Biological Computing
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Why Should We Care About Biological Computing?

Biological Computing, an innovation with the potential to address the short-comings of silicon-based computing, is already a part of your life. Look in the mirror, and behold a highly advanced biological computer. It is radically different from what most people recognize as a computer, but it is a computer nevertheless. It is also a computer that offers valuable lessons to those who are looking for alternatives to traditional computer design. These are lessons about using biological organisms and their components to solve computational problems. Lessons drawn from this very different computing design help shape an alternative that could eventually replace or complement computers as we know them today. And such work is timely, as the theoretical limits of current computer design grow closer.

Moore's Law has long offered a roadmap for advances in computing power. In 1965, Gordon Moore predicted that computer processing power should double approximately every 12 months, eventually amending this prediction to 18 months.[1] Developments in computer chip design have kept up with the current version of Moore's Law, but this pace cannot continue indefinitely. As we will describe below, the laws of physics impose a physical limit on how much processing power can be achieved with a silicon chip.

Similarly, the ability of medicine to treat diseases more effectively is limited by the ability of current bio-technology to interface with the processes of the body. We do not yet have an effective way for silicon-based computers to interact directly with the chemical processes of the human body in order to diagnose and treat illnesses.

Biological computing has the potential to solve both problems. This paper sets the stage for considering this topic by examining the limitations of the silicon-based computing paradigm and discussing the other alternative paradigms. It then focuses on biological computing in all its varieties and considers the benefits and possible problems of this radically different form of computing. First, let us consider the limitations of current computing technology.

What are the Limitations of Current Computing Technology?

As noted above, the processing power of silicon-based computing is possible up to the point of the limitations imposed on it by the laws of physics. But there are additional problems with silicon-based technology that make finding viable alternatives even more imperative.

First, let's look at the limitations imposed by physics. The 'processing power' of computers is usually measured by speed. Here speed means how fast circuits can move information from A to B and how fast the information can be processed once it gets to B.[2] The traditional computing design paradigm focuses

[1] Kanellos, Michael, "Moore's Law will continue to rule," July 10, 2002, http://www.zdnet.com/2100-1103-942688.html
[2] Lopez, Alexander, "Computers are becoming faster and cheaper, but their speed is still limited by the physical restrictions of an electron moving through matter. What technologies are emerging to break

on decreasing the distance that information (in the form of electrical signals) have to travel; in other words, shortening the distance between A and B. This has meant packing more and more processing elements or transistors into the central processing chip of the computer. Each of these transistors is essentially a tiny binary on/off switch. Today, this packing of transistors has reached an amazing level of density. For instance, a common Pentium IV chip packs 55 million transistors in a space the size of a dime.[3] By relentlessly pursuing this miniaturization strategy, computing technology has advanced rapidly in a comparatively short amount of time. To put the advances in perspective, compare the Pentium chip-equipped desktop with the ENIAC computer of the 1940s. That device, with its 17,000 vacuum tubes (the transistor's predecessor) weighed 30 tons and filled an entire room. Yet, its processing power was less than one one hundred thousandth that of the Pentium.

As relentless as this progress has been thus far, it is dependent upon continuing to find new means to shrink transistors so as to fit ever more of them onto a chip. In the coming years, transistors will have decreased in size to such a great extent that the only way to make them smaller is to construct them out of individual atoms or small groupings of atoms. Unfortunately, quantum effects of physics operating on that size scale will prevent the effective transmission of signals. For example, the Heisenberg Uncertainty Principle states that particles (such as the electrons that make up the information signals that flow through computers) can exhibit the strange behavior of being in other places than where they should be. Researchers can never be completely certain where these particles are at any given moment. This means that electrons, which should ideally be speeding down the atomic-scale circuit pathways in future silicon computers, might be someplace else along with the information they were assigned to carry! Given that the circuit pathways of computers must be able to reliably transmit information; this quantum effect that emerges at the atomic scale is clearly a problem. Thus, there is a lower size limit that the laws of physics impose upon silicon-based computers. This limit may be reached as soon as 10-15 years from now.[4]

Reaching this upper limit to the processing power of silicon-based computers could be very problematic for businesses. Though current and future computers will have sufficient power for handling many day-to-day operations, e.g. email, future business software needed for activities such as hyper-realistic strategic planning simulations, mapping more efficient airline routes, etc. will ultimately require more processing power than silicon-based computing will be able to provide. Software designers are always in the process of designing software that forces hardware designers to keep adding more power to their creations. As this continues, it will force silicon-based computers up to their design limits.

