Nanotechnology: DNA COMPUTERS
It's a Small, Small, Small, Small World

Introduction

Manufactured products are made from rearranged atoms.

Manufactured products are made from atoms. The properties of those products depend on how those atoms are arranged. If we rearrange the atoms in coal, we get diamonds. If we rearrange the atoms in sand (and add a pinch of impurities) we get computer chips. If we rearrange the atoms in dirt, water and air we get grass.

Since we first made stone tools and flint knives we have been arranging atoms in great thundering statistical herds by casting, milling, grinding, chipping and the like. We've gotten better at it: we can make more things at lower cost and greater precision than ever before. But at the molecular scale we're still making great ungainly heaps and untidy piles of atoms.

That's changing. In special cases we can already arrange atoms and molecules exactly as we want. Theoretical analyses make it clear we can do a lot more. Eventually, we should be able to arrange and rearrange atoms and molecules much as we might arrange LEGO blocks. In not too many decades we should have a manufacturing technology able to:

Nanotechnology is about rearranging atoms whichever way we want.

- Build products with almost every atom in the right place.
- Do so inexpensively.
- Make most arrangements of atoms consistent with physical law.

Often called *nanotechnology*, *molecular nanotechnology* or *molecular manufacturing*, it will let us make most products lighter, stronger, smarter, cheaper, cleaner and more precise.

The advantages of nanotechnology

One of the basic principles of nanotechnology is positional control. At the macroscopic scale, the idea that we can hold parts in our hands and assemble them by properly positioning them with respect to each other goes back to prehistory: we celebrate ourselves as the tool using species. Our wisdom and our knowledge would have done us scant good without an opposable thumb: we'd still be shivering in the bushes, unable to start a fire.

The technology allows us to work on a macroscopic scale.

At the molecular scale, the idea of holding and positioning molecules is new and almost shocking. However, as long ago as 1959 Richard Feynman, the Nobel prize winning physicist, said that nothing in the laws of physics prevented us from arranging atoms the way we want: "...it is something, in principle, that can be done; but in practice, it has not been done because we are too big."[1]

Products could be much lighter, stronger, and more precise.

What would it mean if we could inexpensively make things with every atom in the right place?

- For starters, we could continue the revolution in computer hardware right down to molecular gates and wires -- something that today's lithographic methods (used to make computer chips) could never hope to do.
- We could inexpensively make very strong and very light materials: shatterproof diamond in precisely the shapes we want, by the ton, and over fifty times lighter than steel of the same strength.
- We could make a Cadillac that weighed fifty kilograms, or a full-sized sofa you could pick up with one hand.
- We could make surgical instruments of such precision and deftness that they could operate on the cells and even molecules from which we are made -- something well beyond today's medical technology.

The list goes on -- almost any manufactured product could be improved, often by orders of magnitude.

What will we be able to make?

Nanotechnology should let us make almost every manufactured product faster, lighter, stronger, smarter, safer and cleaner. We can already see many of the possibilities as these few examples illustrate. New products that solve new problems in new ways are more difficult to foresee, yet their impact is likely to be even greater. Could Edison have foreseen the computer, or Newton the communications satellite?

How DNA Computers Will Work

Even as you read this article, computer chip manufacturers are furiously racing to make the next microprocessor that will topple speed records. Sooner or later, though, this competition is bound to hit a wall. Microprocessors made of silicon will eventually reach their limits of speed and miniaturization. Chip makers need a new material to produce faster computing speeds.

You won't believe where scientists have found the new material they need to build the next generation of microprocessors. Millions of natural supercomputers exist inside living organisms, including your body. DNA (deoxyribonucleic acid) molecules, the material our genes are made of, have the potential to perform calculations many times faster than the world's most powerful human-built computers. DNA might one day be integrated into a computer chip to create a so-called biochip that will push computers even faster. DNA molecules have already been harnessed to perform complex mathematical problems.

While still in their infancy, **DNA computers** will be capable of storing billions of times more data than your personal computer. In this article, you'll learn how scientists are using genetic material to create nano-computers that might take the place of silicon-based computers in the next decade.

A Fledgling Technology

DNA computers can't be found at your local electronics store yet. The technology is still in development, and didn't even exist as a concept a decade ago. In 1994, Leonard Adleman introduced the idea of using DNA to solve complex mathematical problems. Adleman, a computer scientist at the University of Southern California, came to the conclusion that DNA had computational potential after reading the book "Molecular Biology of the Gene," written by James Watson, who co-discovered the structure of DNA in 1953. In fact, DNA is very similar to a computer hard drive in how it stores permanent information about your genes.

Adleman is often called the inventor of DNA computers. His article in a 1994 issue of the journal Science outlined how to use DNA to solve a well-known mathematical problem, called the **directed Hamilton Path problem**, also known as the "traveling salesman" problem. The goal of the problem is to find the shortest route between a number of cities, going through each city only once. As you add more cities to the problem, the problem becomes more difficult. Adleman chose to find the shortest route between seven cities.

