Nanomachines:

Nanotechnology's Big Promise in a Small Package

By BRENT SILBY
Department of Philosophy
University of Canterbury

www.def-logic.com/articles

Introduction

Nanomachines are devices built from individual atoms. Some researchers believe that nanomachines will one day be able to enter living cells to fight disease. They also hope to one day build nanomachines that will be able to rearrange atoms in order to construct new objects. If they succeed, nanomachines could be used to literally turn dirt into food and perhaps eliminate poverty.

In this article I will outline some of the possible uses of nanomachines. I will then assess some of the problems involved in producing such machines. One of the problems I will look at is that of producing self-replicating machines. Will these machines be controllable? Or will their reproduction escalate exponentially, thus putting our whole planet in danger.

My conclusion will be that nanomachines offer humanity hope for the future, so the research should be pursued. However, I will also suggest that the dangers involved in producing self-replicating machines out weigh the potential gains and for this reason, self-replicating machines should not be built.

What are Nanomachines?

As the terminology implies, nanomachines are extremely small devices. Their size is measured in nanometers (a nanometer is about 1 billionth of a meter) and they are built from individual atoms. During the 1980's and 1990's, futurist and visionary K. Eric Drexler popularized the potential of nanomachines. For Drexler, the ultimate goal of nanomachine technology is the production of the 'assembler'. The assembler is a nanomachine designed to manipulate matter at the atomic level. It will be built with extremely small 'pincers' (as small as a chain of atoms) which will be used to move atoms from existing molecules into new structures. The idea is that the assembler will be able to rearrange atoms from raw material in order to produce useful items. In theory, one could shovel dirt into a vat and wait patiently for a team of nanomachine assemblers to convert the dirt into an apple, a chair, or even a computer. The machines in the vat would have a molecular schematic of the object to be built encoded in their 'memory'. They would then systematically rearrange the atoms contained in the dirt to produce the desired item.

This is a representation of a nanomachine. The colored balls represent the individual atoms that comprise the machine. (Picture from Twibell (2000), see references.)

Another goal of nanotechnology is to design nanomachines that can make copies of themselves. The thought is that if a machine can rearrange atoms in order to build new materials, it should also be able to build copies of itself. If this goal is achieved, products produced by nanomachines will be extremely inexpensive. This is because the technology (once perfected) will be self-replicating and will not require specific materials, which might be rare and therefore cost money. Arthur C. Clarke has predicted that nanotechnology will herald an end to conventional monetary systems.

If scientists manage to build nanomachines that can rearrange atoms, a world of exciting possibilities will open up. Purpose designed nanomachines could be used to provide breakthrough treatments for many diseases. Medical nanomachines programmed to recognize and disassemble cancerous cells could be injected into the bloodstream of cancer suffers, thus providing a quick and effective treatment for all types of cancer. Nanomachines could be used to repair damaged tissue and bones. They could even be used to strengthen bones and muscle tissue by building molecular support structures by reassembling nearby tissue. With the ability to manipulate human cells at the atomic level, medical science will rapidly devise treatments for most human illnesses. And since nanomachines will be designed to make copies of themselves, these treatments will be inexpensive and available to the entire population.

Food shortages and starvation will be a thing of the past if nanotechnology is perfected. Nanomachines will be able to turn any material into food, and this food could be used to feed millions of people world wide. Again, since the technology is self replicating, food produced by nanomachines will be low cost and available to all.

As well as food, nanomachines will be able to build other items to satisfy the demands of our growing population of consumers. Clothing, houses, cars, televisions, and computers will be readily available at virtually no cost. Furthermore, there will be no concern about the garbage produced by the new consumerist society because nanomachines will convert it all back into new consumable goods.

Environmental problems such as ozone depletion and global warming could be solved with nanotechnology. Swarms of nanomachines could be released into the upper atmosphere. Once there, they could systematically destroy the ozone depleting chlorofluorocarbons (CFCs) and build new ozone molecules out of water (H_2O) and carbon dioxide (CO_2). Ozone (O_3) is built out of 3 oxygen atoms, and since water and carbondioxide both contain oxygen, the atmosphere contains a plentiful supply of oxygen atoms. While the ozone construction teams are at work in the upper atmosphere, teams of specialized nanomachines could be employed to destroy the excess CO_2 in the lower atmosphere. CO_2 is a heat trapping gas, which has been identified as one of the major contributors to global warming. Removing excess CO_2 could help halt global warming and bring the planet's ecosystem back into balance. This will benefit all species on Earth.