There are two other problems with silicon-based computers. First, the components out of which computer processing chips are made are toxic, e.g. arsenic, and therefore present challenges in both fabrication and disposal.[5] Second, silicon-based computers are not very energy efficient.[6] They waste a great deal of energy in the form of the heat that they generate and the energy they consume.
With these limitations in mind, let's look at some alternatives to the current computing paradigm.

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through this speed barrier?", Scientific American, 1999, available online at: http://www.sciam.com/print_version.cfm?articleID=000B32AA-54FA-1C72-9EB7809EC588

[3] Tynan, Daniel, "Silicon is Slow", Popular Science, 2002, available online at: http://www.popsci.com/popsci/computers/article/0,12543,2411609-4,00.html

[4] Junnakar, Sandeep. "Tomorrow's tech: The domino effect", The New York Times, October 24, 2002.

[5] Bonsor, Kevin, "How DNA computers will work." http://howstuffworks.lycoszone.com/dna-computer.htm

[6] Forbes, Nancy, "Life After Silicon: Ultrascale Computing", The Industrial Physicist, December 1997, pp. 20-23.

What are the Alternatives to Silicon-Based Computers?

Researchers have pursued a number of alternatives to silicon-based computing. , These have included biological, optical, and quantum computing. Optical computing is based on replacing with light pulses instead of the electrical signals that carry information through silicon-based computers. Information can travel at the speed of light through information pathways in the optical computing scheme far faster than the commonly used pathways in silicon-based computers.

Quantum computers, by contrast, use quantum states of subatomic particles to represent information values. While information is essentially limited to binary (on-off) values in silicon and optical computers, quantum computing permits each information element to carry multiple values simultaneously. Quantum computing also exploits the phenomenon of quantum entanglement, which essentially allows any given information state to exist in two locations simultaneously. This allows the equivalent of instantaneous transfers of information from location to location. It should be noted that a great deal of development works remains to be done before either optical computing or quantum computing can produce practical devices for commercial use. [7]

Molecule cascade computing is the newest area in the development of alternatives to traditional computing. This technique is based on forming circuits by creating a precise pattern of carbon monoxide molecules on a copper surface. By nudging a single molecule, it has been possible to cause a cascade of molecules, much like toppling dominoes. Different molecules can represent the 1s and 0s of binary information, making possible calculations. While this technique may make possible circuits hundreds of thousands of times smaller than those used today, it shares with the other alternatives the fact that a number of problems must be solved for it to ever be suitable for practical applications.[8]

What is Biological Computing?

Biological computing is *the use of living organisms or their component parts to perform computing operations or operations associated with computing*, e.g. storage.[9] The various forms of biological computing take a different route than those used by quantum or optical computing to overcome the limitations to performance that silicon-based computers face.

Rather than focusing on increasing the speed of individual computing operations, biological computing focuses on the use of massive parallelism, or the allocation of tiny portions of a computing task to many different processing elements.[10] Each element in and of itself cannot perform its task quickly, but the fact that there is an incredibly huge number of such elements, each performing a small task, means that

[7] If you would like further information on either Quantum Computing or Optical Computing, please refer to the recent ISRC technology briefings on these topics.
[8] Junnakar, Sandeep, "Tomorrow's tech: The domino effect" The New York Times, October 24, 2002.
[9] This definition is a gestalt drawing from a number of sources (e.g. Gardner, Tim, "Biological Computing," Technology Review, May/June 2000, p 70) that focuses only on the use of living things or chemicals found in living things, as opposed to computing merely inspired by living things.
[10] Forbes, Nancy, "Life After Silicon: Ultrascale Computing", The Industrial Physicist, December 1997, pp. 20-23.

the processing operation can be performed far more quickly. Silicon-based computers have used massively parallel processing but will never be capable of the level of massively parallel processing that biological computers can demonstrate. The biological nature of the operation of biological computing also makes it uniquely suited to controlling processes that would require an interface between other biological processes and human technology.

The table below compares biological computing with silicon-based computing in several areas, including the component materials, processing scheme, maximum operations per second, presence of toxic components, and energy efficiency. There are important differences between biological and silicon computers in all of these areas.

