

## INTRODUCTION

### MOLECULAR AND BIOMOLECULAR ELECTRONICS

Biomolecular electronics offer significant promise in addressing some of the interest limitations of semi conductor architectures.

Molecular electronics is an emerging field that lies at the interface of chemical physics, bio physics, electrical engineering and physics, bio physics, electrical engineering and solid state science. It involves the encoding manipulation and retrieval of information at a macromolecular level in contrast to current techniques.

Molecular electronics not only represents the final technological state in the miniaturisation of the Computer circuitry, it also provides promising new methodologies for high speed signal processing, holographic associative memories and three dimensional optical memories.

As mentioned earlier the computer industries are on the process of making the individual components on semi conductor devices competitively smaller. These small chips essentially consists of arrays of switches usually of the kind known as logic gates that flip between two states designated as '0' and '1' in response to the changes in electric currents passing through them.

There is a serious road block in miniaturization, that is the increase in the price of production by a factor of five, for every factor of two in miniaturization. At some points the search for even smaller electronic devices may be limited by economics rather than physics.

All those problems are over come by the use of biological molecules as the active components in biological molecules as the active components in Computer circuitry.

Molecules can potentially serve as Computer switches because their atoms are mobile and change position in a predictable way. If we can direct that atomic motion and there by consistently generate at least two discrete states in a molecule, we can use each state to represent either a '0' or '1'. Such switches offer reduction in the size of hardware because they are themselves small by about one thousand the size of semi conductor transistors used today as gates.

Indeed a biomolecular Computer could in principle be one fiftieth the size of a present day semi conductor Computer composed of similar number of logic elements. Protein based Computers could theoretically operate 100 times faster than modern Computers.

Researchers have introduced parallel processing architectures, which allow multiple sets of data to be manipulated simultaneously. In order to expand memory

capacities they are devising hardware that stores data in three dimensions instead of the usual two, and scientists have built the neural networks that mimic the learning by association capabilities of the brain, an ability necessary for significant progress towards artificial intelligence.

Although no Computer components made entirely or partly from proteins are on the market yet; on going international research efforts are making exciting headway.

Liquid crystal display technology offers a prime example of a hybrid system that has achieved commercial success. Most laptop Computers today depend on LCD's which combine semiconductor devices and organic molecules to control the intensity of the image on the screen.

Several biological molecules are under consideration for use in Computer hardware but the bacterial protein "BACTERTORHODOSPIN" has generated the maximum interest. This protein is by no means the only photochemically active biological material capable of storing and manipulating data but it has received significantly more attention than others. Other proteins under study include the visual pigment rhodospin, photosynthetic reaction centers, phycobiliproteins, phytochromes.

## ORIGIN IN THE SALT MARSHES

Interest in Bacteriorhodopsin dates back to the early 1970's when Walther Stocknius of the University of California at San Francisco and Dieter Oesterhelt discovered that the protein exhibited unusual properties when it was exposed to light.

Bacteriorhodopsin is the light harvesting protein in the purple membrane of a micro organism called Halobacterium Halobium. This bacterium grows in salt marshes where the salt concentration is roughly six times that of seawater. It grows the purple membrane when the oxygen concentration is too low to sustain respiration. The protein upon the absorption of light pumps a proton across the membrane generating a chemical and osmotic potential that serves as an alternative source of energy. Thus Halobacterium Halobium can switch from respiration to photosynthesis when the need arises, a unique capability among organisms.

Survival in harsh environment of a salt marsh where temperatures can exceed 150(0) F for extended periods of time requires a robust protein that resist thermal and photochemical damage. The protein's cyclicality exceeds 10(6), a value higher than that of the most synthetic photochromic materials. Thus the common perception that the biological materials are too fragile for use in computing devices does not apply to Bacteriorhodopsin.

Both rhodospin and Bacteriorhodopsin are complex proteins that include a light absorbing component known as a "chromophore". The chromophore absorbs energy from light, triggering a complex series of internal motions that result in the dramatic changes in the structure of the larger proteins optical and electrical characteristics. For example , when rhodopsin absorbs light in the human eye, the change in structure releases energy that serves as electrical signals, able to convey visual information to the brain.

