Technology
Tactics
Fan Fiction
Database

Forums
Science
Essays
Hate Mail

Site Index
Links
Feedback
What's New

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The Nanotechnology Myth

Nanotechnology is often touted as a catch-all solution for everything. As with bio-technology, it undoubtedly has its uses, and those uses may have widespread and profound (some say dangerous) implications for society. But again, as with organics, nanotechnology is delicate and limited in many ways. That's not to say the idea is useless, but I've seen a lot of people with zero experience in manufacturing techniques making ludicrous pronouncements about how *all* manufacturing will eventually be based on nanotechnology. The word "conventional" seems to be synonymous with "primitive" and "inefficient" in the minds of many, and so we often hear about how we will someday transition from "conventional manufacturing techniques" to nanotechnology.

This idea comes from the fact that nanotech "grows" things, and it's related to the conceit that it's always better to grow than build (of course, since *we* grow, and we're supposedly the pinnacle of creation; see creationist conceit). In reality, manufacturing techniques based on growth rather than conventional fabrication suffer from many serious weaknesses, just as we do. Manufacturing rates are low, and tolerances are loose. For all the talk about the precision of the human body, its gross manufacturing tolerances leave something to be desired. In fact, most humans have one leg slightly longer than the other (along with other assorted imbalances), and one might not even realize that one has an imbalance until the length difference exceeds one inch!

Manufacturing Speed and Accuracy

Nanotechnology disciples tend to talk about the wonders of building something "molecule by molecule", as if this would make all manufacturing cheap and near-instantaneous. However, they never ask the looming question: what's so great about building something molecule by molecule? Do they realize that such microscopically incremental manufacturing techniques already exist?

Electroplate growth manufacturing techniques are real. They build items *atom by atom*, and the result has exceptional chemical and microstructural purity as well as the ability to produce highly accurate and complex shapes (on *one* side; the other side looks like hell). However, they are ridiculously slow, which makes them ridiculously expensive (I still remember the first time I picked up a piece; it was smaller than a tape measure and its price tag was in the tens of thousands of dollars). This is not a problem which will magically go away; many years of development have *not* resulted in significant improvements in speed. Similarly, nickel-vapour deposition technology constructs a metallic form atom by atom by depositing nickel carbonyl vapour onto heated tooling, and again, the principal drawback is low speed and lousy accuracy on the side opposite the tooling (not to mention inapplicability to other base metals and some annoying geometric constraints which I won't bore you with; just trust me when I say that from my experience, it can be a real pain in the ass). The same is true of laser-based rapid-prototyping technologies, which are not only slow and expensive but also limited to weak plastic items.

Nanobots would most likely be even slower than the aforementioned technologies; electroplating and nickel vapour deposition pour on atoms as quickly as they can bond to the underlying material, and nanobots would only add complexity to this process. Accuracy is also a serious problem. Let's say you have a 100,000 nanobots, and you want to make a six-inch metallic ruler. Nothing complicated, right? A simple ruler, with the usual hatch marks for length measurement. Obviously, you want it to be flat and square. Now, you turn your nanobots loose. Presto, they whip up a perfect ruler for you, right? Because they grow it molecule by molecule, it's really slow but it's easy and it's dimensionally perfect, right? Ummmm ...

OK, let's look at this from the perspective of nanobot #1. Just to be generous, let's visualize the nanobot as a tiny little worker spacecraft that you control, so it has *your* human intelligence (rather optimistic for a nanobot, but I *am* trying to be generous). Your objective is to help the other 99,999 nanobots build a ruler, but from your perspective (inside a 10 micron wide nanobot, so you've been shrunk to roughly 1/200000 your original size), this six inch ruler is more than thirty kilometres long! Worse yet, there are some serious logistical problems to work out:

1. How do you co-ordinate your activities with the pilots of the other nanobots? Is there a commander nanobot? Are there middle manager nanobots? Who assigns nanobots to which part of the ruler?

2. How do you know where to start, ie- how do you decide where one end of the ruler is going to be, and where the other end is going to be?

3. How do you communicate with the other nanobots? Radio transmissions? How do you communicate clearly with tens of thousands of other nanobots simultaneously? How do you align your movements with theirs? How do you plan?

4. How much fuel do you carry? That little nanobot vehicle of yours doesn't run on the power of positive thinking, so how much work can it do on a full tank? Where and how do you refuel? How long does it take you to refuel?

