 - .25 micron range. This will decrease even more but there is a finite limit to how far you can reduce the die sizes. The restrictions are twofold. One restriction is simply economic. The cost of producing smaller chips is skyrocketing. More importantly though the laws of physics will eventually halt this progression of decreasing dies. Moore's law states that the number of transistors on a chip will double approximately every 18 months and this has held true ever since he made his prediction in the 1960s. Semiconductor chips are manufactured using a process known as photolithography where the desired circuit features are mapped onto the silicon via a mask and a light source. The problem arises though that your light source must be at least as small as the features you're trying to fashion. This becomes increasingly difficult as the wavelengths of the spectrum are fixed and will not change. Krypton-Fluoride ultraviolet laser light is currently being used as the light source for .25 micron mask operations and although the masks can still be smaller, the task becomes increasingly complex. One developmental system which seeks to overcome these limitations is optical computing. Optical computing relies on photons rather than electrons for data transfer. Electrons although fast have mass and are limited in velocity. Photons on the other hand are based on light waves and as such have no mass and travel at the speed of light. The process of using light to store data is known as holography. Holographic data storage reads and writes entire blocks in a single operation making it extremely fast as a storage medium. The parallel nature of the data access means that speeds of up to 1 Gbps can be achieved and storage densities of 10 GB per cubic

Computer memory based on the protein bacterio-rhodopsin www.bestneo.com centimetre are capable. Polymer memory cubes exist which allow data to be stored and accessed in three dimensions making it very fast for optical storage. Another advantage is that the photons in the optical computer are not subject to electrical or magnetic interference as are their electronic counterparts. Building a system around photonics isn't as easy as it sounds though and many years of research and development will be needed before a successful system can be built. Several groups are working on such a system though. Researchers from TRW Space Technology Group, the University of California-Berkley, the National Institute of Standards and Technology, Hewlett-Packard Research Division and Stanford University are all working together in order to develop a digital computer system based on photonics. One of the difficulties which arise in building such a machine is that it is much more difficult to construct hardware which can control the photons. A second alternative to traditional storage mediums is molecular memory. At first this approach might seem somewhat odd and possibly insane. However some of the greatest scientific minds in history were considered insane at the time. Professor Robert Birge has developed a system to represent binary data using a protein known as bacteriorhodopsin. One might question why proteins would be used to store data. Size in general allows proteins to be a good candidate for data storage and the bacteriorhodopsin was chosen because its sensitivity to light allows it to change structurally and would be a good representation of a logic gate, the primary building block of our memory cell. A series of lasers is then used to excite the protein molecules and read or set their states. Currently speeds of 10 Mbps can be achieved however Professor Birge is convinced that 80 Mbps can be reached. So currently molecular memory isn't very fast in comparison to semiconductor memories but its advantages lie in the cost of developments, storage density, and its non-volatility.

3-DIMENSIONAL OPTICAL MEMORIES

Three-dimensional optical memory storage offers significant promise for the development of a new generation of ultra-high density RAMs (Birge, *Computer*, 63). One of the keys to this process lies in the ability of the protein to occupy different three-dimensional shapes and form cubic matrices in a polymer gel, allowing for truly three-dimensional memory storage. The other major component in the process lies in the use of

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a two-photon laser process to read and write data. As discussed earlier, storage capacity in two-dimensional optical memories is limited to approximately $1/\lambda^2$ (λ = wavelength of light), which comes out to approximately 10^8 bits per square centimeter. Three-dimensional memories, however, can store data at approximately $1/\lambda^3$, which yields densities of 10^{11} to 10^{13} bits per cubic centimeter. The memory storage scheme which we will focus on, proposed by Robert Birge in **Computer** (Nov. 1992), is designed to store up to 18 gigabytes within a data storage system with dimensions of 1.6 cm * 1.6 cm * 2 cm. Bear in mind, this memory capacity is well below the theoretical maximum limit of 512 gigabytes for the same volume (5-cm^3).

PROTEIN-BASED MEMORY

There have been many methods and proteins researched for use in computer applications in recent years. However, among the most promising approaches, and the focus of this particular webpage, is 3-Dimensional Optical RAM storage using the light sensitive protein bacteriorhodopsin.

