Travis Yoshimoto
tsyoshimoto@gmail.com

Manipulating Nature: Limitations of Silicon Computers and the Rise of DNA Computing

Abstract:
Computers run the world in which we live. However, as current computer technology reaches its physical limits, the search for replacement technologies takes the spotlight in order to keep up with the needs of society. Although there is extensive research being done on a variety of alternatives, some engineers and scientists have been focusing on DNA computing. DNA computing is based upon the theory of utilizing DNA to perform the tasks required of traditional computers. There are a number of advantages DNA has over conventional methods that can be attributed to the minute nature of DNA and the data capacity of each strand, which alleviates many of the problems in current computer systems. Since it's inception, DNA computing has proved to be an intriguing concept, but it remains challenging to implement. In recent years, though, there have been advances that show promise in revolutionizing the way that computing is done and to bring about a new age for computers.

Bio:
Travis Yoshimoto is a junior studying Computer Engineering & Computer Science at USC. He plans to continue his studies in a Computer Science Masters program following the completion of his undergraduate degree.

Introduction

It's hard to imagine a world without computers. Computers are utilized in every possible way in our society. However, computers have been relatively recent inventions. In the 19th century, Charles Babbage prototyped a computing machine to assist people with their everyday duties. From that prototype, the first computer was not built until the 1940s [1]. Since then, there have been numerous breakthroughs that have improved upon that initial product. These advances have made computers integral devices in today's society, and with technological advancements released daily, it encourages engineers to continuously look for new ways to increase the efficiency of the modern day computer.

How Does A Computer Work?

It all starts off with transistors – the basic building blocks of a computer. When a computer is running, electrical voltages are constantly placed over transistors to perform the necessary calculations and actions. These transistors form the logic gates that are, in turn, used to execute computer instructions for specific tasks. This makes transistors an essential asset for computers and prompted the intensive research and development of more effective transistors throughout the later 20th century's computer industry boom [2].

Currently, most transistors are made of silicon (see fig. 1) because of its unique properties as a semi-conductor. A semi-conductor is a material that allows a partial electrical flow through it. Although silicon is not the most efficient material

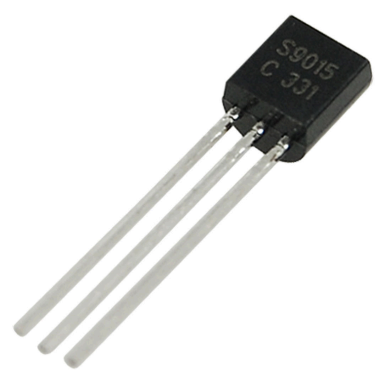

Figure 1: A silicon transistor (http://www.sourcingmap.com/50-pcs-complementary-s9014-50v-01a-045w-silicon-pnp-transistor-s9015-p-158573.html)

for this task, it is popular because of its inexpensive manufacturing costs [2].

Silicon Technology Issues

Despite the advancements made using silicon, it has begun to cause problems. In 1965, Gordon Moore, a scientist at Intel, gave a proposition called Moore's Law, which states that the number of transistors that can be placed in a single area doubles every couple of years. This has been true up to date, but it has now come to a point where it will take more time to double that number with current practices [2]. Recently, the minute nature of the transistors has affected its performance and function. This can cause undesirable results and lead to further issues of larger power consumption and heat dissipation. From a financial perspective, these miniature transistors also have higher manufacturing costs associated with the more complex design of the chips that they are placed on [3]. With both of these performance and cost obstacles, many engineers look toward other avenues to provide faster and cheaper computers.

Alternatives to Silicon

As many researchers and engineers recognized these limitations upon the current design of silicon transistors, some looked toward alternatives from the traditional models. In 2012, Intel introduced a new type of transistor. Their transistor stood upright on top of the computer chips to produce a more 3-dimensional chip instead of a standard 2-dimensional one. This allowed engineers to have greater control over the transistors, but it came at a cost. Along with the improved control, issues of mass-production also came to the forefront, which hindered its acceptance within the market [2].

