Nanoethics: From Utopian Dreams and Apocalyptic Nightmares towards a more Balanced View

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ABSTRACT: *Nanotechnology is a swiftly developing field of technology that is believed to have the potential of great upsides and excessive downsides. In the ethical debate there has been a strong tendency to strongly focus on either the first or the latter. As a consequence ethical assessments of nanotechnology tend to radically diverge. Optimistic visionaries predict truly utopian states of affairs. Pessimistic thinkers present all manner of apocalyptic visions. Whereas the utopian views follow from one-sidedly focusing on the potential benefits of nanotechnology, the apocalyptic perspectives result from giving exclusive attention to possible worst-case scenarios. These radically opposing evaluations hold the risk of conflicts and unwanted backlashes. Furthermore, many of these drastic views are based on simplified and outdated visions of a nanotechnology dominated by self-replicating assemblers and nanomachines. Hence, the present state of the ethical debate on nanotechnology calls for the development of more balanced and better-informed assessments. As a first step in this direction this contribution presents a new method of framing the ethical debate on nanotechnology. Thus, the focus of this paper is on* methodology, *not on* normative analysis.

INTRODUCTION

This contribution first sketches Eric Drexler's early vision of nanotechnology. In his seminal ideas on the subject, molecular nanotechnology is based on universal self-replicating molecular assemblers, devices that he assesses to be of highly ambiguous value. According to Drexler these assemblers could both have highly beneficial as well

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as extremely disadvantageous effects and applications. Although this early conception of nanotechnology is at present regarded as outdated (amongst others by Drexler himself), this paper argues that it has substantially influenced the current ethical debate. In this debate optimistic visionaries promise truly utopian states of affairs, e.g. solving the problem of hunger in the world or significantly expanding our maximum life span. Pessimistic thinkers, on the other hand, prophesy all kinds of worst-case scenarios, for example swarms of self-replicating nanomachines that devour the biosphere. The utopian views follow from one-sidedly focusing on the potential benefits of nanotechnology, whereas the apocalyptic perspective results from giving exclusive attention to possible downsides. This undesirable opposition of radical views holds the risk of conflicts and unwanted backlashes. What is needed, therefore, is the development of more balanced and better-informed ethical assessments of nanotechnology. To this effect this paper presents a new method of framing the ethical debate on nanotechnology.

NANOTECHNOLOGY

Concept

In the literature, a variety of concepts of nanotechnology[a] can be found.[1-3] A fairly broad one considers any technology smaller than microtechnology as nanotechnology. A well-known narrow concept sees nanotechnology as the technology "to program and manipulate matter with molecular precision and to scale it to three-dimensional products of arbitrary size".[4] According to an in-between concept – that seems to be adopted by the majority of contemporary nanotechnologists – the term nanotechnology captures the study, creation and application of all structures with *at least one* dimension of 100 nm or below. If an object does not have any dimensions within this range, it is discounted from the nanotechnological field.[5,6] This definition is also used in conjunction with the American *National Nanotechnology Initiative* funding program.[7]

Drexler's seminal vision of self-replicating molecular assemblers

The ethical debate has been deeply influenced by the brilliant and appealing conception of nanotechnology by Eric Drexler. His work turned out to have the potential to inspire a great deal of both the utopian dreams as well as the apocalyptic nightmares that would later start to dominate and polarize the ethical debate. This amazing ambiguity of Drexler's conception of nanotechnology did not go unnoticed by the author himself. In his words, nanotechnology would bring "[…] dangers and opportunities too vast for the human imagination to grasp."[8 (p.21)]

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a. The prefix *nano-*, derived from νάννος (Greek for dwarf), signifies a unit, viz., 10^{-9} (one billionth). Thus, one nanometer (nm) is one billionth of a meter.