Bacteriorhodopsin is a protein found in the purple membranes of several species of bacteria, most notably *Halobacterium halobium*. This particular bacteria live in salt marshes. Salt marshes have very high salinity and temperatures can reach 140 degrees Fahrenheit. Unlike most proteins, bacteriorhodopsin does not break down at these high temperatures.

Early research in the field of protein-based memories yielded some serious problems with using proteins for practical computer applications. Among the most serious of the problems was the instability and unreliable nature of proteins, which are subject to thermal and photochemical degradation, making room-temperature or higher-temperature use impossible. Largely through trial and error, and thanks in part to nature's own natural selection process, scientists stumbled upon bacteriorhodopsin, a light-harvesting protein that has certain properties which make it a prime candidate for computer applications. While bacteriorhodopsin can be used in any number of schemes to store memory, we will focus our attention on the use of bacteriorhodopsin in 3-Dimensional Optical Memories.

DEVELOPMENT

In the early 1970s Walther Stoeckenius and Dieter Oesterhelt at Rockefeller University in New York discovered that a protein isolated from a salt marsh bacterium exhibited photosensitive properties. They called this protein bacteriorhodopsin because it was very similar to the protein, rhodopsin that is found in the eyes of humans and animals.

Professor Birge was studying the biochemical basis of vision at the University of California at Riverside. He was originally working with a related protein called Rhodopsin, found in the retina of mammals.

He was originally interested purely in understanding how the light-activated changes occurred. In the late 1970s he became interested in bacteriorhodopsin. Professor Birge attempted to apply the photosensitive properties of the protein to the design of computer memories.

While Birge cautiously emphasizes that this technology is still in the developmental stage, its success several years down the road could increase computer memory 300-fold, succeeding the silicon chip as the optimal storage medium. The significance of this advance has not gone unnoticed—*Time Digital* named Birge to its top 50 Cyber Elite list in 1997. Birge's key patent, issued last year, is for a branched photocycle optical memory device, in which a laser-activated process triggers the protein through a series of states, including one state that has a long lifetime and is capable of storing data. A follow-up patent, currently pending, focuses on optimizing a modified version of the protein for the application. "As far as I know, we are the only researchers aggressively pursuing the three-dimensional protein-memory," says Birge, Distinguished Professor of Chemistry in The College of Arts and Sciences, who serves as director of the W.M. Keck Center for Molecular Electronics and research director of the Computer Applications and Software Engineering (CASE) Center.

Birge credits a group of creative graduate students who've worked with him through the years in advancing the technology. "I let them loose and see what they

Computer memory based on the protein bacterio-rhodopsin www.bestneo.com develop," he says. "They've been very successful at making devices and the most important device they're working on now is the 3-D memory."

One of those doctoral students, Jeff Stuart G'98, is director of the Advanced Prototyping Laboratory at the Keck Center. "Our goal is to understand the protein and use its unique properties to create a commercially viable product," says Stuart, a biochemist. "Dr. Birge's design represents the culmination of a lot of research by different scientists, but he's the one who figured out how to use bR as a memory medium in three dimensions."

In the lab Stuart points to a prototype, complete with lasers, on a tabletop. He explains the branched photocycle, which represents changes in the protein as its hit with lasers of varying intensity. The whole sequence—from the initial resting state through stages where information is written and stored—happens in a flash: 10 milliseconds. "It's really quite an elegant process," Stuart says. "There are many potential applications for this protein in the way it interacts with light. It's also great to be involved in such a project. Many scientists never get to work on a project as exciting as this."

Down the road, the rugged little protein may get a workout in parallel-processing computing and even associative memory, based on bar's holographic properties. Like many new technologies, it spawned a start-up company based at the CASE Center that acquired a license to some of the technology. While Birge remains focused on the research, he isn't interested in becoming a high-tech entrepreneur. "In about two years, we'll know whether this technology is going to fly. If it looks like it's really going to take off, a large company may have to come in and buy the technology and pursue it," he says. "I have no interest in the commercialization of this technology beyond what we can do in the lab."

Chaiken, Birge's Keck Center colleague, takes a different approach, enjoying a mix of research and entrepreneurship. "The need for memory is insatiable," he says. If his vision pans out, a new high-capacity storage device he's developing could be introduced in a couple of years to a targeted market. Sitting in his office early one Monday morning,

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he flashes a blue laser beam against the wall. "There haven't really been any blue lasers this small until now," says Chaiken, who launched Laser Chemical Corporation to commercialize the technology. "And they're needed to produce new drives and other products."