### COMPUTER APPLICATIONS

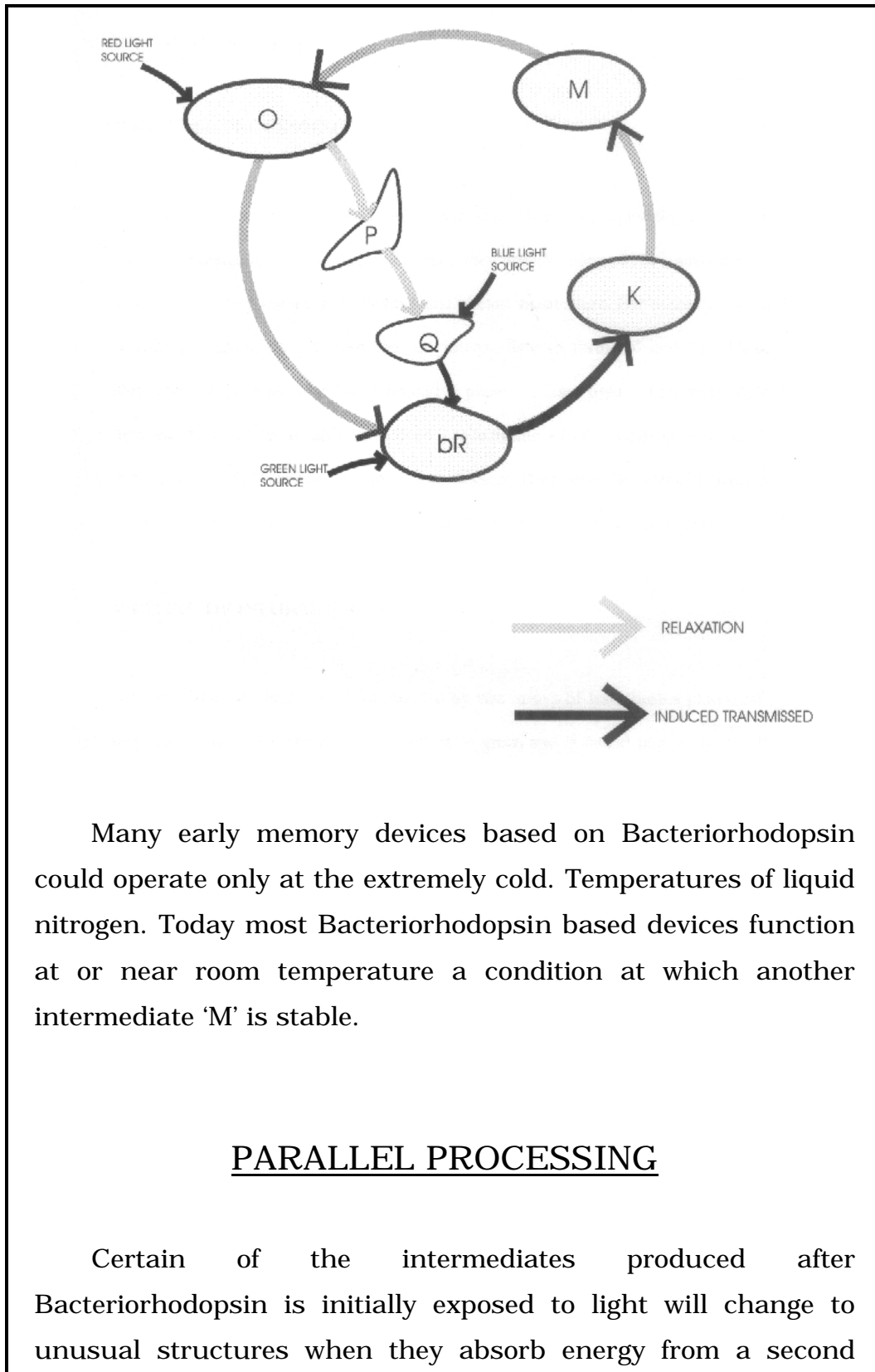
Bacteriorhodopsin was on focus instead of rhodopsin because of the formers greater stability and better optical properties. Also it can be prepared in large quantities.