In Drexler's early work on nanotechnology, self-replicating molecular assemblers played an absolutely crucial role. His conception of these self-replicating nanomachines was inspired by earlier ideas about the possibility of self-replicating machines by John von Neumann and about the possibility of molecular maneuvering by Richard Feynman. Von Neumann developed a theory of a self-replicating system as consisting of a constructor with a computer and a self-replication software program to build replicas of the whole system by using surrounding material as building parts.[9] Feynman was the first to theorize about the possibility of molecular maneuvering. In a presentation he gave on December 29th 1959 at the annual meeting of the American Physical Society he stated that the "[…] principles of physics […] do not speak against the possibility of maneuvering things atom by atom".[10 (p.65)] Drexler combined both ideas in his notion of a self-replicating assembler, which is basically a self-replicating system using individual atoms and molecules as basic material to construct replicas of itself.

According to Drexler a molecular assembler is a molecular machine that can be programmed to build virtually any molecular structure or device from simpler chemical building blocks. This nanoscale construction device can position molecules in every which way, thereby facilitating, for example, chemical reactions. Through precise sequences of manipulations, a computer-steered assembler could thus – atom-by-atom or molecule-by-molecule – construct any chemically stable structure that it has been programmed to assemble. Given this multi-purpose capacity, assemblers could obviously also be programmed to create replicas of themselves. Starting self-replication would lead to an exponential growth of the number of available assemblers. After you would have generated enough of them to serve your purpose (which would only take a brief lapse of time in any scenario), you would stop self-replication and reprogram the assemblers for specific tasks in order to construct certain macro-scale objects. From a commercial point of view, self-replication would have the interesting advantage of being able to manufacture macro-scale products in a feasible time frame. After all, if accomplished by only one assembler, constructing, for example, a car in a molecule-by-molecule way could take ages. If, on the other hand, millions or billions of assemblers could work together simultaneously, things would look far more optimistic. Thus self-replicating assemblers were indispensable if nanotechnological production was to become a practically feasible reality. However, Drexler clearly saw the ambivalent consequences that these assemblers might engender: "With assemblers, we will be able to remake our world or destroy it".[8 (p.14)]

In addition to abundant and cheap production, environmental protection, vastly improved space travel and many other benefits of molecular assemblers and nanomachines that Drexler forecasts are innumerable medical gains. After all, diseases, old age and all manner of non-pathological human defects can all be viewed as unfavorable atomic and molecular configurations. These may again be attributable to different causes – e.g. bacteria, viruses, genome mutations or accidents. If molecular assemblers were available, they could be used to create more specialized medical nanomachines with the capacity to eliminate these undesirable configurations down to the last detail, as well as to restructure less favorable configurations as desired at a molecular level. Thus molecular nanotechnology would not only eradicate disease and pain but also create countless new ways of enhancing favorable traits of perfectly healthy individuals and achieve a lengthened maximum lifespan.

However, self-replicating assemblers do also pose basic threats to people and to life on earth. They might run amok, for example through a software failure, and might not be able to stop self-replication anymore. Hence we would have an exponentially growing population of self-replicating assemblers. If these assemblers would be able to use biological materials for assembly purposes, they might eat up the whole biosphere (the "grey goo" scenario).[b] Furthermore, replicators could be used as weapons more effectively than nuclear bombs. After all "[…] to devastate Earth with bombs would require masses of exotic hardware and rare isotopes, but to destroy all life with replicators would require only a single speck made of ordinary elements".[8 (p.174)] Many of the utopian dreams and the apocalyptic nightmares that later came to dominate the ethical debate about nanotechnology were inspired by Drexler's early conception of the awesome ambiguities of molecular nanotechnology.

An obsolete view

Drexler's early view of the central importance of self-replicating molecular assemblers to nanotechnology has been criticized from two different angles. First, it has been doubted whether it is at all physically possible to create self-replicating assemblers. Although many authors from different disciplines concurred with Drexler in holding that it is possible to develop molecular assemblers,[11-15] there are also skeptics – particularly in the last few years – who deny that the creation of molecular assemblers is physically possible.[16,17]

Another point of critique focuses not on the hitherto undecided issue of the physical possibility of making self-replicating assemblers but on their importance for nanotechnological production. This point of criticism is more important than the above-mentioned issue, because recently, even Drexler himself changed his opinions about the pivotal role of self-replicating molecular assemblers for the further development of nanotechnology. He now argues that building fully self-replicating machines would not only be very difficult, what is more, "[…] the development and use of highly productive systems of nanomachinery (nanofactories) need not involve the construction of autonomous self-replicating nanomachines".[18 (p.869)] Therefore, it would be easier and more efficient to develop molecular manufacturing without these devices. Useful products will be made in desktop-scale nanofactories. The danger is not so much that these factories will do something uncontrolled, but that they will be used to produce novel potent weaponry.[18]

b. The biosphere would, so to speak, be transformed into goo of grey nanomachines – hence, the terminology of *grey-goo* scenario.