There have also been considerations of quantum computers to solve the issues of silicon transistors. Quantum computers differ from traditional ones because of particular elements called quantum bits. These quantum bits uniquely allow the computer to run a large number of items all at the same time. Recently, there have been advances made by companies such as D-Wave to generate a quantum computer. However, D-Wave's claims of developing a true quantum computer are still in dispute [4]. The real difficulty in physically building a quantum computer is in controlling how the particles interact with one another - there has to be a massive amount of control over these particles for them to generate the desired results [5]. Both the improved silicon transistors and the quantum computer show promise, but they are still in development and far from making their way into the everyday computer.

A Biological Answer

Although there are other alternatives to the silicon transistor, the use of DNA computing is an option that is both intriguing and promising. DNA, which stands for Deoxyribonucleic acid, is the essential building block for all living organisms. In one strand of DNA, there is an enormous amount of data and many scientists have been intrigued with how to utilize this information.

At first glance, it seems improbable that DNA could be controlled for computing. Nevertheless, back in 1964, R. Feynman, a theoretical physicist, first proposed the assembly of a computer from molecules. Although he was not able to create such a machine, his vision provided a unique outlook that trended away from the silicon-based computer. The concept proved to be difficult to implement and it took another 20 years before an American theoretical computer scientist name Leonard Adleman finally turned that proposal into a reality [6].

After much experimentation, Adleman was able to use DNA to solve a NP-complete problem, an enigma that has no efficient algorithm to solve it. These NP-complete problems can be grow to be so intensive that they take as long as the universe has been around to solve. However, Adleman demonstrated, in a scaled down experiment, the power that DNA computing holds on problems such as these. He took a problem that a non-scientific study stated would take 54 seconds to solve and deciphered it within about a second [7].

Adleman specifically worked on a quandary known as the Hamiltonian Path problem. This problem is similar to the idea of analyzing airplane flight paths. Assuming there is a map of one-way airplane flight paths between airports, one must find a specific path to visit every city once from a designated starting airport to an ending airport. To demonstrate his theory of DNA computing, Adleman decided to use 7 cities and 14 one-way paths between them as laid out in Fig. 2.

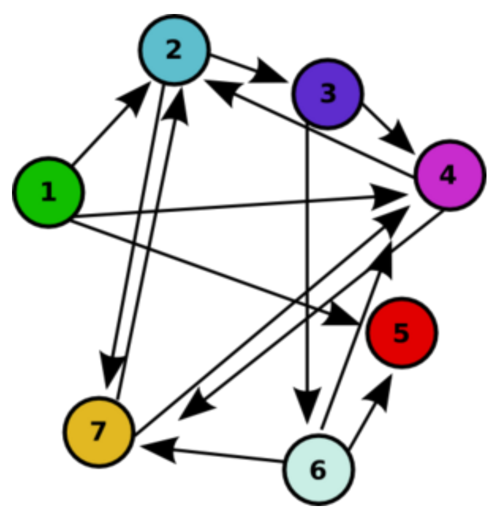

Figure 2: Adleman's Hamiltonian Path problem with 7 cities and 14 paths

In order to accomplish this feat, Adleman manipulated strands of DNA. To do this, he had to examine its physical structure. Within DNA, there are four different bases: Adenine (A), Guanine (G), Cytosine (C), and Thymine (T). Together, these four form the basic building blocks of DNA and combine in a unique way; A forms a special bond with T and C with G. Adleman highlighted how this is correlated to a sort of "key-lock encoding" method that could be used to solve the problem. By arranging DNA strand bases in strategic ways, Adleman could design certain strands to match up with other strands. These paired strands, could then be viewed as possible outcomes or solutions. From there, he just had to sift through the incorrect results and locate those that were viable [7].

Adleman set the stage for further research in the field and proved that the advantages of DNA computing could be realized through the solution of the Hamiltonian Path problem. The technique that he used to obtain these results demonstrates one method to manipulate DNA. This technique opens up the discussion of utilizing DNA for actual computation problems.