The applications under study for computer processors and the memories on which they operate exploit what is called the photocycle - the series of structured changes Bacteriorhodopsin under goes in response to light.

### PHOTOCYCLE OF BACTERIORHODOPSIN

The sequence of structural changes induced by light - allows for the storage of data in memory. Green light transforms

the initial resting state known as bR to the intermediate 'k'. This takes place in a few trillions of a second. Next 'k' relaxes forming 'M' and then to the 'O' state. If the 'O' intermediate is exposed to red light a so-called branching reaction occurs. Structure 'O' converts to 'P' state which quickly relaxes to the Q state — a form that remains stable almost indefinitely. Blue light will however convert it back to bR. Any two long lasting states can be assigned the binary values '0' and '1', making it possible to store information as a series of Bacteriorhodopsin molecules in one state or the other. Most devices under study make use of the resting state and one intermediate of Bacteriorhodopsin. One state is designated as '0' and the other as '1' and the switching between the states is controlled by a laser beam. (Figure 1)



Many early memory devices based on Bacteriorhodopsin could operate only at the extremely cold. Temperatures of liquid nitrogen. Today most Bacteriorhodopsin based devices function at or near room temperature a condition at which another intermediate 'M' is stable.

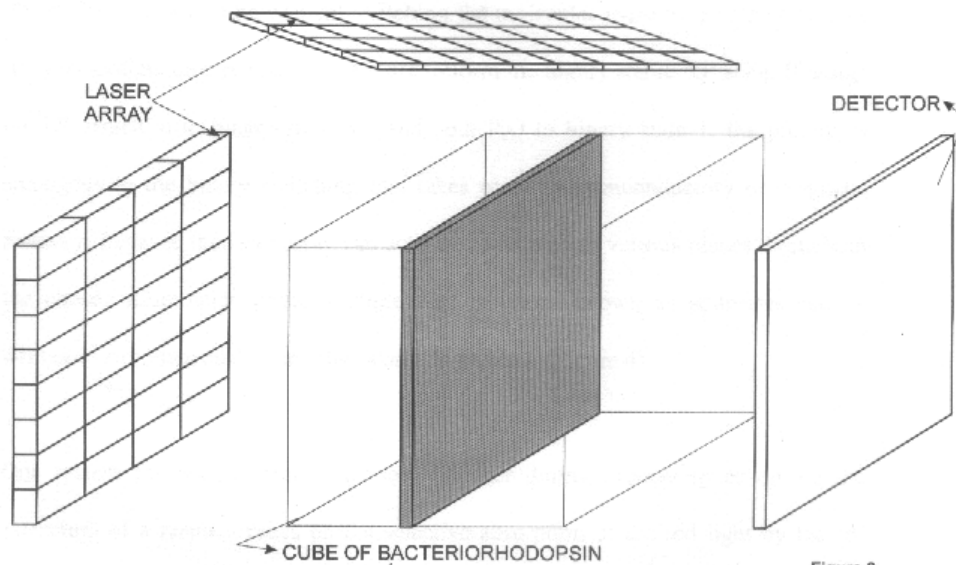
### PARALLEL PROCESSING

Certain of the intermediates produced after Bacteriorhodopsin is initially exposed to light will change to unusual structures when they absorb energy from a second

laser beam in a process known as sequential one photon architecture. For example such a branching reaction occurs from the 'O' intermediate to form 'p' and 'q'. These structures are generated by two consecutive pulses of laser light — first green light then red. Although 'p' is fairly short lived it relaxes into a form known as 'q' which is stable for extended periods even up to several years. Because of its extended stability the 'Q' state has great significance in the search for long term high-density memory.

### WRITING OF INFORMATION

A cube of bacteriorhodopsin is surrounded by two arrays of laser beams placed 90° from each other. One array of lasers all set to green and is called paging beams. It activates the photocycle of the protein. (Figure 2)



Writing of information into cubes of bacteriorhodopsin and reading out of that information is accomplished with these laser beams. The writing process is begun by firing these green laser beams through a plane of the cube. This step begins the protein photocycle.

