

Nanotechnology: Questions Deserving an Answer

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Background

I attended with some interest and considerable skepticism a presentation by Dr Ralph C. Merkle on the current state of Nanotechnology and the future directions of the research. The material reminded me of the enthusiasm surrounding the genesis of Artificial Intelligence (AI) in the mid-1970's and '80's. Then, based upon the development of some primitive software written mostly in Lisp, extravagant claims emerged – “We will soon be able to build a brain!”

Significant amounts of investment followed – DARPA/ARPA/DARPA spent millions of dollars (prematurely) on the military applications of AI¹, while simultaneously trying to “dial back” the public expectations of the technology. Many of the products of AI research did manage to make their way into the main stream of computation. The AI community claims credit for time-shared computing and a number of “successful” expert systems in medicine, autonomous vehicles and computer configuration. Neural Networks (NNs) attempted to attack the “construction of a brain” project.

The reality of the achievements falls orders of magnitude below the original, lofty goals to create a brain. In particular, lacking any real understanding of the interactions within a brain that cause conscious thought, NNs were reduced to clever artifacts able to be trained by a simple “reward and punishment” algorithm to a small number of classification tasks that are actually easier and more manageable achieved with conventional programming.

All that to say that the current “hype” surrounding Nanotechnology has the same ring to it.

Summary of the Ideas

I begin by summarizing what I believe to be claimed in the presentations I have seen.

1. We can pick up an atom and move it

By using a molecule-sized probe guided by a Scanning Tunnel Microscope (STM), we have actually picked up one atom from one location and placed it in another.

2. We have designed some atomically credible nano-machines

There are actual atomic models of gears and bearings that (presumably) obey the laws of atomic physics and can remain stable. Since these configurations do not occur naturally,

¹ The author's retrospective on one such project is at http://www.dms489.com/PA_index.html

I assume that they would be created by “manually” assembling the atoms. *The first question that must be addressed: Are the intermediate states achieved during this assembly process also naturally stable, or must all the atoms involved be simultaneously assembled?*

3. We have conceived an atomic arm

A schematic diagram has been drawn indicating a “feasible” arm with a length around 100 nm and a small tip of the right order of magnitude to pick up and move atoms.

4. We have run the numbers on the stability of this arm

Basic math suggests that if such an atomic arm could be built, it would be sufficiently stable at room temperature to retain its position within the kind of tolerance necessary to manipulate atoms².

5. We have conceived a self-replicating “microbot”

Based on using two such atomic arms connected to something of comparable size, we have conceived a miniature device able to construct other little things just like it.³

6. We have conceived an assembly process

Based on the idea of turning loose myriads of these microbots, we should be able to assemble big things like redwood trees. This doesn't seem too bad a target since nature takes hundreds of years to grow one.

7. Because we design the materials at the atomic level, they will significantly out-perform existing materials.

Given the ability to assemble materials atomically, one should be able to custom design exotic materials with amazing properties. Existing products become more efficient, and a whole new generation of products becomes feasible.

Specific Concerns

My concerns about the “technology”⁴ are in three areas where the presentation materials make enormous “leaps of faith” for one more used to the rigors of engineering and manufacturing.

1. Micro-Control

Engineering implementation of this chain of events appears to be dependent on creating autonomous micro-assembly devices – devices of the order of 100nm in size. Otherwise, the concept is doomed to manual assembly of small numbers atomic-level components – automobile production before Henry Ford. So we need to look at the feasibility of the

² The actual claim made was that it could be controlled within that tolerance – a claim I will discuss below.

³ Another claim I will discuss below.

⁴ I quote this because current experimental achievements fall well short of conventional definitions of a technology. Perhaps I can refer to it more appropriately as a “concept.”

microbot described in 5 above, especially the atomic implementation of its control devices.

Control is the intelligent integration of sensing and actuation. The original “I moved an atom” experiment was undoubtedly performed using the STM (itself an enormously complex machine) to sense the location of the atom, an atomic probe moved by some kind of multi-axis actuator and significant amounts of special-purpose computation to present the probe location to an operator, receive and interpret operator commands and drive the probe to the right location. This is complex enough with a human in the loop with the necessary knowledge to know where to look for the atoms and how to interpret the view seen by the STM. The nanotechnology concept appears to require that this assembly process be performed without human intervention – robotically.

Robotics technology, however, has yet to reach the stage where even vehicles can be driven autonomously for more than a mile or two across known terrain with a car packed full of computers.

The second question is that must be addressed: can we really we expect in the foreseeable future to make a “taskable microbot?” It will need the following characteristics:

- Two arms with a length equivalent to about 500 atoms containing some kind of actuators that can position the tip of the arm in 3 space within an Angstrom or two,
- The ability to sense where the atom to be moved is located (ignoring for a moment the problem of moving close enough to it), and where it should be moved to, and
- Processing power necessary to interpret the sensed location of the atom and control the arms along an appropriate trajectory.