The blue laser—which is also of interest to Birge's team for use in the erasing process—is produced by Nanolambda Corporation, an upstate New York company that is collaborating with Chaiken's Laser Chemical Corporation to make prototype drives. The laser is a component in a Photochromic Optical Memory System (POMS) created by Chaiken and scientist Joseph Osman of the Air Force Research Laboratory in Rome, New York. They developed POMS out of their patented data storage process. By switching between blue and infrared lasers on a layer of tungsten-oxide—for which Chaiken has a separate patent—data can be written, stored, and erased. Basically, the interaction with the lasers alters the material's color, thus distinguishing between written and unwritten spots. Chaiken, who also holds a patent relating to transparent metal films, says the key to the system is its ability to store large volumes of information. "We're shooting for a capacity of at least 2,000 gigabytes on a single slab (1 foot by 2 feet by 1/2 inch)," he says. "Everybody is going for density these days, but what's important is capacity, in my opinion and reading of the market. The POMS technical advantage derives from the fact that other media, i.e., magneto-optic, phase change (DVD), and conventional magnetic material, can't be manufactured in such large pieces."

Rather than fumbling with zip drives or dozens of disks, he wants to store huge amounts of information in one place. "We hope to get away from the round spinning disk paradigm and use simple rectilinear motion instead. The whole paradigm will be different," he says. "Our first generation product will be simply recordable, and on the second generation we'll introduce erasability."

Chaiken, of course, doesn't plan on burying the CD-ROM or floppy disk markets. Instead, he's after a niche market, envisioning such customers as government agencies and hospitals—any place that files away warehouses of information and can benefit from replacing filing cabinets with an easily searched high-capacity medium. "Just as the

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transportation market supports many types of products and models, you're going to look out on the parking lot of storage devices and see lots of different ones. There's plenty of room in the market for them, and I wish them luck because I'll want those other products for my own applications. But when you want a lot of capacity on a single volume, very often you'll want to come to us instead of using magnetic tape," he says. "We're trying to produce prototypes of a product that could be on the market as soon as possible to get a good grip on the particular market share we're targeting."

PROCESS OF PROTEIN EXTRACTION.

Anyone who has ever fallen on grass knows that nature has chemicals that are as permanent as ink. At least one of those chemicals holds promise as an "electronic ink" that can be used in improved computer displays.

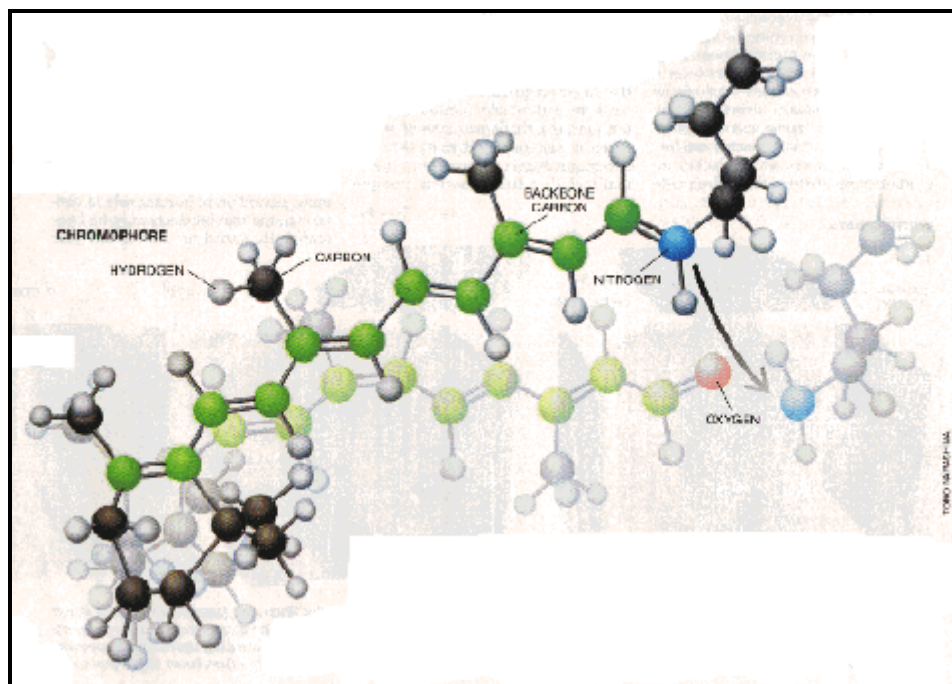
The chemical is bacteriorhodopsin, a purple protein essential to the cell wall of *Halobacterium halobium*, a mysterious resident of salt-marshes and lakes. When nutrients get scarce, this bacteriorhodopsin becomes a light-converting enzyme that keeps the organism's life cycle going. It's a protein powerhouse that in times of famine flips back and forth between purple and yellow colors. If controllable, this could be valuable in computer display panels.