The perfection of nanotechnology and the production of nanomachines could herald a new age for humanity. Starvation, illness, and environmental problems could quickly come to an end. But how realistic are the goals of nanotechnology? Will it ever be possible to produce machines the size of atoms? And if so, how feasible is it to build nanomachines that can build objects from the atom up? Is it possible for nanomachines to build copies of themselves? Before we get carried away with the promises of nanotechnology, we should take a look at some of the problems that are yet to be solved.

Challenges to overcome

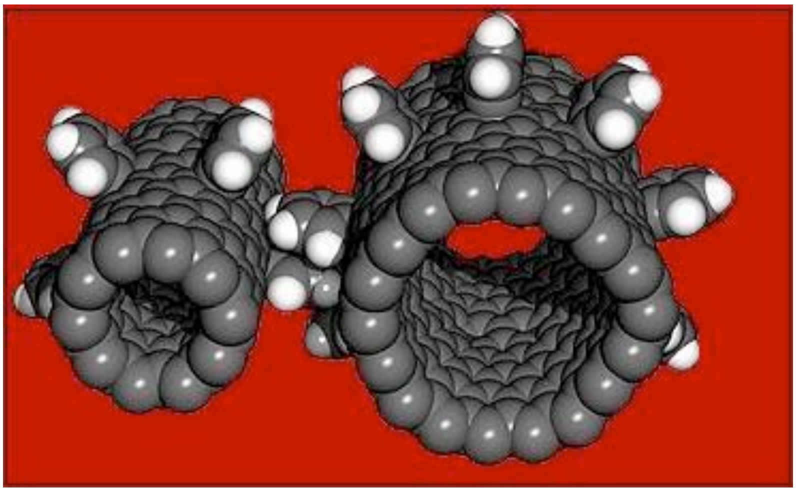
An important challenge to overcome is one of engineering. How can we physically build machines out of atoms? Rearranging atoms into new shapes is essentially building new molecules (nanomachines are sometimes called 'molecular machines') and this is no easy task. Using contemporary technology to rearrange atoms has been said to be analogous to assembling LEGO blocks while wearing boxing gloves. It is virtually impossible to snap individual atoms together. All we can do is crudely push large piles of them together and hope for the best. Scientists hope that once this initial challenge is overcome, nanomachines will usher in a new age of molecular engineering and previous problems will be a thing of the past. The new nanomachines will allow scientists to take off the boxing gloves and accurately snap together individual atoms to build virtually any molecule (within the laws of physics, of course).

This is nice in principle, but the question of how to build the *first* nanomachines remains. Nanotechnologists think that it will be impossible to build the first nanomachines by using large scale equipment (Chen C. 2000). Although progress is being made in the miniaturization of integrated circuits and in the ultra-fine finishing of high quality optical components, the large scale technology being used doesn't let us take off the boxing gloves. There is a limit to how far down these machines can go. Super smooth lens polishing is one thing, but moving individual atoms is something else all together. Nanotechnologists need to get the boxing gloves off before they can build the first nanomachines.

One way to work without boxing gloves is to patiently experiment with chemical synthesis. The idea is to build molecules of increasing complexity by allowing atoms to assemble or rearrange in natural ways. When molecules are mixed, they naturally form new molecules. Through extensive experimentation, more control can be gained over how molecules are formed. In time, it is conceivable that chemists will be able to position individual atoms by using a range of techniques developed in chemical synthesis.

One of these techniques might involve the removal and relocation of hydrogen atoms. This technique could be developed with knowledge of how hydrogen atoms interact with other atoms. For example, it is known that the *propynyl* radical C3H3 (its made out of 3 carbon atoms and 3 hydrogen atoms) is 'attracted' to hydrogen. It is also known that this radical has two ends. At one end there is a highly reactive radical, while at the other end there is stable carbon. This feature means that chemists may be able to synthesize a larger molecule with the *propynyl* radical at one end (the rest of the molecule would be built from the stable carbon end). If this larger molecule was held on a positioning device, it could be used to extract hydrogen from a range of different molecules by passing them by the reactive radical (Merkle R.C. 1993).

Chemical synthesis is promising. In computer simulations, molecularly stable gears and cogs have been formed through chemical synthesis.



A representation of nanogears made from graphitetubes billionths of a meter wide. (Picture from the NanoGallery, see references)

If chemists and engineers succeed in building nanomachines the hope is that these machines will be able to build a whole range of new molecules from the atom up. If all goes well, scientists will never have to move atoms round while wearing boxing gloves and the lengthy experimental process of chemical synthesis will no longer be required. But will it be that easy?