State of the field at present

Current research in nanotechnology is directed towards the production, study and application of a wide array of different nanoscale structures, for example, buckminsterfullerenes, nanotubes, nanoparticles, nanocapsules, nanopores, molecular motors, a variety of biomolecules, quantum dots and quantum wires. These nanostructures have interesting emerging novel applications in fields as different as medicine, information processing and – storage, the automotive industry, cosmetics, water treatment and remediation, energy production and conversion, construction and textiles. There are two approaches as to creating nanostructures: "top-down" and "bottom-up". The top-down techniques are mostly extensions of methods already employed in small-scale assembly at the micron scale, for example, photolithography. By further miniaturization, the nanodimension is entered. Bottom-up fabrication methods for manufacture are studied within synthetic chemistry, which is, almost by definition, the science of producing nanoscale structures. They are also inspired by regularly occurring processes in nature such as crystal growth and self-assembly. Living nature, for example, constantly shapes complex macroscopic structures from individual molecules. Inspired by the seemingly limitless applications of nanotechnology, many countries have set up programs to financially support its further development. Moreover, investing in the further development of specific nanotechnological projects is also rapidly getting more interesting for private companies.

THE ETHICAL DEBATE ABOUT NANOTECHNOLOGY

Utopian dreams

Time and again, it is argued that, if only molecular nanotechnology were to be fully developed, a large part of the world's current problems could be solved and a whole array of ideals achieved. To begin with, molecule-by-molecule manufacturing would be self-sufficient and dirt free. Leftover molecules would be recycled. Next, molecule-by-molecule manufacturing could create unprecedented objects and materials. Using molecular manufacturing techniques, we would be able to produce inexpensive high-quality products. Molecular manufacturing could also be used to fabricate food rather than growing it. After all, food is simply a combination of molecules in certain configurations. Hence, the problem of hunger could be effectively solved by efficient molecule-by-molecule mass production of food.

Especially in medicine, nanotechnology is said to work miracles. Molecular manufacturing will provide low-priced and superior equipment for medical research and health care, which will then be available far and wide. Medical nanomachines will be programmed to travel through our bloodstream to clean out fatty deposits thus reducing the probability of cardio-vascular diseases. Moreover medical diagnosis and drug-delivery will be transformed. In addition, preventive medicine will be greatly improved by nanorobots that would provide a defense against invading viruses in our bodies. Thus, nanotechnology has been hailed as the solution to many medical problems.[12]

Not only will it be possible to overcome contemporary diseases, pain and other unpleasant bodily symptoms, it is even expected that nanotechnology will contribute to the enhancement of favorable capabilities and properties.[12,19,20] With regard to the enhancement of the human body, it is expected that nanotechnology will enable the construction of stronger and enhanced tissues and organs. For instance, cells specific to certain tissues or organs could be reconstructed and be made immune against all known pathogens, thereby making our present immune system obsolete.[12] In addition, nanotechnology would enable an almost infinite improvement of our mental capacities. It would, for example, be possible to enhance our memory as well as all our data processing capacities.[19] However, with regard to enhancing the human mind the scenario of '*uploading*' is the *non plus ultra*. Uploading involves transferring the contents of the human brain to a computer. Specialized medical nanomachines would scan the brain atom-by-atom. Next, the information would be digitized and implemented on an electronic medium thereby creating software resident intelligences whose lives would last *in secula seculorum*.[12,22]