Silicon-Based Computing vs. Biological Computing (DNA Computing)

Comparison Criterion	Silicon-Based	Biological
Component Materials	Silicon and Other Inorganic Materials	Biological Materials, e.g. amino acids
Processing Scheme	Sequential and Limited Massively Parallel Processing	Massively Parallel Processing in DNA computing and closely related forms of biological computing
Maximum Operations Per Second	10^{12} (Currently)	10^{14} (Currently)
Quantum Effects A Problem?	Yes	No
Toxic Components?	Yes	No
Energy Efficient?	No	Yes

We have considered biological computing in general up to this point, but there are specific forms of biological computing that offer certain advantages. We now look at these alternative forms.

What are the Forms of Biological Computing?

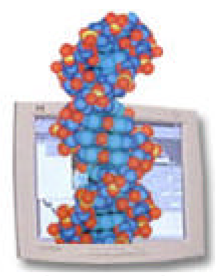
Research in the field of biological computing is focusing on the development of a number of different, though related, forms of technology. While all of these forms share the biological components listed above, they share little else and are best thought of as distant cousins. Some of these technologies will likely be applicable to a variety of problems, while others are best thought of as tools suited to specific purposes.

DNA Computing

DNA computers use strands of DNA (deoxyribonucleic acid) to perform computing operations.[11] DNA, which encodes the design specifications for living things, is composed of four amino acids: Adenine, Cytosine, Guanine, and Thymine. In DNA, adenine will only chemically bind to thymine and cytosine will only bind to guanine. This regular, predictable binding behavior allows DNA strands to arrange themselves into the famous double helix of complete DNA molecules; this particular characteristic also makes DNA well suited to computation.

[11] Levin, David, "DNA Computing", IEEE Computing in Science & Engineering, May-June 2002, pp. 5-8.

DNA computers process information by making and breaking the chemical bonds between the DNA components. DNA computing involves using a strand of DNA to represent a problem in math or logic. The structure of the DNA allows the elements of the problem to be represented in a form that is analogous to the binary code structure (1s and 0s) that characterizes the most basic form of computer language. Trillions of unique strands of DNA are able to represent all of the possible solutions to a problem. The 'possible solution' strands are allowed to react with the 'problem' strands. Given the binding rules for DNA's components, the strands that complement one another will bind, yielding a collection of whole DNA molecules that contain the solutions. A number of processing steps are performed on the resulting mixture to isolate a correct solution from all the possibilities. The results are then analyzed by the electronic portion of the computer. The ability of trillions of reactions to occur simultaneously provides the equivalent of massively parallel processing in silicon-based computers, in which a huge number of possible problem solutions or searches through pools of information for the answer are performed at the same time.



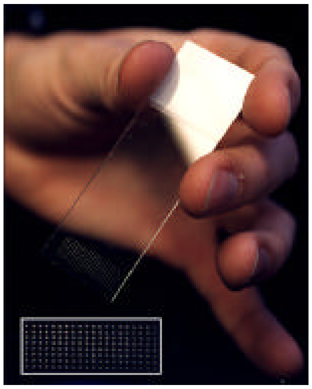
NASA: http://www.jpl.nasa.gov/

By their mode of functioning, these DNA computers can be applied to solving a variety of problems, just as the traditional silicon-based computers can. This ability to be a general purpose tool that can be programmed to handle various tasks means that DNA computers meet the accepted standard for being classed as a true computer according to the Turing machine concept developed by Dr. Alan Turing in 1936. DNA computing has already begun to prove its worth by solving complicated logic problems. The first major development came in 1994, when Dr. Leonard Adleman was able to create and use a DNA computer to solve what is known as the "traveling salesman" problem. This involved using DNA strands to pick the most direct route by which a salesman would visit each of 7 cities while passing through each of the cities only once. Though this is something that a human being could do in a relatively short time with a piece of scratch paper and a pencil, it was an important proof of concept. That was just the start. Further, in March of 2002, NASA announced that a team led by the same Dr. Adleman developed a DNA computer that solved a problem that required evaluating one million alternatives for their ability to meet 24 separate criteria. Work, such as that done by Dr. Adleman, is aimed at increasing the complexity of problems that such computers can solve, while also developing measures to reduce the levels of errors in the process.