5. What is your propulsion system? You're not getting a free ride in someone's bloodstream like the sort of

nanobot which looks for cancerous cells (a more sensible application of nanotechnology), so how do you maneuver about on the manufacturing table in order to help assemble this ruler? How do you jet up into the air to get on top of it if you need to? How much power do you have to combat gravity and air currents?

6. How do you deal with lost nanobots? In a normal manufacturing environment, air currents, static discharge, and other environmental disturbances could easily blow a nanobot out of the group or seriously damage it. Does the plan adjust automatically for worker turnover? Or must this ruler be manufactured in a vacuum-sealed clean-room environment? This is rapidly shaping up to be a ridiculously expensive ruler!

7. How much payload can you carry? If you're grabbing molecules or tiny particles and attaching them to this ruler, where do you get them from? How many can you carry per trip? How much energy does it take to weld each chunk of metal to the ruler? Do you realize that if you use larger particles per trip, the resulting ruler will have greater porosity? What are you going to do, weld molten metal into the gaps? Consider the energy costs of doing *that!*

8. How do you assure dimensional accuracy of the overall ruler? The nanobot working on the other end of the ruler is (as far as you're concerned) more than 30 kilometres away, remember? How do you know he's not higher than you are? Do you set up a laser-based perimeter system in order to confine your activities within simple geometric bounds? If so, how do you make more complex shapes than a flat ruler? Do you use tooling in order to confine your activities? If so, what conceivable advantage does this process have over simple die-casting?

Hmmm ... a bit more complicated than we thought, eh? And this starts from the assumption that each nanobot is as intelligent as a *human being*, which is ridiculously optimistic. Now let's compare this to the "primitive" conventional method of making a flat ruler. Pour some metal into a die, wait for it to cool, and you're done. Alternatively, take a strip of metal, put into a stamping press, hit the green button and BANG! One stamped-steel ruler. Do you still think all manufacturing will be replaced by nanotechnology once we work the bugs out?

"But humans are grown, and that works, so you're making it sound harder than it is!" some may protest. But they would be missing the point. As mentioned previously, our manufacturing accuracy leaves something to be desired, and is *well* below the standards expected of machined parts. A $1 compact disc is manufactured with tighter tolerances than the human body, which can't even make two arms, two legs, two eyes, or two of *anything* which match to within what a typical manufacturer would consider tight tolerances. Moreover, initial growth stages must take place in a special environment (the womb), so the process doesn't work on a table in the middle of a factory. A constant stream of nutrients (ie- fuel) must be fed into the body so it can grow itself. And what about speed? It takes approximately 16-18 *years* to manufacture a mature human being, remember? If it took that long to make a car, would you wait? What about waste? A human being will emit more than 1E10 joules of waste heat before it is mature, in addition to producing some 5,000 litres of urine and several hundred kilograms of feces (dry weight), all while consuming enormous amounts of both solid and liquid nutrients and burning them at 25% efficiency. Is this really a manufacturing model that we want to emulate for industry?

People who propose one-stop "cure-all" solutions usually haven't thought clearly and thoroughly about them; in reality, there is no conceivable advantage in 99% of the applications where nanotechnology disciples would have us use it. Small robots are good for doing small things (eg- killing a cancer cell), but not for doing big things (eg- making an engine block). Moreover, accuracy is a serious problem with any atom-by-atom or molecule-by-molecule manufacturing scheme; whereas an engine block can be easily finished to within close tolerances with large CNC grinding tools, that same block would be nightmarishly difficult to manufacture to the same tolerance using nanobots (to say nothing of the staggering difference in speed and efficiency between casting the block and building it atom by atom with nanobots).

Anti-Ship Weaponry

Nanotechnology may be rather limited for heavy manufacturing, but there is no doubt that nanotechnology could be just as effective as biotechnology when it comes to killing people, if we wanted to use it that way. After all, it is merely emulating already-existing natural nanotechnology devices (bacteria and viruses). Causing the death of a human being at the cellular level is a small-scale, highly parallel process which requires no central co-ordination, no payloads, and no exposure to harsh environmental conditions, thus making it ideal for bio-tech or nano-tech (it's best if the nanotech machines can be made to run off the ambient nutrients found in the human bloodstream). However, this is where the nanotech disciples start to diverge from reality, because they usually don't stop there.

