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Molecular Assemblers: Building From the Molecule Up

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"But I am not afraid to consider the final question as to whether, ultimately - in the great future - we can arrange the atoms the way we want; the very atoms, all the way down!"

-Richard Feynman

That quote, came from his 1959 speech "There's Plenty of Room at the Bottom", generally considered to be the conceptual origin of nanotechnology. While largely still theoretical, significant strides have been made towards building what would later become known as molecular assemblers. So far miniaturization has taken a top-down approach, trying to find ways to make things we already know at smaller and smaller scales, but this has a fundamental limitation that will soon be reached at around 50 nm[1].

Nanotechnology, on the other hand takes a bottom-up approach, attempting to rebuild macro scale devices from the ground up, from atoms or molecules[1]. The world of possible properties and applications for devices and structures built with molecular precision is endless. This is the design goal of molecular assemblers: to build things molecule by molecule. Since they are largely theoretical still, this paper will explore a number of the different potential applications that have been envisioned, as well as some examples of nanomachines that have already been developed. Also some examples from nature will be outlined as proofs-of-concept of the molecular assembler. Finally, the paper will go over the problem of run-away self-replication of molecular assemblers.

Molecular assemblers are nanoscale machines that manipulate the molecules in their environment to build more complex structures. Hypothetically, anything that can be manipulated on the molecular level could be used as a building material[1]. Naturally, this leaves the answer quite open-ended due to the vast possibilities for molecular manipulation. Molecular assemblers could build quantum computers, macroscale objects, other nanorobots, other nanostructures, or even copies of itself[1]. Current iterations of molecular assemblers are very narrow in their function, being able to catalyze very specific reactions involving specific molecules. But ideally as time progresses a more general "universal assembler" could be developed that can manipulate a wide array of molecules and consequently be able to build almost anything[1]. Note that the term molecular assembler is intentionally used as opposed to atomic assemblers. It's been shown that controlling atoms individually is incredibly difficult[2]. Molecules are much more stable than atoms and are already device-like, as they have properties that can be manipulated with electricity or light[2]. It is hard to harvest atoms from the environment, as they commonly exist in a bound state and would require energy to unbind[2]. As a result of these limitations, the field is focused on designing molecular assemblers as opposed to atomic assemblers.

Like any machine, the molecular assembler would be composed of individual components in which each performs a specific action, which together with the other components result in the assembler performing a function[2]. At the very least, it would require an energy source, a component to bind and unbind molecules, a component that moves the molecule to the desired location, a computer that can dictate the function or a receiver if using a broadcast architecture, and a motor for movement[1]. A number of different energy sources for nanoscale machinery have already been hypothesized and developed. Taking a lead from nature, examples include ATP, and sunlight[1]. Ben Feringa from the University of Groningen in the Netherlands was able to make a solar powered nanomotor, out of only 58 atoms[3]. Photochemical and electrochemical based sources are good energy reservoirs, as they do not produce waste products which can affect the function of the assembler. They also create processes that are reversible, which are both desirable properties for nanomachinery[2]. Scientists from the Lawrence Berkeley National Laboratory were able to make a conveyor belt out of carbon nanotubes[4]. By controlling the electrical current in the nanotube they were able to direct the velocity of an indium particle's movement within the nanotube[4]. These are examples of nanoscale machines that already exist and could certainly be useful if incorporated into molecular assembler design.

While our ability to manipulate atoms with the level of precision to make almost anything may seem farfetched, there are a number of examples from nature we can look to for inspiration. Ribosomes are essentially biological molecular assemblers. They are composed of a number of different proteins and RNA's. They come together to read an mRNA and take amino acids from the cytosol to form a protein. This is an exact mirror to what molecular assemblers do, but replace amino acids with molecules, mRNA with computer, cytosol with the environment. Proteins may not necessarily even have to be replaced, as it is likely that molecular assemblers will include them in their design. If nature can build a biological molecular assembler, it is highly probable that an artificial assembler can be constructed.

One of the amazing potential advantages of advanced molecular assemblers, is that the expense to produce something is reduced to only its materials costs, and the software to run the assembler[1]. Truly the ultimate in miniaturized 3D-printers, you could print anything you need when these are fully developed, from clothing to medicine[1]. Until then, researchers will be working within the current limitations of the field. There are examples of functional molecular assemblers, but they are nowhere near the generalized universal assemblers envisioned of the future. They can perform very specific actions involving very specific molecules. One such example is Cucurbit[8]uril which can perform [2 + 2] photocycloaddition of stryrl dyes[5]. [2 + 2] photocycloaddition is a photochemical reaction that involves two unsaturated molecules being combined to form a product molecule[5]. Two atoms are involved from each of the two molecules being bound, and this gives the notation [2 + 2][5].

Along with all of the amazing potential promised by nanotechnology and molecular assemblers, it isn't without it's perils if certain contingencies aren't properly accounted and prepared for. In order to make a nanoscale factory, it isn't efficient to make a single molecular assembler and watch it build your design, one molecule at a time[1]. It is much more efficient to have the molecular assembler self-replicate a few thousand times, and then have all the new assemblers begin building in tandem[1]. Unfortunately, the so-called "grey goo" problem arises if an assembler becomes coded to replicate indefinitely. This could begin either due to an individual with malicious intent, or unintentionally due to a replication glitch. In replicating thousands of times, similar to DNA mutations, a glitch could happen that causes an assembler to become "cancerous" and replicate with no signal to stop[1]. Unfortunately, if rampant self-replication occurred, the biomass of the Earth would likely be the prime target[1]. This is because carbon and glucose are likely to be incorporated into the replicator's designs and would therefore be of high value to the replicator[1]. There are a number of ways to deal with this concern though, so that the grey goo problem can be fairly easily avoided. Among them is using the broadcast architecture mentioned earlier, which involves having the code for self-replication present on a single computer that broadcasts it to all of the nanomachines, so that at anytime the broadcast and thus replication can be stopped[1]. The broadcast architecture is not infallible however, and could be defeated if someone was determined enough[1]. Designers can also structure the process to require exotic or uncommon materials so that it becomes a limiting factor for replication[1]. Other more extravagant ideas include having a nanorobot immune system, designed to seek out rampantly replicating nanorobots and eliminate them[1]. Ironically, this immune system would itself need to be self-replicating[1].

Advanced universal molecular assemblers are mainly theoretical but there are a number of advances in nanotechnology that indicates they may be possible in the near future. The number of individual nanomachine components being developed, the current single function molecular assemblers that already exist, and the precedent already set by nature, are all strong indicators that a more general molecular assembler is possible. Their amazing potential for an advanced version to make nearly anything is an exciting prospect for humanity. The dangers of potential runaway replication certainly exist, but numerous different protection methods already exist and will be developed alongside the technology.

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