Not all DNA computing adheres to the format established by Dr. Adleman's work. A variant of DNA computing is being designed to emulate more closely the structure of conventional computers. Scientists at the University of Rochester in 1997 developed logic gates made of DNA.[12] Instead of using electrical signals to perform logical operations, DNA logic gates rely on inputs and outputs of DNA. They are designed to detect fragments of genetic material and splice the fragments together to form a single output. In November of 2001, scientists in Israel developed a series of tiny DNA computers, trillions of which can fit in solution in a test tube. These computers use a form of software, also made of DNA, and can compute with high reliability.

[12] Bonsor, Kevin, "How DNA computers will work." http://howstuffworks.lycoszone.com/dna-computer.htm

DNA Chips

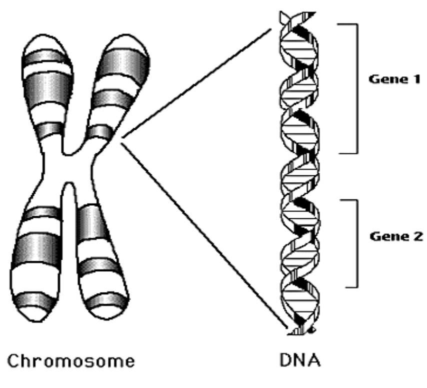


Plant Research International: http://www.wageningen-ur.nl/news/2001-10_en.htm

A closely related technology is the DNA chip. Such a device, shown in the picture to the left, is similar in principle to DNA computers but is simpler in structure. The basic concept involves the use of large numbers of DNA strands, which are bound to tiny glass chips.[13] Each of these strands, or probes, is able to bind to sample sequences of genetic material. These chips allow researchers to evaluate thousands of genetic sequences simultaneously, for use in developing treatments for disease. Research into the continued improvement and additional applications of DNA chips is occurring at many universities, including the University of Houston. At UH, researchers B. Montgomery Pettitt, Ka-Yiu Wong, and Xiaolian Gao are leading some of the efforts to further develop this promising technology. Local company Xeotron Corporation produces DNA chips for biomedical research.[14]

Genetic "Programs" and Genetic "Robots"

Researchers are developing genetic 'computer programs' that could be introduced into and replicated by living cells in order to control their processes. Research has already produced engineered sequences of genetic material that can cause the living cell in which it is implanted to produce one of two possible genes. This would be effectively analogous to computer programs. This technology could serve as 'switches' to control the chemicals that living organisms synthesize. Development efforts are underway to add data processing elements, memory storage elements, and communication elements, to produce tiny genetic "robots" that could reside in cells. This would allow a level of interface with living processes on a microscopic level that is not possible using strictly silicon-based computing technology. Such a technique could provide an unprecedented level of control over such processes.



Access Excellence @ The National Health Museum: http://www.accessexcellence.org/AB/66/genes.html

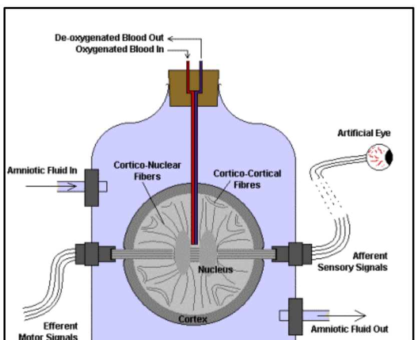
This could offer a way for humans to 'self-treat' a number of presently untreatable genetically-based illnesses, while allowing a team of tiny "physicians" to remain on call to correct other problems as they arise.

[13] "DNA Chips", Technology Review, January-February 2001, pp. 118-119.
[14] Xeotron Corporation's home page can be reached at: http://198.65.244.205/data/pub/Home.asp.

Silicon-Based Computer / Living Organism Hybrids

BBC News: http://news.co.uk/1/hi/sci/tech/35822.stm

Another variant of biological computing development seeks to unite living organisms with silicon-based computing technology.[15] The purpose of this is to use living organisms to control technology. Such technology involves linking living neural cells to silicon-based computing components. The reason for doing this is that the brains of humans, and to a lesser degree, those of lower organisms, have abilities to understand complicated problems that no amount of silicon-based processing power will be able to handle. Further, they are able to solve problems correctly, even with only partial information. This field is in an extremely early stage of development. For example, researchers at Georgia Tech have used leech neurons to perform mathematical operations, as shown in the picture above.[16] Further, other researchers have managed to link the brain of a lamprey eel to a robot for the purposes of controlling it. The brain has already shown the ability to process information from the surrounding environment and direct the robot's movements in response to the stimuli. Some researchers are quite interested in extending development work in this area to human beings, albeit in slow steps. Recently, British cybernetics professor Kevin Warwick was the personal participant in an experiment in which a computer chip was attached to a main nerve in his arm. The chip remained in his arm for four months, allowing him to control a robot on wheels.