A common nanotechnology idea on the newsgroups is the nanobot as unstoppable attacker against *spaceships*. Some sci-fi fanboys like to write scenarios in which a swarm of nanobots attacks a helpless starship, eats through its hull atom by atom, and then swarms through its insides, killing its crew and devastating its equipment. Does that sound unstoppable to you? The Star Trek Voyager staff writers even put this idea onscreen, in the form of modified Borg nanoprobes which were launched into space against seemingly unstoppable alien warships from another dimension. Does that seem realistic? If you think so, then please consider these problems:

1. Iron stays together because its energy state is lower when bonded to other iron atoms. Therefore, even if we ignore the actual mechanism and assume perfect efficiency, the work required to liberate a piece of iron from the surrounding matrix is non-trivial. This is a serious problem for nanobots which have literally microscopic fuel reserves. And if we *don't* ignore the mechanism, we must also account for its inherent inefficiencies and limitations.

2. In the vacuum of space, there is no ambient chemical energy source for the nanobot. Even if the nanobot

carried enough fuel to liberate a microscopic chunk of metal from the target spacecraft's hull, it would run out of fuel and go dead immediately afterwards. In other words, since each nanobot couldn't dislodge more than a microscopic piece of metal from the target hull, you would have to hit the hull with such a large volume of nanobots that you'd be much better off simply hurling a macroscopic projectile at it (to say nothing of the incredible cost of manufacturing all of those nanobots, as opposed to a single slug or shell).

3. The small size of nanobots obviously precludes thick electrical shielding. Therefore, a simple jolt of electrical current through the hull-plates would instantly destroy any nanobots on its surface. In other words, countermeasures against nanobot attacks would be ridiculously easy to devise, even if we disregard commonplace sci-fi contraptions such as particle shielding and forcefields. Moreover, intense magnetic fields and other defensive systems might very well disable nanobots as a completely unintended side-effect of normal operation.

4. Rates of heat transfer are correlated to surface area, while heat content is correlated to volume. Obviously, the ratio of surface area to volume is much larger for a microscopic object than it is for a macroscopic object, which means that microscopic objects are *extremely* vulnerable to heat. This is why a piece of hull armour might survive an intense radiation bombardment while a thin antenna made of the same material might melt away (it's also why a bunch of ice chips will melt faster than one big ice cube). In other words, the normal radiative heat flux on the tiny shell of an exposed nanobot in space (depending on its proximity to the nearest star) might very well be enough to fry its innards (this is a problem for the idea of solar-powered nanobots in space; their fuel source may destroy them). It goes without saying that the heat flux in the vicinity of a pitched battle involving nuclear-yield weapons would *certainly* fry an exposed nanobot (unless you carefully manufacture a thickly shielded casing for each nanobot, which would make it *much* larger, thus defeating the purpose and decreasing the ratio of useful machinery to dead weight).

On the upside, nanobots would probably be able to withstand much greater accelerations than macrosopic machines without damage, because of the relationship of size to proportional strength (see the "Size Matters" page). However, this would *not* suffice to make them an effective anti-ship weapon.

Anti-Personnel Weaponry

The best weapons application for nanobots is obviously against ground personnel, rather than spaceships. But even in that role, they have their own particular limitations, and can hardly be regarded as an omnipotent weapon. That's not to say they can't kill people, but everything's relative, and the real question is: are they *more* effective than other forms of weaponry? Let's compare an enormous swarm of nanobots to a nuclear weapon, judging by various criteria:

1. Destructive impact: nukes win. A nuclear weapon causes devastation far in excess of that which could be wrought by a swarm of nanobots.

2. Cost: again, nukes win. A nuclear weapon is relatively inexpensive compared to trillions of micro-miniaturized machines.

3. Collateral damage: nanobots win. A nuclear weapon destroys and devastates cities (and depending on its design and detonation altitude, it may also produce deadly long-lived radioactive fallout), but nanobots would theoretically kill the humans while leaving the cities intact. If they have a built-in self-termination date (or they simply tend to wear out or break down after a certain period of time), the planet could be safe for immediate occupation.