The process of making the protein cube has many different steps. First the bacterial DNA is spliced and mutated to make the protein more efficient for use as a volumetric memory. Then, the bacteria must be grown in large batches and the protein extracted. Finally, the purified protein is put into the cube and used as a volumetric storage medium. The cube is read by two lasers as binary code. One laser is used to activate the protein in a section of the cube. The other laser is used to write or read binary information in the same section. The data is assigned as either a zero or a one. The binary code is then analyzed by the computer as various pieces of information.

BACTERIORHODOPSIN PHOTOCYCLE

Bacteriorhodopsin is a photochemically active protein found in the purple membrane of the bacteria *Halobacterium salinarium*, which was known as *Halobacterium halobium*. The polypeptide chain is made of seven closely spaced alpha-helical segments looped across the lipid bilayer. The interhelical space contains the all-*trans*-retinal chromophore which is linked to lys-216 on helix G as a protonated Schiff base.

Photochemically active means that it reacts to light. It has a photochemical reaction cycle, or photocycle. This cycle basically transports protons from inside the cell to outside the cell in the bacteria *Halobacterium halobium*. The native photocycle has several spectroscopically unique steps, bR \rightarrow K \leftrightarrow L \leftrightarrow M1 \rightarrow M2 \leftrightarrow N \leftrightarrow O, which occur in a roughly linear order. The bR state is the protein in its native state and each intermediate is represented by a letter of the alphabet. However, the important, main photochemical event in this cycle is a trans to cis photoisomerization around the thirteenth Carbon atom to the fourteenth carbon double bond in the chromophore.



This is the chromophore

At around the temperature of 80 K, the native protein undergoes this photocycle and switches between a green absorbing state and a red absorbing state. At approximately room temperature, the protein switches between a green absorbing state and a blue absorbing state. In both the ground (green) and excited (red or blue) states, the chromophore displays several metastable configurations. The main event follows these steps:

1. A change in the shape of the conformational potential energy surface resulting from electron excitation
2. A conformational change
3. A non-radiative decay to the ground state

The single critical step in the proton pumping ability of the protein is the transfer of the Schiff base proton to Asp85, and piece of the protein, in the L → M reaction. Absorption of light leads to rapid photoisomerization in the excited state because the barrier to conformational change in that state is negative. In a manner of thinking, the conformational motion of the excited state acts to gate the conformational motion of the ground state.

In the L state, the Schiff base exhibits strong H-bonding with close water molecules and distorts the chromophore near the Schiff base. The two necessary coordinators for these water molecules are the anionic Asp85 and Asp212. That coincides with the Trp182 interacting with the retinal skeleton by the 9-methyl group. These events bring about the deprotonation of the Schiff base.

Also in the L intermediate state, the backbone has good local structural flexibility. This is evidenced by the many different change in the peptide C to O double bond stretching vibrational frequencies. Some of these frequency variations correlate to the O to H single bond stretching vibrational frequencies. This indicates that the structural changes can come from changing interaction with water molecules. A network of H-bonding including bonds between water and peptides, exists between two pieces of the protein, Asp85 and Asp96. This network exhibits changes most often in the bR to L