You could probably draw this problem out on paper and come to a solution faster than Adleman did using his DNA test-tube computer. Here are the steps taken in the

Adleman DNA computer experiment:

1. Strands of DNA represent the seven cities. In genes, genetic coding is represented by the letters A, T, C and G. Some sequence of these four letters represented each city and possible flight path.
2. These molecules are then mixed in a test tube, with some of these DNA strands sticking together. A chain of these strands represents a possible answer.
3. Within a few seconds, all of the possible combinations of DNA strands, which represent answers, are created in the test tube.
4. Adleman eliminates the wrong molecules through chemical reactions, which leaves behind only the flight paths that connect all seven cities.

The success of the Adleman DNA computer proves that DNA can be used to calculate complex mathematical problems. However, this early DNA computer is far from challenging silicon-based computers in terms of **speed**. The Adleman DNA computer created a group of possible answers very quickly, but it took days for Adleman to narrow down the possibilities. Another drawback of his DNA computer is that it requires **human assistance**. The goal of the DNA computing field is to create a device that can work independent of human involvement.

TA Successor to Silicon

Silicon microprocessors have been the heart of the computing world for more than 40 years. In that time, manufacturers have crammed more and more electronic devices onto their microprocessors. In accordance with **Moore's Law**, the number of electronic devices put on a microprocessor has doubled every 18 months. Moore's Law is named after Intel founder Gordon Moore, who predicted in 1965 that microprocessors would double in complexity every two years. Many have predicted that Moore's Law will soon reach its end, because of the physical speed and miniaturization limitations of silicon microprocessors.

DNA computers have the potential to take computing to new levels, picking up where Moore's Law leaves off. There are several advantages to using DNA instead of silicon:

- As long as there are cellular organisms, there will always be a **supply** of DNA.
- The large supply of DNA makes it a **cheap** resource.
- Unlike the toxic materials used to make traditional microprocessors, DNA biochips can be made **cleanly**.
- DNA computers are many times **smaller** than today's computers.

DNA's key advantage is that it will make computers smaller than any computer that has come before them, while at the same time holding more data. One pound of DNA has the capacity to store more information than all the electronic computers ever built; and the computing power of a teardrop-sized DNA computer, using the DNA logic gates, will be more powerful than the world's most powerful supercomputer. More than 10 trillion DNA molecules can fit into an area no larger than 1 cubic centimeter (0.06 cubic inches). With this small amount of DNA, a computer would be able to hold 10 terabytes of data, and perform 10 trillion calculations at a time. By adding more DNA, more calculations could be performed.

Unlike conventional computers, DNA computers perform calculations **parallel** to other calculations. Conventional computers operate linearly, taking on tasks one at a time. It is parallel computing that allows DNA to solve complex mathematical problems in hours, whereas it might take electrical computers hundreds of years to complete them.

The first DNA computers are unlikely to feature word processing, e-mailing and solitaire programs. Instead, their powerful computing power will be used by national governments for cracking secret codes, or by airlines wanting to map more efficient routes. Studying DNA computers may also lead us to a better understanding of a more complex computer -- the human brain.

hree years after Adleman's experiment, researchers at the University of Rochester developed logic gates made of DNA. Logic gates are a vital part of how your computer carries out functions that you command it to do. These gates convert binary code moving through the computer into a series of signals that the computer uses to perform operations. Currently, logic gates interpret input signals from silicon transistors, and convert those signals into an output signal that allows the computer to perform complex functions.

The Rochester team's DNA logic gates are the first step toward creating a computer that has a structure similar to that of an electronic PC. Instead of using electrical signals to perform logical operations, these DNA logic gates rely on DNA code. They detect fragments of **genetic material** as input, splice together these fragments and form a single output. For instance, a **genetic gate** called the "And gate" links two DNA inputs by chemically binding them so they're locked in an end-to-end structure, similar to the way two Legos might be fastened by a third Lego between them. The researchers believe that these logic gates might be combined with DNA microchips to create a breakthrough in DNA computing.

DNA computer components -- **logic gates** and **biochips** -- will take years to develop into a practical, workable DNA computer. If such a computer is ever built, scientists say that it will be more compact, accurate and efficient than conventional computers. In the next section, we'll look at how DNA computers could surpass their silicon-based predecessors, and what tasks these computers would perform.

1. Improved transportation

Lighter materials will make air and space travel more economical.