In order to make new molecules, a nanomachine has to somehow 'grab' individual atoms with its pincers and move them into new positions or attach them to other molecules. This seems to be quite simple, but as George M. Whitesides (2001) points out, there are serious problems that need to be overcome. Consider, for example, the fact that a nanomachine's pincers will be made out of several atoms and will therefore be larger than the individual atoms that it needs to move around. This means that the intricacy and accuracy of the nanomachine's movement will be severely limited. It will be clumsy. Assembling atoms would be like trying to piece together a mechanical wristwatch with your fingers rather than small tweezers.

Another problem arises from the fact that individual atoms are compelled to 'attach' to other atoms. Some atomic bonds can be extremely strong (especially with carbon atoms) so pulling them apart will require large amounts of energy. Furthermore, since carbon atoms attach to just about anything it seems likely that they will bond to the nanomachine's pincers after they've been pried away from their original molecules (Whitesides 2001). The only way to remove them could be to move them to molecules that they are more strongly attracted to. But then there is the possibility that the entire nanomachine will stick to the molecule. The situation is analogous to trying to build a wristwatch with magnetized tweezers and screwdrivers. It can't be done because the individual components stick to the tools.

Drexler et al (2001) brush aside these problems. They suggest that such concerns arise from a misunderstanding of how nanomachines work. For example, the idea that nanomachines use 'pincers' to move objects around is nothing more than a poor metaphor. In reality, nanomachines might contain an active tip (like the hydrogen extractor described above), which is no larger than the atom it is designed to manipulate. So Whitesides' concerns about the size of a nanomachine's pincers are easily answered. However, his concerns about the bonding of carbon atoms to nanomachines seem more difficult to answer. Drexler attempts to bury the problem by citing theoretical work done with the hydrogen extraction tool and by referring to experimental work done with hydrogen atoms. He doesn't directly address concerns about manipulating carbon atoms. This is important, because carbon is one of the most common atoms found on Earth and will no doubt be involved if nanomachines are used to build new molecules. Progress made with hydrogen might not translate easily to future work on carbon atoms.

Drexler does, however, mention some very promising work by Wilson Ho and Hyojune Lee. In an experiment, Ho and Lee

"...used an STM tip first to locate two carbon monoxide (CO) molecules and one iron (Fe) atom adsorbed on a silver surface in vacuum at 13 K. Next, they lowered the tip over one CO molecule and increased the voltage and current flow of the instrument to pick up the molecule; then they moved the tip-bound molecule over the surface-bound Fe atom and reversed the current flow, causing the CO molecule to covalently bond to the Fe atom, forming an iron carbonyl Fe(CO) molecule on the surface. Finally, the researchers repeated the procedure, returning to the exact site of the first Fe(CO) and adding a second CO molecule to the Fe(CO), forming a molecule of $Fe(CO)_2$*, which in subsequent images of the surface appeared as a tiny "rabbit ears" structure, covalently bound to the silver surface. Ho's group has also demonstrated single-atom hydrogen abstraction experimentally, using an STM*" (Drexler et al. 2001).

This type of work will hopefully lead to more complex manipulation of atoms, and this could result in the development of tools that successfully 'pick and place' carbon atoms.

As our technological capacities develop, the promise of nanomachine technology becomes more of a reality. We may one day see the successful creation of nanomachine assemblers. These machines could end hunger and bring in a new age of advancement for humanity. Nanotechnology offers us big promises in a small package. However, the advantages it promises do not come for free. They come with some very big risks.

Big risks come in small packages

Cutting edge technology can take a while to catch on in the commercial world. However, there is one place in which it catches on very quickly: The

Military! During humanity's history, technological research has moved fastest when there is a potential military application. The danger is that this trend will continue with nanotechnology. Imagine the possible uses of nanomachines in warfare. Self replicating nanomachines designed to target and destroy organic material could be released over enemy territory reducing the population to dust within a matter of hours. If these machines were designed to destroy each other after (say) 24 hours, the enemy's country would be left empty and safe to be invaded by military forces. Biological warfare would be a thing of the past since nanomachine warfare would be so much safer (well, for the 'good guys' anyway).

The only way to prevent this use of nanomachines would be through international agreements. Unfortunately, not all countries are willing to sign such agreements. And those who *do* sign might be tempted to develop the technology in secret--just incase the enemy is doing the same thing. Perhaps the most we could hope for would be a stalemate situation like the one between the United States and the U.S.S.R during the cold war. If both sides have the technology, they might be too nervous to use it, since they know that the other side will retaliate.

A more serious danger of nanomachine technology involves the ability to self replicate. Imagine that a nanomachine has the ability to make a copy of itself by rearranging the atoms contained in any nearby matter. Since it is producing an exact copy of itself, it is likely that the 'offspring' machine will be able to replicate. This is, after all, the way in which nanotechnologists intend to keep the cost of nanomachines down.