Artificial Brains.com: http://glendhu.com/ai/bluesky/biobrains.html

Engineered Living Organisms

The most radical form of biological computing research goes one step beyond hybrids, with the intent of engineering a living organism. Work is proceeding to culture neural networks from living nervous tissue. Currently, the work being done at Science Applications International Corporation focuses on growing nerve fibers on artificial surfaces, though it is possible that the ultimate product of such research could be an entire living organism that would be a brain in a jar.’ Any moral and ethical issues aside, such a development is not likely to happen any time soon. Still, scientists in the field are taking the initial steps to make that radical development a reality.

[15] Innovations @ Georgia Tech news release, http://www.innovations.gatech.edu/livingcomputers/index-textonly.html
[16] Innovations @ Georgia Tech news release, http://www.innovations.gatech.edu/livingcomputers/index-textonly.html

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What are the Benefits of Biological Computing?

The various forms of biological computing possess a number of benefits over their silicon-based counterparts. There are six main benefits that biological computing can offer.

First, *a biological computing process can be far more energy efficient than the computational processes of silicon-based computers*.[17] In the case of DNA computing, the biological reactions involved produce very little heat, wasting far less energy in the process. This allows for these computing processes to be up to one billion times as energy efficient as their electronic counterparts.

Second, *DNA is capable of storing an astounding amount of information for a given volume*. [18] To illustrate, one gram of DNA can hold as much information as one trillion audio CDs. This offers the possibility of computers with previously impossible storage capabilities. For businesses, this ability to store and access data in a far smaller space could sharply reduce costs associated with storing and accessing data.

Third, *the component materials are plentiful in supply and easily obtained in most cases*.[19] Also, the components, e.g. DNA, are non-toxic. This compares quite favorably with silicon-based computers, which are composed of toxic materials and require the production of large amounts of toxic waste as byproducts of their production. In most cases, the biological components can be synthesized in a lab quite cheaply. In addition, the structure of genetic material makes possible computers that in the future could assemble themselves out of simpler components.

Fourth, *biological computing allows for massively parallel computing*. [20] While silicon-based computing has already shown itself to be capable of limited massively-parallel processing of information, biological computing is able to do it to a far greater degree. For comparison, the fastest supercomputers can perform around 10^{12} operations per second, but even current results with DNA computing has produced levels of 10^{14} operations per second or one hundred times faster. Experts believe that it should be possible to produce massively parallel processing in biological computers at a level of 10^{17} operations per second or more, or a level that silicon-based computers will never be able to match.

Fifth, some forms of biological computing, e.g. the genetic "programs", *promise the ability to control cellular level chemical production events that offers a level of intimate interface with biological processes that is simply not possible with existing computing technologies*.[21] The implication is that genetically

[17] Forbes, Nancy, "Life After Silicon: Ultrascale Computing", The Industrial Physicist, December 1997, pp. 20-23.
[18] For a link to the article "Wet 'n Wild Computers, visit: http://whyfiles.org/shorties/dna_computer.html
[19] Bonsor, Kevin, "How DNA computers will work", http://howstuffworks.lycoszone.com/dna-computer.htm
[20] Dassen, J.H.M., "DNA Computing: Promises, Problems and Perspective", IEEE Potentials, December 1997-January 1998, pp. 27-28
[21] Gardner, Timothy S., "Genetic Applets: Biological Circuits for Cellular Control", 2001 IEEE International Solid-State Circuits Conference Digest of Technical Papers, 2001.

engineered life forms incorporating such control mechanisms could provide businesses engaged in chemical production with a new form of cheaper and far more efficient factory. Vats of such life forms could produce a wide variety of chemicals cheaply.