Nanotechnology is also expected to enable us to prevail over biological death in another way. The cryonics community has also enthusiastically embraced nanotechnology. Cryonics involves freezing people who have been declared legally dead and waiting until technology is advanced enough to reverse the cause of death as well as the freezing damage.[14] Nanotechnology is expected to produce real miracles in reversing all the adverse configurations of molecules in the frozen organism after it has been thawed out.[23,24] Nanotechnology is finally also expected to lead to social advances. The achievements of nanotechnology, especially nanomedicine, will make people more content and peaceful. It will be a great deal easier to live together in ideal harmony with perfect bodies and flawlessly functioning brains.[19]

Apocalyptic nightmares

Besides utopian outlooks, catastrophic scenarios abound in the ethical debate on nanotechnology. Rapid developments in molecular manufacturing and the concomitant inexpensive manufacturing could cause severe economic disruption involving the sudden abundance of low-priced products, rapidly changing employment patterns and the problem of copying of designs. Moreover, molecular manufacturing might also invite premeditated misuse in warfare or terrorism. Also, infinitesimally small surveillance devices such as nanoscale tracking devices, nanosensors, nanocameras and nanomicrophones could enable dictatorial observation and control of subjects in a way that is unprecedented. Nanotechnology would enable total surveillance of entire civilian populations without them even noticing it.[25,26]

Some of the most serious risks of molecular assemblers have been brought to the attention of the public by Bill Joy, co-founder and scientific leader of *Sun Microsystems*. Joy is especially worried about the research with regard to assemblers.

After all, these nanomachines will have the worrisome capacity of self-replication. Technical faults, for example problems with the software of the onboard computer of an assembler, could cause unbridled self-replication. In that case, since the newly produced assemblers would also start replicating themselves, the total number of assemblers would grow exponentially. If these uncontrolled assemblers used a wide variety of raw materials as resources for self-replication, they could devour the whole biosphere in an amazingly short while.[22,27,28]

Another danger has to do with the fact that many private companies will try to develop and produce assemblers. After all, the perspective to put them on to the market will seem lucrative for many. Hence, it will be difficult for central governments to retain control over the development of assemblers.[c] Therefore, there will always be the danger of abuse of assemblers by criminals and terrorists, for example, to develop weapons of mass destruction.[27] The catastrophic dangers of self-replicating nanotechnology enter the limelight of public opinion through Michael Crichton's novel *Prey* in which a swarm of nanomachines has escaped from a laboratory into the environment.[29]

TOWARD A MORE BALANCED AND BETTER INFORMED ETHICAL ASSESSMENT

The dominance of utopian dreams and apocalyptic nightmares in the debate on the future perspectives of nanotechnology holds the risk of undesirable conflicts and unnecessary backlashes. These radical views are the product of one-sided perspectives. Moreover, many of them inspired by an out-of-date Drexlerian conception of a nanotechnology centered around self-replicating molecular assemblers. Hence, the present state of debate on nanotechnology calls for the development of ethical views that are both more balanced as well as better informed by what is actually going on in specific fields of nanotechnological research.

In response to this important challenge, a three-step method of debating the ethical issues in nanotechnology is here presented. Use of this method results in a rational and systematic assessment of the ethical desirability of further development of a specific field of nanoresearch.[d] This ethical desirability hinges on the following three conditions:

(1) The objectives underlying further development in the specific nanotechnological research field at hand must be worth striving for. If this condition were not fulfilled, further development of the research field would mean an envisaging of objectives that are not valuable or, worse, definitely unwelcome. Continuing this research would then not make sense from an ethical point of view. Technology

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c. In contrast, the nuclear, biological and chemical technologies that were used in the 20th century to build weapons of mass destruction were largely developed in government laboratories for military purposes.

d. The method presented here does not presuppose a specific axiological or normative theory.

development should be directed towards a good or an end. Otherwise, technology is developed for its own sake, isolated from any human good.[e]

(2) A research field must, in its further development, actually contribute to a realization of these objectives. Even if the objectives would be really desirable, if this second condition were not fulfilled, further development of the research field would not enable the objectives to be realized. All the efforts, intelligence and recourses that would be invested to this effect, would then be a waste.