If we ignore the enormous challenge of the sensing and actuation technology, and concentrate just on the computing capacity, a processor built today might be housed in a cubic meter of space. In order to be practical, our microbot need to contain this processing capability in a cube around 100 nm on a side with a volume of 10^{-21} cubic meters. Accepting the typical improvement rate of a factor of 2 every 18 months, it would seem that we can expect this kind of capability about 10^{60} years from now.

Add to this the enormous difficulty of making either sensor or actuator to that scale, and finding answers to the second question becomes really challenging.

Possible answers:

- One might claim that the computational problem facing vision for robots is neatly solved by delivering to the robot its raw materials in a rack with a known configuration. The robot can then proceed blindly picking up and doing its operations. However, the main point of this micro-manufacturing is to be able to take atoms that are not nicely arranged, and arrange them. If they are already nicely arranged, the process is not necessary at all.

2. The Curse of Dimensionality

So we assume for a moment that microbots become available to perform the “atomic level” manufacture of primitive components – say of the order of 100 atoms each. ***Based on the following discussion, the third question that must be addressed is this: How many manufacturing integration steps and how many “manual” assemblies will be needed to manufacture the proposed “sugar cube” that could contain all the world’s knowledge?***

It seems that these assembly components will be designed so that they can begin to “snap together” components like themselves and so create larger components⁵. So this self-assembly process continues where each layer of the process multiplies by 2 (as it appeared in the presentation) the complexity of the manufactured product. The claim is then that in a small number of integration steps, we can go from the original micro-assemblies to substantial sized products in a relatively small number of steps.

However, is this really a small number? Suppose our finished product is the sugar cube that is 1cm on a side, for a volume of 10^{-6} cubic meters. Since the volume of one primitive component is about 10^{-28} cubic meters, we have to produce something like 10^{22} micro-assemblies to fill that sugar cube. That is not a few stages of size doubling – it is around 60 stages. To produce one sugar cube, one would have to manufacture something like 10,000,000,000,000,000,000,000 micro-assemblies, each one painstaking assembled from atoms by microbots.

The dimensionality of this problem hurts on two fronts. An army of a billion microbots each assembling one micro-assembly every second (a very aggressive pace for finding, picking up and putting down 100 atoms) would take something over 300,000 years to assemble enough material to make a sugar cube. After that, the 60+ assembly stages would require significantly less resources.

3. Distributing the design?

Let us assume, however, that we can in fact get enough working microbots built and can compress the time for assembling our redwood tree. ***The fourth question that must be addressed is this: How do these myriad self-assembling things “know” what to build?***

For the resulting product to be useful, it has to follow some kind of overall design, and the question becomes how each little assembler in this ant hill “knows” what to build. It seems there are two choices, neither of which can stand much scrutiny.

A. Build it in.

One could perhaps build into each little assembly thing the knowledge about what to make. While apparently feasible at first glance, size is again our enemy. Since the larger things are assembled from smaller things, the complete design has to be contained in the smallest micro-assemblies and “parceled out” as necessary to the higher order assemblers. Redwood trees and other living things pass around their design by replicating a DNA molecule with the complete design description in each cell. Cells of

⁵ I don’t want to throw in too many rabbit trails, but I did wonder again about the same control problem – sensing, actuation and processing – discussed above.

different types “discern” their position in the design and cause cell replication as required to implement the design.

However, the cells of a tree are huge compared to our micro-engines, and the DNA molecule that captures their design contains billions of atoms. Even if this amount of storage were possible, we add to the crushing computational burden of our microbots the complexity in the systems and software necessary to implement the design decomposition.

B. Distribute the Design

If we can't build in the design, we have to have an external controller “telling each assembly process what to do.” Another serious challenge. Today, we get incredibly inefficient operation from any data network with, say, 10^4 nodes connected, and we anticipate communicating efficiently with 10^{22} independent processes all awaiting the next instruction?

Summary and Conclusions

So I rest my case. It seems that there are four fundamental questions between today's reality and tomorrow's Nanotechnology achievements:

1. stability of the nano-structures during assembly,
2. positional control of microbots performing the assemblies,
3. the dimensionality of the assembly process, and
4. the delivery and management of the design.

Back in the heady days of AI research, we were happy to invest significant amounts of our time and other peoples' money pursuing some worth sub-goals in the grand vision of AI. Very quickly, the conversations would turn from the grand vision to “picking the low-hanging fruit.” I suggest that we dial way back on the rhetoric proposing light-weight space vehicles, and little devices floating through the blood stream destroying foreign objects, and start establishing feasible goals for the foreseeable future.