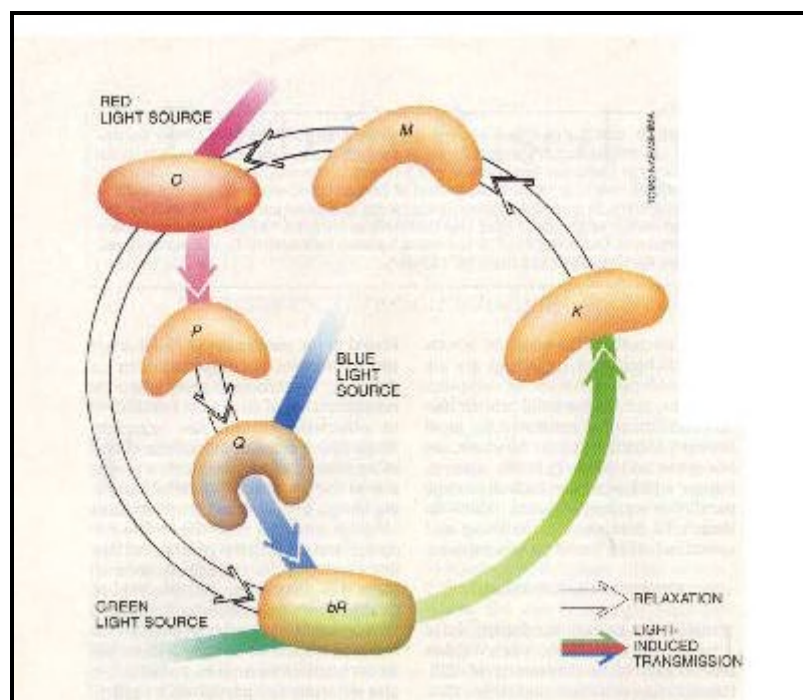
Computer memory based on the protein bacterio-rhodopsin www.bestneo.com transformation, which would be the first step in writing to a block of bacteriorhodopsin memory.

In the K intermediate, an H-bonding change of the peptide C to O double bond of a valine residue, called Val49, occurs. This stays on in the L intermediate, but is gone in the M intermediate. This is affected by a mutation in the protein.

Water appears to affect the C to O double bond affects the protein at specific regions. Some, which exhibit O to H single bond stretching frequencies, interact with the C to O double bond of the Val49 piece.

The relative stability of some of the intermediate states determines their usefulness in computing applications. The initial state of the native protein, often designated bR, is quite stable. Some of the intermediates are stable at about 80K and some are stable at room temperature, lending themselves to different types of RAM.

For computers, the two or three most stable states of the protein would be used to record data in binary form. This is the proposed photocycle for computing needs:



The photocycle for computer memory

An interesting intermediate in the photocycle is the *O* intermediate. The *O* intermediate is an all-trans structure like the native protein state. The native state is a light-adapted state. The *O* state is the red absorbing state.

The M state, or unprotonated Schiff base, does not accumulate in the photocycle. This is strange since this protein transports protons. This could mean two things. The first is that the M state cannot be observed because the kinetics is set against its build-up. The other is that the Schiff base does not deprotonate and the transport is based on a completely different mechanism than the wild type protein. The two kinetic reasons for this lack of M are that the rate of decay of M is faster than the rate of formation or that the $L \leftrightarrow M$ and $M \leftrightarrow N$ equilibrium are tilted away from the M state.

DATA WRITING TECHNIQUE

Bacteriorhodopsin, after being initially exposed to light (in our case a laser beam), will change to between photoisomers during the main photochemical event when it absorbs energy from a second laser beam. This process is known as sequential one-photon architecture, or two-photon absorption. While early efforts to make use of this property were carried out at cryogenic temperatures (liquid nitrogen temperatures), modern research has made use of the different states of bacteriorhodopsin to carry out these operations at room-temperature.

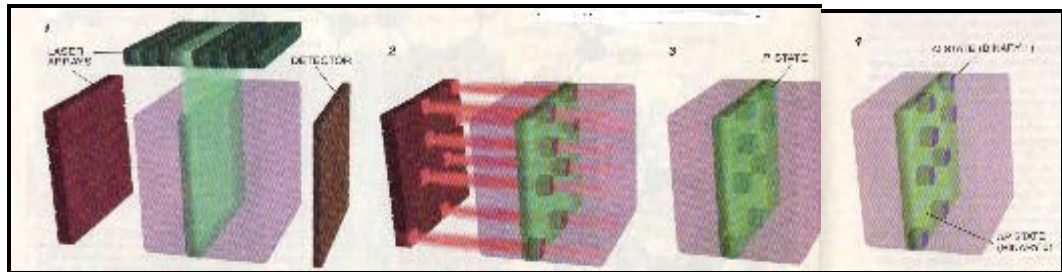
The process breaks down like this:

Upon initially being struck with light (a laser beam), the bacteriorhodopsin alters its structure from the bR native state to a form we will call the *O* state. After a second pulse of light, the *O* state then changes to a *P* form, which quickly reverts to a very stable *Q* state, which is stable for long periods of time (even up to several years).