Sixth, *computing devices that are living or composed of living components have the potential to* share two characteristics that allow living organisms to adapt so well to changing conditions: the capability of *healing injuries and the capacity to self-improve*.[22] Development work is being done to give non-biological human technology such capabilities, but it is doubtful that such technology will ever be able to do these things as well as biological components can.

What are the Potential Problems with Biological Computing?

A number of problems with biological computing must be resolved before it can reach its full potential.

First, *in some cases the types of genetic sequences that would have to be synthesized to make full-functioned genetic "applets" or genetic "robots" possible would be prohibitively expensive* using current methods.[23] In addition a way of establishing reliable chemical-based communications with huge numbers of these automata in huge numbers of cells would have to be developed, as would a means of simultaneously programming billions of these devices.

Second, despite their capacity for massively parallel calculations, *the individual operations of DNA computers are quite slow in comparison to those of their silicon-based counterparts*.[24] Thus, while there is a greater capacity for calculations, these do not necessarily translate into speed advantages.

Third, *DNA computing requires quantities of DNA that can only be used once*, since reuse would contaminate reaction vessels and lead to less accurate results.[25] Within the scientific community, there is much debate as to how much DNA would be required to perform useful calculations. Some researchers believe that useful calculations would require 10^{70} distinct DNA sequences, a significant proportion of the number of the 10^{80} atoms believed to exist in the universe.[26] Of course, others have shown that complicated problems, e.g. evaluating the seventy quadrillion (70,000,000,000,000,000) possible keys of the U.S. government's Data Encryption Standard, could be successfully completed with less than a liter of DNA.[27]

[22] Innovations @ Georgia Tech news release, http://www.innovations.gatech.edu/livingcomputers/index-textonly.html
[23] Gardner, Timothy S., "Genetic Applets: Biological Circuits for Cellular Control", 2001 IEEE International Solid-State Circuits Conference Digest of Technical Papers, 2001.

[24] Dassen, J.H.M., "DNA Computing: Promises, Problems and Perspective", IEEE Potentials, December 1997-January 1998, pp. 27-28
[25] "Nanotechnology will drive the evolution of the DNA molecule as functional components", Olympus Techno Zone, http://www.olympus.co.jp/en/magazine/TechZone/Vol54_e/page5.html
[26] Cox, J. Colin and Andrew Ellington, "DNA Computation", Current Biology, volume 11, number 9.
[27] "DNA Based Computing" http://cism.jpl.nasa.gov/program/RCT/DNACompUD.html

Fourth, *DNA computing is prone to errors at a level that would be considered unacceptable by the silicon-based computing industry*.[28] According to one estimate, the error rate of DNA computing is roughly equivalent to that of some of the less optimistic estimates of the accuracy of the original Intel Pentium chip or the equivalent of 1 mistake in 10^5 operations. Processing advances that incorporate error reduction measures are being developed to narrow this gap, however. Until those efforts are successful, these computers will play a complementary role to silicon-based computers, rather than render them obsolete.

Finally, *biological computing raises problematic ethical and moral concerns*. For example, the idea of scientists being able to create a living brain creature 'raises a number of troubling questions: Would it be treated humanely? Would it be regarded as a person and, if so, would it be accorded rights? Do we have a right to create life if we somehow develop the ability to do so? Might this technology develop "a mind of its own" and turn against its creators? While these questions may evoke memories of bad science fiction movies, they concern real issues that our society will likely have to face in the not-so-distant future.

The table below summarizes the pros and cons of biological computing.

Pros and Cons of Biological Computing

Pros for Biological Computing	Cons against Biological Computing
Highly Energy Efficient	Genetic "Applets" and "Robots" Expensive to Create Using Current Methods
High Memory Capacity	DNA Computers: Individual Operations are Slow
Plentiful and Cheap Materials in Most Cases	DNA Computers: DNA can not be Reused
Nontoxic Components	DNA Computers: Some Computing Operations might take a Huge Amount of DNA
Capable of High Processing Rate: Up To 10^{17} Operations per Second	DNA Computing: Error Rates Still Comparatively High
Unequaled Level of Control Over Biological Processes	Moral and Ethical Issues of Creating/Engineering Life for Computing
Capabilities of Self-Assembly, Self-Healing, and Self-Improvement	Technology Requires Additional Development to Enable Communication between Components and Large Scale Programming
Could provide Unparalleled Level of Control over Biological Processes	

What is the Time Line for Biological Computing?