After a few milliseconds when the number of '0' intermediates reaches near maximum the other laser array, this time of red beam is fired. (Figure 3)

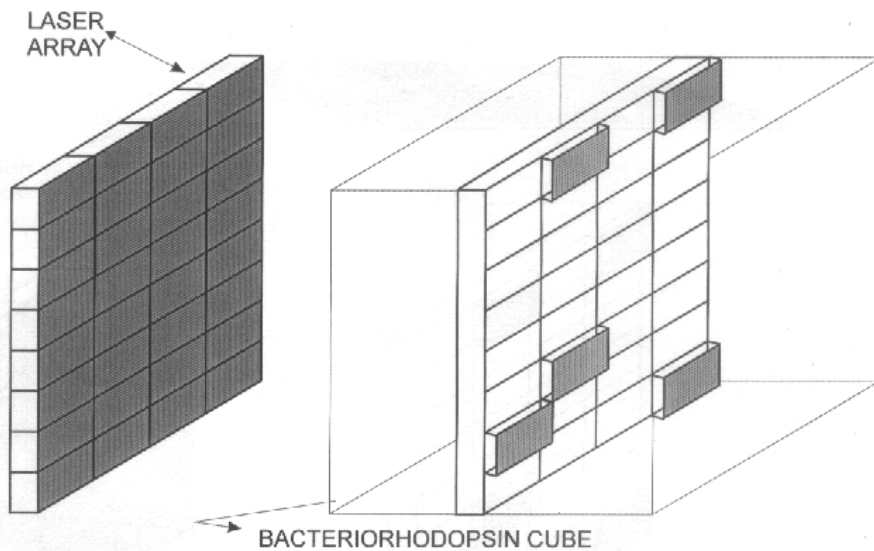


Figure 3

This second array is programmed to illuminate only the region of the activated square where data bits are to be written, switching the molecules there to 'p' structure. The 'p' intermediate then relaxes its structure to form the highly stable 'Q' state. If assign the bR structure to binary state '0' and both P,Q to binary state 1, the process is analogous to the binary switching that takes place in semiconductory or magnetic memory. Because the laser array can activate molecules in various places throughout the chosen illuminated page, multiple data locations known as addresses can be written to simultaneously - in other words in parallel. (Figure 4)

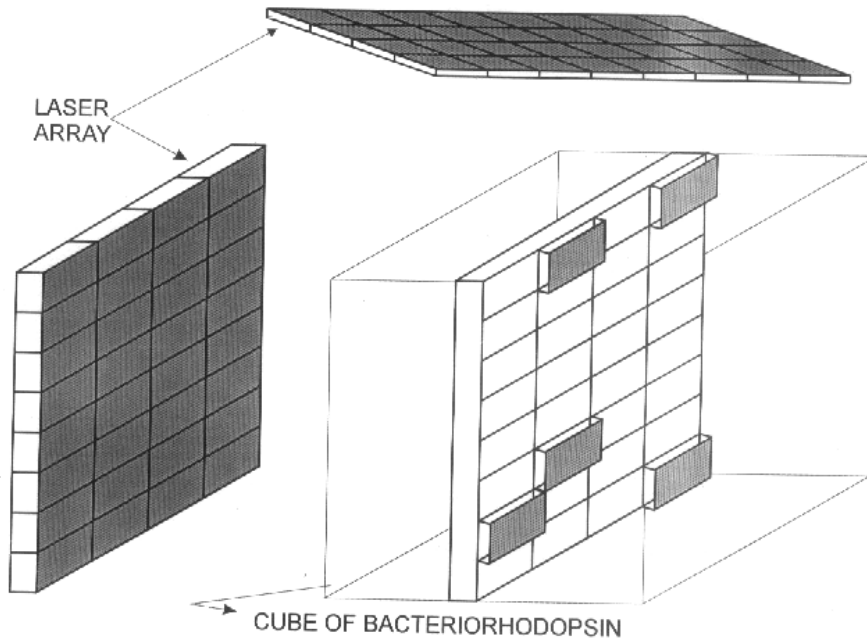


Figure 4

Our system for reading stored memory whether during processing or during the extraction of a result - relies on the selective absorption of the red light by the 'o' intermediate. The red lasers of low intensities are fired. Molecules that were originally in the bR state absorb the red light and the molecules in the p or q state allow the low light levels to pass through. Hence the resulting pattern of dark and light - that is '0's and '1's can be picked by a detector placed directly opposite from the red laser array.