What Makes DNA Computing So Great?

There are many benefits that make DNA computing an attractive alternative to the current standards. It is estimated that a DNA computer could run 10,000 times faster than the speed of today's supercomputers. The sheer number of DNA strands that fit in a small area allows many operations to process at the same time [6]. This processing power takes many of the problems, such as Adleman's, that are unsolvable using current technology one step closer to obtaining a solution. Additionally, the vast number of DNA strands provides a large amount of memory capacity, which could further reduce the physical space needed within computers. Lastly, the calculations from this technique require much less energy than conventional electrical circuits [3]. From this list of advantages, it appears that DNA computing should be making its way into our home computers and laptops. However, the road to even harnessing this power has been a rocky one and Adleman's success proved to be difficult to build upon.

Constraints Of Using DNA

Adleman's advancements in this field were groundbreaking, but his implementation cast some doubts about the realistic implementation of DNA computing. One issue is that communication between DNA strands is difficult. After the individual strands match up, new strands have trouble communicating with one another. Moreover, through this process of having them physically collide to supply the results, there is a high probability that the strands pair up incorrectly [8]. In Adleman's experiment, he sifted through the erroneous results to find the solution for one problem, but that process also revealed the labor-intensive sifting process and the ratio of correct to incorrect results given.

Additionally, the method that Adleman employed would not be scalable. In order to solve the same Hamiltonian path problem for 200 cities, the number of strands would increase exponentially. The problem would then require the equivalent of the earth's weight worth in DNA [9]. These all provide prominent hurdles that DNA computing has to overcome despite gaining initial traction through Adleman's discovery.

DNA Computing Advances

Despite the aforementioned limitations, there have been several advances made in DNA computing. In 2009, researchers from Donghua University in Shanghai, China suggested how to incorporate two distinct data structures with DNA: a stack and a queue.

Within the world of computing, data structures play a key component in efficient programs. These researchers have suggested the manipulation of certain enzymes, base pairs, and primers in order to mimic the features of those data structures. Through this advancement, DNA computing becomes more accessible and realistic for further development [10].

On the other hand, there have been further applications for these DNA computers within the human body. A team from Stanford University worked on DNA and RNA transistors that are placed in living cells. In this implementation, RNA travels along the DNA as an electron would on a wire; the DNA serves as the medium by which the RNA moves to transmit the data. The vision for this technology is to have cells that diagnose certain diseases or problems within the body and be able to report that data. With these "transcriptors," as they call them, they have the final addition to a living computer inside of a cell. Previously, they also created a type of DNA rewriteable storage and a process for cells to communicate with one another. Thus, they have all of the tools to assemble a basic computer that lives inside of a cell [1]. This provides a larger step forward towards making the vision of a biological computer into a reality and shows how a new field of study can arise from the pursuits of accomplishing DNA computing.

In addition, a different team from Stanford University used DNA to create a new semi-conductor material that they coined "graphene." This material takes advantage of both its structural features and chemical attributes to act as a viable semi-conductor. Graphene is a single layer of carbon atoms that is arranged in a honeycomb manner, which resembles a chicken wire. The carbon atoms are arranged to allow electricity to flow through it in an extremely efficient manner. These transistors were initially difficult to mass-produce, but scientists have used DNA to address that issue. The process involves using the carbon atoms within the DNA strands and capitalizing upon the spiral structure of the DNA to create ribbons for semi-conductor use as shown in Fig. 3 [11]. In this process, DNA was not used in the same manner as Adleman, but it illustrates feasible silicon alternatives. It is not necessarily one method that may become the new norm for computers but a combination of existing semi-viable approaches.