The data writing technique proposed by Dr. Birge involves the use of a three-dimensional data storage system. In this case, a cube of bacteriorhodopsin in a polymer gel is surrounded by two arrays of laser beams placed at 90 degree angles from each

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other. One array of lasers, all set to green (called "paging" beams), activates the photocycle of the protein in any selected square plane, or page, within the cube. After a few milliseconds, the number of intermediate *O* stages of bacteriorhodopsin reaches near maximum. Now the other set, or array, of lasers - this time of red beams - is fired.

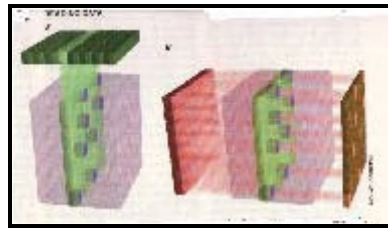


The write process

The second array is programmed to strike only the region of the activated square where the data bits are to be written, switching molecules there to the *P* structure. The *P* intermediate then quickly relaxes to the highly stable *Q* state. We then assign the initially-excited state, the *O* state, to a binary value of 0, and the *P* and *Q* states are assigned a binary value of 1. This process is now analogous to the binary switching system which is used in existing semiconductor and magnetic memories. However, because the laser array can activate molecules in various places throughout the selected page or plane, multiple data locations (known as "addresses") can be written simultaneously - or in other words, in parallel.

DATA READING TECHNIQUE

The system for reading stored memory, either during processing or extraction of a result, relies on the selective absorption of red light by the *O* intermediate state of bacteriorhodopsin. To read multiple bits of data in parallel, we start just as we do in the writing process. First, the green paging beam is fired at the square of protein to be read. After two milliseconds (enough time for the maximum amount of *O* intermediates to appear), the entire red laser array is turned on at a very low intensity of red light. The molecules that are in the binary state 1 (*P* or *Q* intermediate states) do not absorb the red light, or change their states, as they have already been excited by the intense red light during the data writing stage.



The read process

However, the molecules which started out in the binary state 0 (the *O* intermediate state), do absorb the low-intensity red beams. A detector then images (reads) the light passing through the cube of memory and records the location of the *O* and *P* or *Q* structures; or in terms of binary code, the detector reads 0's and 1's. The process is complete in approximately 10 milliseconds, a rate of 10 megabytes per second for each page of memory.

Birge has built a prototype memory system where bacteriorhodopsin stores data in a 3-D matrix. He builds this matrix by placing the protein into a cuvette (a transparent vessel) filled with a polyacrylamide gel. The cuvette is oblong and 1 by 1 by 2 inches in size. The protein, which is in the bR state, gets fixed in place by the polymerization of the gel. A battery of krypton lasers and a charge-injection device (CID) array surround the cuvette and are used to write and read data.