(3) Any ethical problems concomitant with the further development and application of the research field must be justifiable or surmountable. If this condition were not fulfilled, the objectives might both be desirable and realizable following further developments in the research field, but the concomitant ethical problems would be unacceptable.

If, after a detailed analysis, it should surmise that one or more of these conditions could not be met for a certain research field, then its further development would appear to be ethically problematic or even undesirable. The only logical consequence remaining would then be to adapt the research field accordingly or even to halt its progress altogether. Given these three conditions for ethical desirability of further development of a specific field of nanoresearch, a systemic and rational ethical debate could be framed along the following three steps.

I: ARE THE OBJECTIVES WORTH STRIVING FOR?

1) What specific field of nanotechnology is to be assessed?

The debate of this first step can proceed along three sub-questions. The first concerns the specific field that has to be assessed. Up to now, broad and sweeping statements about nanotechnology as such have dominated the debate. However, for an ethical debate to be discriminating and well informed by actual scientific developments, it should focus more specifically on a particular field of nanotechnological research. Instead the current debate has specialized in generalizing in an all-encompassing way.[cf.26] Therefore, more in depth and better-informed ethical research is needed. For a sound ethical debate it is important to realize that nanotechnology is by no means one single effort. Rather, it is a complex of countless different research projects with a vast variety of goals. Hence, different fields of nanotechnological research can be distinguished that will not necessarily demonstrate identical or even similar objectives and ethical aspects, for example: 1) materials and manufacturing, 2) nanoelectronics

e. Ideally, we should first discuss our needs, fundamental purposes and social ends in order to move on to make choices about ways of achieving these goals, for example by further developing certain fields of technological research. Yet, technology development does not always proceed in this way. What is more, technology often seems to develop in a seemingly autonomous way. It can even influence the way we conceive and assess our goals. Be this as it may, it remains imperative to reflect prospectively about the goals that we try to achieve in developing certain technologies.

and computer technology, 3) medicine and health, 4) aeronautics and space exploration, 5) environment and energy, 6) biotechnology and agriculture and 7) security.[f] Evidently, the ethical assessments of developments in these fields are likely to differ as the objectives and the ethical problems encountered will be different. For example, it makes an important difference whether one reflects on the ethics of nanotechnologically-manufactured memory enhancing neuroimplants, filters with nanopores for the recycling of water or nanodevices for surveillance purposes.

2) What are the objectives of that specific field of nanotechnology?

Having specified the nanotechnological field to be ethically assessed, the next sub-question focuses on the objectives that the research in that field aims to achieve. It is important to realize that one single field of nanotechnological research can have different objectives. Let us take the example of nanomedicine to illustrate this thought. Up to now, there have been two distinct groups of objectives that are connected with the further development of nanomedicine. On the one hand, there is a group of more traditional objectives such as improved prevention of pain and disease, better diagnosis and superior therapy.[30,31] On the other hand, there are different objectives that have to do with the enhancement of certain human properties, for example the improvement of memory, perfection of our sensory qualities and advance in our cognitive skills.[8,19-21,32]

3) Are these objectives worth striving for?

After having specified the nanotechnological field to be assessed as well as having identified the objectives of that field, it should be asked whether these objectives are valuable. It is essential to realize that not all objectives that a certain field of nanoresearch aims to achieve are necessarily valuable. Moreover, objectives that seem attractive at first sight sometimes turn out to be less so after a more thorough enquiry. Whereas, for instance, the more traditional group of objectives of nanomedicine, such as prevention, diagnosis and therapy, are by and large valuable, the appeal of enhancement of human properties – though *prima facie* attractive – turns out to be questionable after more analysis. First, it is not really clear what kind of changes of human properties would count as an improvement. The criteria to demarcate changes that involve an improvement and those that are neutral or – worse – that entail deterioration are lacking. Second, development and clinical application of enhancement techniques could result in undesirable forms of medicalization, making perfectly normal properties and features seem pathologic and in need of medical attention. Third, it is questionable whether enhancement can be seen as having priority given the scarcity of resources in health care.