So now we have 2 nanomachines that can replicate. One more cycle will produce 2 more, which leaves a total of 4.

4 becomes 8.

8 becomes 16.

16 becomes 32, and so on.

After only 27 generations we would have over 134 million nanomachines on our hands. Since they are molecular, this doesn't seem like a big number. But the number could keep growing. After 39 generations there would be over 549 billion nanomachines on the planet. The point is obvious. Without a way of controlling the reproduction of nanomachines, the planet is in danger of being over run. Furthermore, since the nanomachines are using the planet's resources as raw material with which to replicate, the danger is that the planet could eventually be *transformed* into a seething mass of nanomachines.

George Whitesides (2001) responds to this problem by pointing out that Earth has already been ravaged by molecular machines--namely, biological cells. This is true. Earth was a much different place 3.5 billion years ago before the emergence of life. Self replicating cells have, over 3.5 billion years, completely transformed the planet. They have changed the planet from a world of inorganic minerals with a CO2 rich atmosphere, to a world that is perfect for biological life.

But this fact doesn't negate the danger in creating replicating nanomachines. In fact, Whitesides has reminded us that it *is* possible for molecular machines to replicate exponentially and transform the planet. If self replicating nanomachines get out of control, then they could alter the planet to such an extent that it is no longer suitable for biological life.

A possible solution to the problem is to limit the replicating abilities of nanomachines. For example, a mechanism could be developed by which new nanomachines are tagged with a number. This number could represent their generation. So, a nanomachine labeled 'gen 2' would produce offspring labeled 'gen 3', and their offspring would be labeled 'gen 4'. The replicating algorithm could be designed to only function if the generation number is less than 4. Also, nanomachines with a generation number higher than 1 could be encoded with a function that limits the number of reproductive cycles they can execute. By building in these safeguards, we may be able to control the population of nanomachines while at the same time allowing the existence of a number necessary to facilitate some of the advantages mentioned earlier.

However, these safeguards may not be enough. The biological world has shown us that evolution occurs and cannot be stopped. The same may be true of the nano-world. Consider the idea that each time a nanomachine makes a copy of itself, there is a possibility that an error could be made during the copying process. Such errors could be very small--perhaps no larger than a single 'bit' of information. Now imagine what would happen if an error occurred while a nanomachine was building its offspring's copying mechanism. To be more specific, imagine that a single 'bit' error occurred when encoding the function that limits the machine's replicative abilities. So, instead of checking that the machine's generation number is less than 4, it checks to see that it is less than 40. When this error is passed on to the machine's offspring, they will reproduce providing their generation number is less than 40. Since the error will be passed on to each subsequent generation, there will be a substantial explosion in nanomachine population. A single error could have the potential to send the nanomachine population out of control. And the more reproducing nanomachines there are, the greater the chance of another error occurring in at least one of them.

The only way to avoid the problem of uncontrollable replication is to avoid building self-replicating nanomachines. It may be true that self-replicating machines are the only way to ensure a cheap supply of nanomachines, but the potential risks outweigh the benefits. If nanomachines are built individually in labs, they will still be useful to cure disease and they will still be potentially useful for rearranging molecules to build new objects such as food. The only drawback is that none of it will come for free. Someone will still have to pay for the construction of the machines, and this means that their products will have to be paid for by consumers. So, poverty will not be eradicated. However, it could be that producing food with nanomachines is faster and cheaper than conventional means, which will mean that poverty may be eased a bit. Furthermore, if governments are willing to invest in the technology, nanomachines may be able to be used to fix some of our environmental problems by repairing the damage we've done to the atmosphere. So the research is worth continuing.

Conclusion

Nanomachines offer humanity hope for the future. The idea that we could one day cure diseases, fix the atmosphere, and reduce poverty in the world is an exciting one. If scientists can overcome the technical difficulties involved in producing nanomachines capable of these goals, then the fruits of their efforts will benefit us all. However, we must be cautious. The temptation to build self-replicating machines is strong, since it will give us an endless supply of new nanomachines at virutally no cost but self-replicating machines have the potential to get out of control. The best efforts to limit their replicative abilities may be insufficient, and our planet could be at risk of being over run by machines that can consume anything to produce more machines at an astounding rate.

The benefits of building nanomachines that can manipulate matter are real and cannot be ignored, so the technology should be pursued with vigor. However, the risks in producing self-replicating machines outweigh the benefits, so I conclude that self-replicating nanomachine technology should not be pursued. We should focus our efforts on perfecting machines that can produce the benefits outlined in this article while never building machines that can make copies of themselves.

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