4. Delivery: nukes win. A nuclear missile can theoretically be shot down in flight despite its great speed, but it can also easily navigate to the target through all manner of upper-atmospheric disturbances and electromagnetic fields, as well as inclement weather conditions on the way down such as high wind, lightning storms, rain, etc. If it is *not* shot down, it will deliver 100% of its payload to the designated target, all concentrated in one place with devastating effect. Nanobots, on the other hand, might not be detected on the way in, but they could also be blown hundreds of miles off-course by high winds, or damaged (perhaps totally neutralized) by magnetic fields, cosmic rays, upper-atmosphere ionization, etc. In fact, given the inevitability of dispersion on the way down, it is virtually impossible to concentrate a strike on a particular target from orbit, and excessive dispersion might make them useless (no machine is *perfect*; how much damage could one nanobot possibly do before it breaks down or wears out, even if we assume it can extract unlimited fuel from its environment?)

5. Countermeasures: nukes win. The only real countermeasure against a nuclear weapon is to try to shoot it down in flight. With only a few minutes of warning at most, there won't be sufficient warning to evacuate citizens or move the bulk of the population into shelters, assuming enough shelters exist. A cloud of nanobots, on the other hand, might not even be detected en route. However, if they *are* detected, they can be easily neutralized. A nuclear airburst in the midst of a nanobot cloud would vapourize most of them and disable the rest, with minimal fallout and very localized collateral damage. The electromagnetic pulse *alone* should neutralize them. This leads us to the second countermeasure, which is reactive rather than proactive: nanobots, unlike nuclear weapons, can be stymied by countermeasures even *after* they reach the target. Non-nuclear EMP weapons (yes, we're already developing them) could clear large areas of nanobots without killing anyone or destroying cities, high-voltage ionizing field circuits in air vents could protect sealed shelters, armoured vehicles, etc., and electromagnetic pulses could even be used to treat victims after infection.

Some might argue that self-replication is the key to making nanobots more effective despite these weaknesses. In theory, self-replicating nanobots could be deposited on a planet and it wouldn't matter if 99% of them are destroyed or blown off course, because they would continue to replicate until they become an overwhelming "grey goo" all over the planet. However, there are some rather glaring feasibility issues associated with this idea. How much energy (ie- fuel) does it take for a nanobot to manufacture a duplicate of itself? What special tools would it require in order to do this, and how would the inclusion of those tools increase its expense and size? How would they affect its ability to perform its primary function? Remember that unlike a bacterium, it's not made from organic materials. It needs refined metals and other specialized raw materials, but where is it going to find them? How much travelling would it have to do in search of those materials, and how much energy will this take? How is it going to fuel up the nanobot that it just made, given that it probably used up its reserves in order to build it? Is it going to replenish from solar power? If so, how will it work at night, indoors, on overcast days, or inside a human body? How long will it last under increased ultraviolet radiation (which does more than merely cause skin cancer; it actually breaks up chemical bonds over time, which is why it bleaches paint and destroys plastic) if it must remain exposed to direct sunlight in order to function? Do you remember the effect of microscopic size on vulnerability to radiation?

Moreover, the idea of nanobot self-replication also opens up a *huge* can of worms from a safety perspective, and I think it *highly* unlikely that any reasonable person would take the risk. Anything less than 100% perfect replication opens up the possibility of evolution over multiple generations, and I don't think I need to explain the dangers inherent in an evolving species of nanobot, not only to its victims but also potentially to its inventors. And after all of this, it's still not a good weapon. Nanobots would still be vulnerable to various countermeasures, it's difficult to tell whether an area is clean, and it would be difficult to regain control if they get out of containment, thus forcing you to employ the same countermeasures yourself. Any weapon which poses as much risk to you as it does to your enemy is not a particularly good weapon.

Nanobots in Sci-fi

While Star Wars has largely stayed away from sci-fi chic ideas such as unstoppable nanobots, Star Trek and Babylon 5 have both embraced them wholeheartedly (the latter doing so in its old age, as it became more Trek-like). A few examples come to mind:

Star Trek TNG, "Evolution": tiny nanites get out of control, start to evolve, and take over the Enterprise's main computer. This episode is actually quite realistic in many respects; Stubbs zaps them with low-level ionizing radiation which kills them easily, even at levels which are relatively harmless to humans. This makes sense, given the theoretical vulnerability of microscopic machines to harsh ambient conditions. They were able to duplicate very easily, but they were in an environment (a starship's computer) where raw materials and energy supplies were presumably both plentiful, so that makes sense too. Unfortunately, there were also a couple of downsides. The nanites rapidly developed collective intelligence, which does not necessarily follow; it is human egotism which leads us to assume that all life will eventually evolve into something which thinks as we do. In reality, billions of years of evolution and millions of species have only produced a handful of species whose capacity for thought even remotely approximates our own, and it has *never* produced a species with collective intelligence distributed throughout a vast group. Another problem is that the plot revolves around the nanites being one of Wesley's experiments gone wrong, which would mean that the Federation does not regard nanobots as a controlled technology. This, in turn, seems remarkably stupid. Letting Wesley play with nanotechnology in uncontrolled conditions is like giving bio-weapons to a curious schoolboy.