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f. Perhaps an even more fine-grained distinction of fields will be needed.

II: WILL THE RESEARCH CONTRIBUTE TO A REALIZATION OF ITS OBJECTIVES?

If the objectives are valuable but not achievable or very unlikely to be achieved by advances in a specified field of research, it seems pointless to push the research forward. Of course, it is not possible to predict advances in science or technology in detail and with certainty.[33] Nevertheless, in many cases it will be possible to give a well-argued assessment of the probability of achieving certain objectives in a specified field of research on the basis of the corpus of existing scientific literature. Again focusing on nanomedicine as an example, it can be said that it is very likely that there will be progress in achieving the goals of better diagnosis and new therapeutic options given the advances that have been made already in drug targeting,[30,34] diagnosis,[30,31] prostheses and implants,[35] and cancer therapies.[30,31] With regard to the other objective of nanomedicine, the enhancement of man, no such progress is known from the scientific literature up to now.

III: ARE THE ETHICAL PROBLEMS JUSTIFIABLE OR SURMOUNTABLE?

1) What are the ethical problems connected with further development of the field of research?

The analysis of this third step proceeds along two sub-questions. The first involves determining the ethical problems that are connected with the further developments in a specified nanotechnological field. Ethical problems connected with further development of nanoresearch are not necessarily the same in different fields of nanotechnological inquiry. For example, present research on nanotechnologically manufactured coatings of prostheses to improve their biocompatibility can hardly be said to pose the same ethical questions as, for instance, projects focused on producing perfect mosquito nets to reduce the problem of infectious disease or research on new nanochips that can read individual genomes in a feasible timeframe.

To date, the ethical debate on nanotechnology has been dominated by discussions about risks. A few examples are risks of disruption of the basis of economies,[26] environmental damage,[36,25] an unstable arms race,[27] the grey goo scenario,[22,8,27,28] and the black goo scenario.[22] Other ethical problems that have been discussed in relation with nanotechnology have to do with equity and justice,[25] privacy,[25,26] playing God and respect for nature.[37] Unfortunately, these ethical problems have been mostly discussed on a very general level. As a rule, these problems have not been linked to specific fields of nanotechnological enquiry.

2) Are these ethical problems surmountable?

After having determined the ethical problems that are connected with further developments in a specified nanotechnological field, analysis should decide whether they can be dealt with or not. After all, if it happens that the ethical problems are not surmountable, it seems ethically objectionable to further develop the research. Let us take risk management as an example of the attempt to avoid certain ethical problems (i.e. the disproportionality of benefits and risks). To reduce the risks of the further development of a particular field of nanotechnology, research should be done as to the specific risk profile of the field at hand, i.e. the nature, magnitude and probability of the risks.[38-40] This research might result in the development of feasible options of dealing with these risks effectively.[cf.4]

CONCLUSION

A great deal of the highly polarized ethical debate about nanotechnology has been profoundly influenced by Drexler's early vision of a molecular nanotechnology based on self-replicating assemblers. In the meantime research in nanotechnology has moved ahead substantially. Molecular assemblers will most likely not play a pivotal role, as many popular accounts still want us to believe. Therefore, the strong disagreement of utopian dreams and apocalyptic nightmares in the debate on the future perspectives of nanotechnology seems to be based on an outdated conception of nanotechnology. Furthermore, these radical views are the product of one-sided perspectives that hold the risk of undesirable conflicts and unnecessary backlashes. Hence, it is necessary to develop ethical assessments of nanotechnology that are both more balanced and better informed by the actual scientific developments.

In order to develop such assessments, this contribution presented a three-step method of framing the ethical debate on nanotechnology. The implementation of this method results in a rational and systematic assessment of the ethical desirability of further development of specific fields of nanoresearch. Reflection upon the ethical desirability of developing certain fields of nanotechnological research should start as early as possible and should ideally proceed in a way that is both open and understandable to a broad public.[cf.41] Wherever feasible, critical ethical debate should not be left until the newly developed nanotechnologies in question are already undergoing application and suddenly adverse events occur that could trigger disproportionate and undesirable public backlashes.

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