In a number of forms, biological computing is already being used outside of research labs. DNA chips for analysis of genetic sequences in pharmaceutical development have been commercially available since the

[28] Cox, J. Colin and Andrew Ellington, "The complexities of DNA computation", Tibtech April 1999, pp 151-154.

late 1990s. Further, Olympus Optical unveiled a commercially practical DNA computer for gene analysis in February 2002.[29] Use of this computer should be made commercially available to researchers in 2003. Gene analysis and encryption applications will probably be the focus of development work for a number of years after that. Within 5 years, DNA computing should advance to the point that all components needed for the computations should be small enough that they can be housed on a single silicon chip.[30] As for the more radical developments in biological computing, e.g. engineered living organisms, the forecast, is far less clear. In their ultimate form, these technologies will require a far more advanced understanding of biological processes than we have now. Thus, commercially-viable biological computing has already arrived, but the future development of this field is difficult to predict.

How can my organization become involved in biological computing?

Businesses that want to take advantage of the benefits that biological computing can offer in the future will have to begin thinking creatively now. For example, how might my organization use the massively parallel processing power and efficiency offered by DNA computing? One possibility might be an adaptive means of developing more efficient routing of intranet traffic on a company's network when company office space and funds for paying for utilities are scarce. This is only one example. So, get creative and think about how your organization could best use this technology as it grows more mature. This may mean considering entirely new segments for your organization to enter, e.g. the development and use of genetically engineered bacteria to travel down oil pipe lines, check for leaks, and transmit reports to company personnel. Not a lot of work has been done on developing future applications of this technology, so your organization can have an early advantage if it begins brain-storming now. Given the potential capabilities of these new technologies, the old cliché "The possibilities are endless" actually could prove true for biological computing.

For More Information

Research Groups and Labs

- To learn more about Dr. Leonard Adelman's work at USC for NASA, consult "DNA Based Computing," by visiting: http://cism.jpl.nasa.gov/program/RCT/DNACompUD.html
- To learn more about the work that is being done at Georgia Tech to combine technology and living tissue, visit: http://www.innovations.gatech.edu/livingcomputers/index-textonly.html
- Details of the work done by Japan's Molecular Computation Project can be found at: http://hagi.is.s.u-tokyo.ac.jp/MCP/

Online Resources

- An interesting, practical guide to DNA Computing can be found on the web page "Wet-n-Wild Computers" at: http://whyfiles.org/shorties/dna_computer.html
- To learn more about Olympus Optical's recently unveiled DNA computer, visit: http://www.pcworld.com/resource/printable/article/0,aid,82403,00.asp

[29] "The ultimate DNA computers will provide intelligent treatment inside individual cells," Olympus Techno Zone, http://www.olympus.co.jp/en/magazine/TechZone/Vol54_e/page6.html
[30] "The ultimate DNA computers will provide intelligent treatment inside individual cells," Olympus Techno Zone, http://www.olympus.co.jp/en/magazine/TechZone/Vol54_e/page6.html

- To learn more details of the development effort behind this innovative device, visit Olympus Japan's web site at: http://www.olympus.co.jp/en/magazine/TecZone/Vol54_e/page1.html
- Another excellent, general source of information about DNA computers can be found in the article written by Kevin Bonsor, "How DNA computers will work" at the Lycos web site: http://howstuffworks.lycoszone.com/dna-computer.htm
- Details of some recent advances in DNA computers are available from NASA's web site at: http://www.jpl.nasa.gov/releases/2002/release_2002_63.html
- Learn more about efforts to link Eel brain tissue to a robot at: http://www.techtv.com/news/print/0,23102,3332505,00.html
- An easy-to-understand guide to DNA Computers can be found at: http://dna2z.com/dnacpu/dne.html
- For more information on development of tiny DNA computers and software in Israel, visit: http://in.news.yahoo.com/011121/107/199x5.html
- Information about some of the DNA chip development work at the University of Houston can be found at: http://www.uh.edu/admin/media/nr/102001/biochip.htm
- To learn more about Kevin Warwick, the British cyberneticist who became a living being/computer hybrid, go to: http://www.msnbc.com/news/816611.asp?cp1=1.

Recommended Readings

- Levin, David, "DNA Computing", IEEE Computing in Science & Engineering, May-June 2002, pp. 5-8.
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