The whole process is completed in approximately 10 milliseconds, rate of 10 megabytes per second for each page of memory.

## NEURAL NETWORKS

### HOLOGRAPHIC ASSOCIATIVE MEMORIES

Associative memories operate quite differently from the serial memories that dominate current computer architectures. Associative memories take an input datablock or image, and independently of the central processor. Scan the entire memory for the datablock that matches the inputs. For some implementations the memory will find the closest match, if it cannot find a perfect match.

A promising application of bacteriorhodopsin is under development at the Centre for Molecular Electronics. It uses thin films of bR as the photoactive component in Fourier transform holographic associative memories. The holographic associative memories also facilitate the existence of cryogenic RAMs and Random Access Cache memories. Because the human brain operates in a neural associative mode many computer scientists believe large capacity associative memories are necessary to fully achieve artificial intelligence.

Many laboratories have developed an associative memory device that relies on holographic properties of thin films of Bacteriorhodopsin. Holograms allow multiple images to be stored in the same segment of memory Bacteriorhodopsin sin

can be written to and read from many more times than can crystal which suffer from fatigue after repeated read and write cycles. Associative memories have significant potential for applications in optical computer architectures, optically coupled neural networks computer, robotic vision hardware and genetic pattern recognition systems.

### THREE DIMENSIONAL MEMORIES

In addition to facilitating parallel processing the three dimensional cubes of Bacteriorhodopsin provide much more memory space than do two dimensional optical memories. Two dimensional memories have a storage capacity that is limited to about 100 million bit per square centimetre. In contrast three dimensional optical memories can theoretically approach storage densities of one trillion bits per cubic centimetre. Nevertheless most investigators believe a 300 fold improvement in storage capacity over two dimensional devices should be possible.

Speed is also an important benefit of volumetric memories. The combination of three dimensional storage with the use of parallel architectures enhanced the speed of such memories. The entire writing process described above takes place in about 10 milliseconds. If we illuminate a square measuring 1024 bits by 1024 bits within a larger cube of protein. We can write 1048576 bit of data or about 105 kilobytes into memory in a 10 millisecond cycle. These values represent an over all write speed

of 10 million characters per second. Cubes of memory should be extremely uniform in their composition to ensure accurate reading and writing.

## CONCLUSION

The Hybrid computers we envision should be highly flexible. The computer will be able to handle large pools of data, carry out complex scientific simulations or serve as a unique platform for investigations of artificial intelligence.

With close to a terabyte (1d bytes) of memory in cubes of Bacteriorhodopsin, this machine would handle large data bases with alacrity.

The hybrid computers of some type are likely to be available within the next few years. Soon they will evolve into the dominant architecture for certain types of computing such as for scientific calculations, and multimedia applications.

Imagine the advantage of carrying in your pocket a small cube storing the equivalent of a comprehensive encyclopaedia and all the words you have written in the past 10 years. We are indeed at the threshold of an exiting new era in computing.