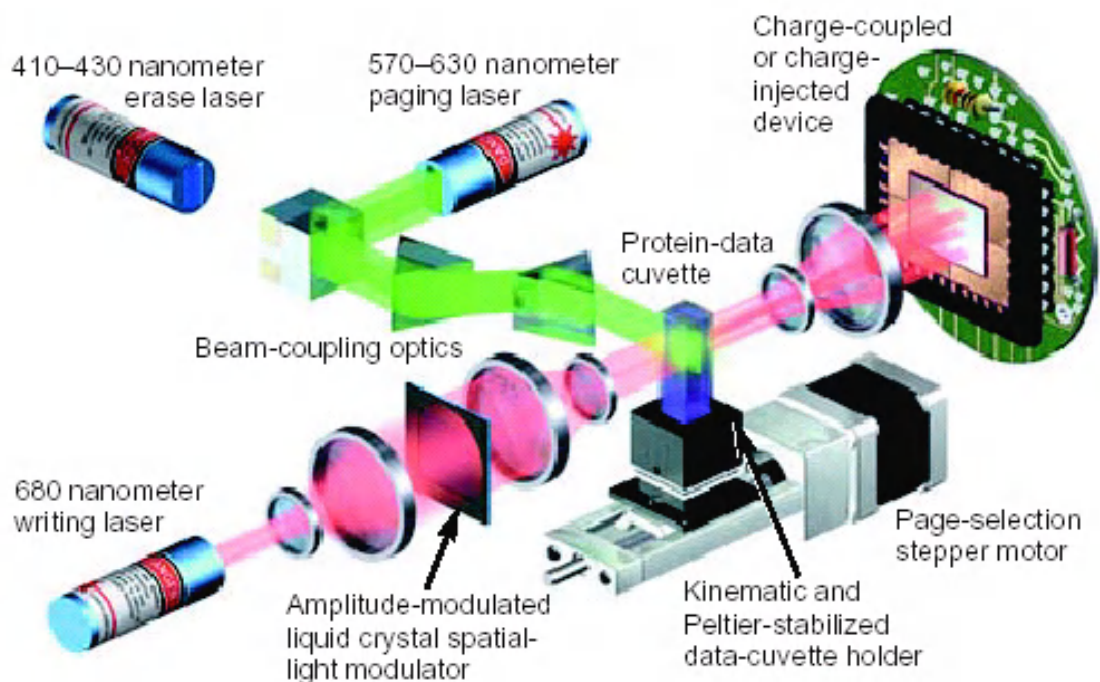
Clearly, there are many advantages to protein-based memory, among the most significant being cost, size, and memory density. However, there are still several barriers standing in the way of mass-produced protein-based memories. Find out more about what needs to be done before protein-based RAMs appear on the market.

DATA ERASING

To erase data, a brief pulse from a blue laser returns molecules in the *Q* state back to the rest state. The blue light doesn't necessarily have to be a laser; you can bulk-erase the cuvette by exposing it to an incandescent light with ultraviolet output.

REFRESHING THE MEMORY

To ensure data integrity during selective page-erase operations, Birge caches several adjacent data pages. The read/write operations also use 2 additional parity bits to guard against errors. A page of data can be read nondestructively about 5000 times. Each page is monitored by a counter, and after 1024 reads, the page is refreshed via a new write operation.



ACTUAL IMPLEMENTATION

INTRINSIC WORTH

However, the merits of molecular storage have garnered sufficient interest that three of NASA's Space Shuttle missions explored methods to improve the manufacture of the data cubes by using microgravity. The resulting material was more homogeneous and provided an enhanced storage density. It remains to be seen, however, whether microgravity manufacturing will be sufficiently cost-effective to justify the observed factor-of-four improvement.

Can molecular storage compete with traditional semiconductor memory? The design certainly has its merits. First, it's based on a protein that's inexpensive to produce in quantity. In fact, genetic engineering is being used to boost the output of the protein by the bacterium. Second, the system has the ability to operate over a wider range of temperatures than semiconductor memory.

Third, the data is stable. If you turn off the memory system's power, the bacteriorhodopsin molecules retain their information. This makes for an energy-efficient computer that can be powered down yet still be ready to work with immediately because the contents of its memory are preserved.

Data recorded on a bacteriorhodopsin storage device would be stable for approximately five years. "We have lab samples that have held information reliably for two years," he says. Another important feature of bacteriorhodopsin is that these two states have widely different absorption spectra. This makes it easy to determine a molecule's current state using a laser tuned to the proper frequency.

Finally, you can remove the small data cubes and ship gigabytes of data around for storage or backups. Because the cubes contain no moving parts, it's safer than using a small hard drive or cartridge for this task.

CONCLUSION

Birge's system, which he categorizes as a level-I prototype (i.e., a proof of concept), sits on a lab bench. He has received additional funding from the U.S. Air Force, Syracuse University (Syracuse, NY), and the W. M. Keck Foundation to develop a level-II prototype. Such a prototype would fit and operate within a desktop personal computer. "We're a year or two away from doing internal testing on a level-II prototype," says Birge. "Within three to five years, we could have a level-III beta-test prototype ready, which would be a commercial product."