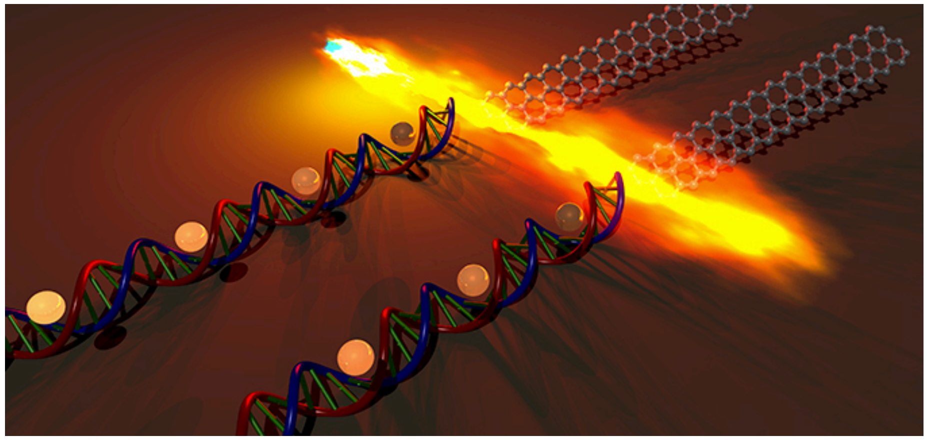
Figure 3: Formation of the graphene ribbon (http://engineering.stanford.edu/news/stanford-scientists-use-dna-assemble-transistor-graphene)

Looking to the Future

Although there are differing reactions to DNA computing and the other alternatives, there is a trend to look beyond the traditional silicon transistor. There have been vast advances that continue to be made in the search for a practical replacement. Consequently, many of these experiments lead to previously unknown research applications. Even though many of these options are not as developed as they could be, innovative technologies such as the graphene chip demonstrate that the next computer may be a combination of any number of new technologies. The future of computing lies in those engineers that think beyond the realm of traditional thinking and look for the solutions in the unexpected.

References

[1] Myers, Andrew. (2013, Mar 28). *Biological transistor enables computing within living cells, study says* [Online] Available: https://med.stanford.edu/ism/2013/march/bil-gates.html

[2] The Economist. (2014, Mar 8). *When silicon leaves the valley* [Online] Available: http://www.economist.com/news/technology-quarterly/21598327-semiconductors-it-becomes-harder-cram-more-transistors-slice

[3] Hassan, Shazia. "Limitations of Silicon Based Computation and Future Prospects," in *2nd International Conference on Communication Software and Networks*, 2010, pp. 559-561.

[4] Hsu, Jeremy. (2014, Feb 10). *D-Wave's Quantum Computing Claim Disputed Again* [Online] Available: http://spectrum.ieee.org/tech-talk/computing/hardware/dwaves-quantum-computing-claim-disputed

[5] Davis, Nicole (2014, Mar 6). *Quantum computing explained: harnessing particle physics to work* [Online] Available: http://www.theguardian.com/science/2014/mar/06/quantum-computing-explained-particle-mechanics

[6] Watada, J.; binti Abu Bakar, R., "DNA Computing and Its Applications," *Intelligent Systems Design and Applications, 2008. ISDA '08. Eighth International Conference on* , vol.2, no., pp.288, 294, 26-28 Nov. 2008.

[7] Adleman, Leonard M. "Computing with DNA," *Scientific American, Inc.* pp. 34-41, Aug. 1998.

[8] Dassen, J. H M, "DNA computing," *Potentials, IEEE*, vol.16, no.5, pp.27-28, Dec 1997/Jan 1998.

[9] Ezzaine, Z. "DNA Computing: applications and challenges," *Nanotechnology*, vol. 17, no. 2, pp R27-R39, 2006.

[10] Wanggen Li; Yongsheng Ding; Yaoying Huang; Xiaojiao Ye, "Linear Data Structure for DNA Computer," *Fuzzy Systems and Knowledge Discovery, 2009. FSKD '09. Sixth International Conference on*, vol.7, pp.141-145, 14-16 Aug. 2009

[11] Abate, Tom. (2013, Sept 5). *Stanford Scientists Use DNA To Assemble A Transistor From Graphene,* [Online] Available: http://engineering.stanford.edu/news/stanford-scientists-use-dna-assemble-transistor-graphene