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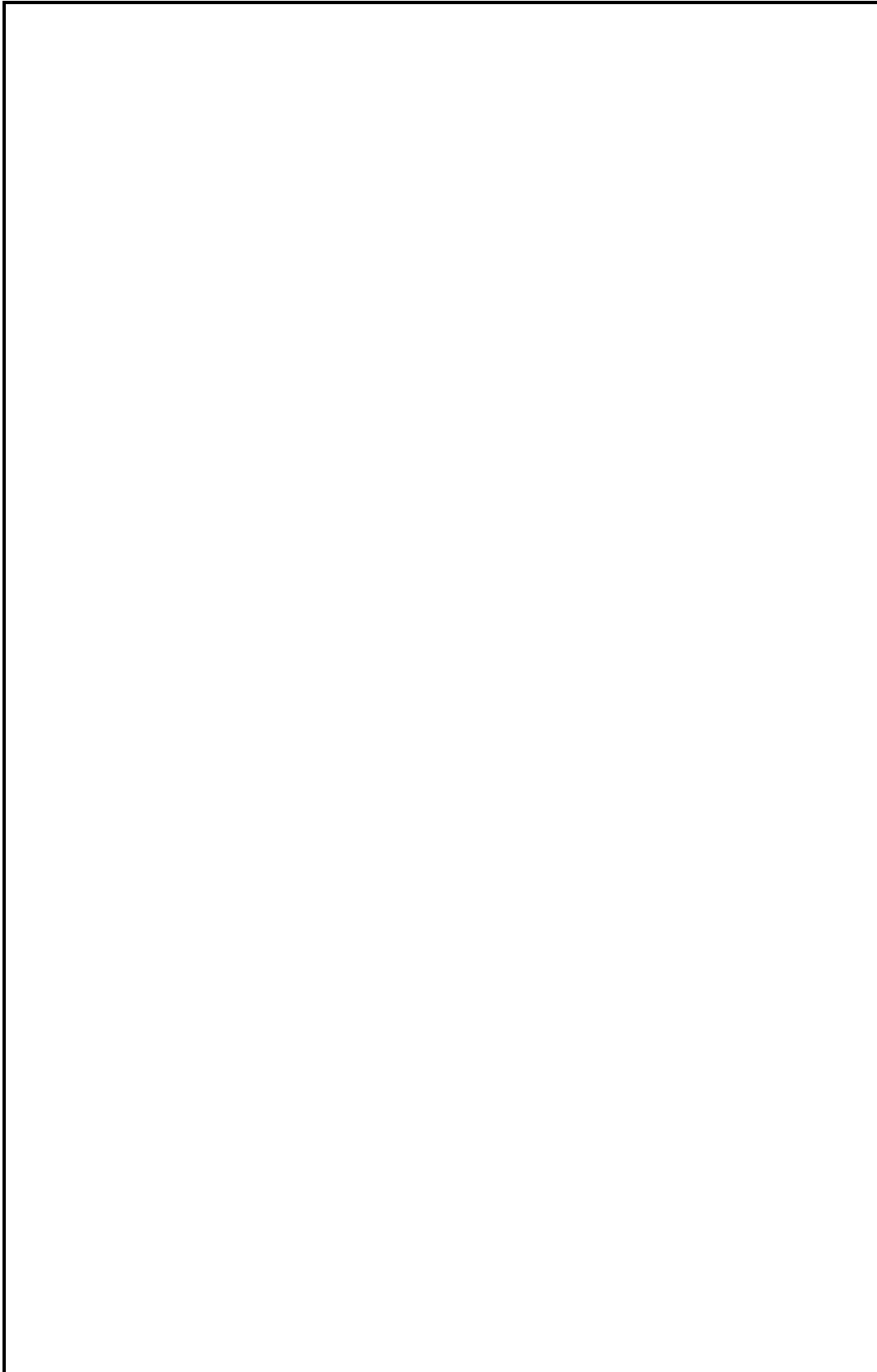
## ABSTRACT

The world's most advanced super Computer does not require semi-conductor chip. The human brain consists of organic molecules that combine to form a highly sophisticated network able to calculate, perceive, manipulate, self-repair, think and heal. Digital computers can certainly perform calculation much faster and more precisely than humans can, but even simple organisms are superior to computers in the other five domains.

Computer designers may never be able to design machines having all the faculties of a natural brain, but many of us think that we can exploit some special properties of biological molecules - particularly proteins - to build Computer components that are smaller, faster and more powerful than any other electronic device on the drawing board thus far.

The size issue is especially pressing since the 1960's the Computer industry has been compelled to make the individual components on semiconductor chips smaller and smaller in order to manufacture larger memories and more powerful processors economically. If the trend towards miniaturisation continues the size of a single large gate will approach the size of molecules by about 2030. But unfortunately for each factor of two in miniaturisation the cost of manufacturing a chip increases by five. On the other hand the use of biological molecules as active components in Computer circuitry may offer an alternative approach that is more economical. Devices fabricated from biological molecules promise compact size and faster data storage. They lend themselves to use in parallel processing computers, three dimensional memories and neural networks.

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