Star Trek Voyager, "Scorpion": we are told (and shown, with pretty pictures dumbed down nicely for the sort of people who actually *enjoy* Voyager) that Borg assimilation is based on nanoprobes which invade the body and turn you into a Borg from the inside out. This is, of course, but one of the many continuity problems introduced by the increasingly careless Star Trek writing staff; the Borg did not assimilate anyone or anything when they first appeared, then they assimilated Picard through surgical alteration in order to gain a tactical advantage, and now their entire society is based on assimilation and they use these magic-tech nanoprobes? Argh. Anyway, these nanoprobes enter your body, and then within minutes, Borg hardware sprouts from your body. Small problem: where the hell are they getting all of the metal from? Let's assume they can actually run off the nutrients in your bloodstream (which limits their rate of work, but at least keeps them from running out of juice entirely); they still have to come up with the raw materials to make all this hardware! Can they perform elemental transmutation and replication now? If the nanoprobes can do that, why can't a Borg drone manufacture certain critical components when necessary, as seen in the Voyager episode "Imperfection", where a malfunction in 7 of 9's "cortical node" threatened her life until they salvaged a replacement from a dead drone? It's just another example of the "it's nanotech, so we don't have to observe common sense!" sci-fi chic mentality (and of course, thousands of self-professed fanboy "science experts" watch Voyager and never notice this painfully obvious problem with the idea).

Babylon 5: "A Call to Arms": President Sheridan and a large fleet of warships attack and destroy a Shadow planet-killer en route to Earth. It's funny what passes for a "planet-killer" in the B5 universe, isn't it? A few thousand gigatons worth of missiles that kills everybody on the surface? A single ISD can outgun that easily, but B5 fans should take heart in the fact that the monstrous firepower of Star Wars ships (as exemplified most strikingly by the Death Star, which is staggeringly powerful even if scaled down to ISD size) is actually an area in which it is less *realistic* than B5. Anyway, returning to the subject at hand, the Drakh unleash a horrible bio-weapon at the end of this episode (which we eventually discover to be some kind of nanotechnology). They deploy the weapon from orbit, and it looks like a black spray coming out of the ships (concentrations at ground level would have been insignificant, but the devices could apparently self-replicate). There was a nice shot of Sheridan's face as his emotions changed from the elation of victory to the sickening horror of defeat, watching the plague sinking down toward Earth. However, what we *should* have seen was a quick-thinking order for any vessel with nuclear missiles to set them for upper-altitude detonation and fire them immediately. Upper-atmospheric nuclear explosions will create an intense and widespread ionization and thermal radiation effect which should have fried the plague on the way down *regardless* of whether it was biological or nanotechnological, while causing very limited damage at surface level unless the yields are extremely large. The potential for casualties was there (anyone looking up at the sky would have been blinded), but surely the

population would have been warned not to look up at a space battle in orbit, where nuclear missiles are a distinct possibility. Alternatively, he could have ordered space detonations, which would have a much weaker effect than upper-atmospheric detonations but would still terminate the plague if he acted quickly enough. This is ultimately another example of a sci-fi writer subscribing to the sci-fi chic notion that nanotech is unstoppable. At the very least, you'd think Sheidan would have tried *something*, instead of just sitting there with a defeated look on his face! I thought it was *completely*
out of character for Sheridan to give up like that, and it was obviously just an excuse to lead into the "Crusade" series (which revolved around their attempts to find a cure for this plague).

Conclusion

Still here? Not bored yet? Good, because I'm done. I'm not trying to attack the idea of nanotech per se; it could very well have some very interesting applications. But as with all new things, it's all too tempting to think of it as a panacea, and like every other cure-all in the history of technology, it's not. In my opinion, its best applications have to do with medicine and computers, although it's always possible that people will think of other creative ways to use it. However, what they *won't*
do is obsolete all heavy manufacturing techniques, hurl nanobot clouds against spaceships in combat, or drop a cloud of nanobots from orbit and expect to accomplish anything.

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