- Today, most airplanes are made from metal despite the fact that diamond has a strength-to-weight ratio over 50 times that of aerospace aluminum. Diamond is expensive, we can't make it in the shapes we want, and it shatters. Nanotechnology will let us inexpensively make shatterproof diamond (with a structure that might resemble diamond fibers) in exactly the shapes we want. This would let us make a Boeing 747 whose unloaded weight was 50 times lighter but just as strong.
- Today, travel in space is very expensive and reserved for an elite few. Nanotechnology will dramatically reduce the costs and increase the capabilities of space ships and space flight.[2] The strength-to-weight ratio and the cost of components are absolutely critical to the performance and economy of space ships: with nanotechnology, both of these parameters will be improved…[3] Beyond inexpensively providing remarkably light and strong materials for space ships, nanotechnology will

also provide extremely powerful computers with which to guide both those ships and a wide range of other activities in space.

2. Atom computers

Computers of the future will use atoms instead of chips for memory.

- Today, computer chips are made using lithography -- literally, "stone writing." If the computer hardware revolution is to continue at its current pace, in a decade or so we'll have to move beyond lithography to some new post lithographic manufacturing technology. Ultimately, each logic element will be made from just a few atoms.
- Designs for computer gates with less than 1,000 atoms have already been proposed -- but each atom in such a small device has to be in exactly the right place. To economically build and interconnect trillions upon trillions of such small and precise devices in a complex three dimensional pattern we'll need a manufacturing technology well beyond today's lithography: we'll need nanotechnology.
- With it, we should be able to build mass storage devices that can store more than a hundred billion billion bytes in a volume the size of a sugar cube; RAM that can store a mere billion billion bytes in such a volume; and massively parallel computers of the same size that can deliver a billion billion instructions per second.

3. Military applications

Weaponry can incorporate computer power but is this prudent?

- Today, "smart" weapons are fairly big -- we have the "smart bomb" but not the "smart bullet." In the future, even weapons as small as a single bullet could pack more computer power than the largest supercomputer in existence today, allowing them to perform real time image analysis of their surroundings and communicate with weapons tracking systems to acquire and navigate to targets with greater precision and control.

- We'll also be able to build weapons both inexpensively and much more rapidly, at the same time taking full advantage of the remarkable materials properties of diamond. Rapid and inexpensive manufacture of great quantities of stronger more precise weapons guided by massively increased computational power will alter the way we fight wars. Changes of this magnitude could destabilize existing power structures in unpredictable ways. Military applications of nanotechnology raise a number of concerns that prudence suggests we begin to investigate before, rather than after, we develop this new technology.[4]

4. Solar energy

Solar energy can replace other resources.

- Nanotechnology will cut costs both of the solar cells and the equipment needed to deploy them, making solar power economical. In this application we need not make new or technically superior solar cells: making inexpensively what we already know how to make expensively would move solar power into the mainstream.

5. Medical uses

Medicine can heal at the molecular or cellular level.

- It is not modern medicine that does the healing, but the cells themselves: we are but onlookers. If we had surgical tools that were molecular both in their size and precision, we could develop a medical technology that for the first time would let us directly heal the injuries at the molecular and cellular level that are the root causes of disease and ill health. With the precision of drugs combined with the intelligent guidance of the surgeon's scalpel, we can expect a quantum leap in our medical capabilities.[5]

How long?

The single most frequently asked question about nanotechnology is: How long? How long before it will let us make molecular computers? How long before inexpensive solar cells let us use clean solar power instead of oil, coal, and nuclear fuel? How long before we can explore space at a reasonable cost?[6]

The scientifically correct answer is: *I don't know*.

From relays to vacuum tubes to transistors to integrated circuits to Very Large Scale Integrated circuits (VLSI) we have seen steady declines in the size and cost of logic elements and steady increases in their performance.[7]

Conclusion: Nanotechnology is prediced to be developed by 2020 but much depends on our commitment to its research.

- Extrapolation of these trends suggests we will have to develop molecular manufacturing in the 2010 to 2020 time frame if we are to keep the computer hardware revolution on schedule.
- Of course, extrapolating past trends is a philosophically debatable method of technology forecasting. While no fundamental law of nature prevents us from developing nanotechnology on this schedule (or even faster), there is equally no law that says this schedule will not slip.
- Much worse, though, is that such trends imply that there is some

> ordained schedule -- that nanotechnology will appear regardless of what we do or don't do. Nothing could be further from the truth. How long it takes to develop this technology depends very much on what we do. If we pursue it systematically, it will happen sooner. If we ignore it, or simply hope that someone will stumble over it, it will take much longer. And by using theoretical, computational and experimental approaches together, we can reach the goal more quickly and reliably than by using any single approach alone.

While some advances are made through serendipitous accidents or a flash of insight, others require more work. It seems unlikely that a scientist would forget to turn off the Bunsen burner in his lab one afternoon and return to find he'd accidentally made a Space Shuttle.

Like the first human landing on the moon, the Manhattan project, or the development of the modern computer, the development of molecular manufacturing will require the coordinated efforts of many people for many years. How long will it take? A lot depends on when we start.