Nanotechnology and Nature

On two criteria for understanding their relationship

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Abstract: Two criteria are proposed for characterizing the diverse and not yet perspicuous relations between nanotechnology and nature. They assume a concept of nature as that which is not made by human action. One of the criteria endorses a distinction between natural and artificial objects in nanotechnology; the other allows for a discussion of the potential nanotechnological modification of nature. Insofar as current trends may be taken as indicative of future development, nanotechnology might increasingly use the model of nature as a point of orientation, while many of its products will continue to be clearly distinguished from nature.

Keywords: *nanotechnology, concept of nature, laws of nature, life, artificial life*.

1. Introduction

The relationship between nanotechnology and nature does not presently admit of uniform description. By way of an introductory presentation of the problem, I would like to sketch a provisional characterization based upon central aspects of nanotechnological and natural objects respectively. Nanotechnological objects rank among those technically produced objects that emerge from processes "that exhibit fundamental control of the physical and chemical attributes of molecular-scale structures" (Stix 2001, p. 9). Nanotechnology brings with it the possibility of a precisely projectable alteration of nature on the scale of molecules. Nanotechnology comprises not only the manipulation of natural molecules, but also the creation of molecules not found in nature. In this sense, molecules or other objects are natural if they are not produced through human action.

The multifariousness of the relationship between nanotechnology and nature is expressed in the fact that some nanotechnological objects are clearly distinct from comparable natural objects, while others are identical to natural

HYLE – International Journal for Philosophy of Chemistry, Vol. 11 (2005), No. 1, 77-95.

objects. I shall begin with some examples of non-natural nanotechnological products, recognizable – as is the case with other products of human action – by their obviously artificial origin.

- For medical purposes, certain molecules are synthesized that are designed to direct medicine to particular parts of the body, and which – as far as is known – do not exist in nature.
- The production of materials by means of nanotechnology is of interest to the materials sciences because these materials possess characteristics (*e.g.* firmness) that make them more suitable for the fabrication of macroscopic products than those made from natural substances.
- Miniscule electrical and mechanical systems are to be constructed analogously to larger systems utilized today, which are not modeled upon natural patterns.

Nano-products that do not exist in nature form an artificial world whose relationship to nature is problematic. On the one hand, uncontrolled releases from such nano-objects could constitute a new dimension of life-threatening pollutants. On the other hand, it cannot be ruled out that even the controlled insertion of non-natural nanoproducts into nature – particularly into the human body – may entail substantial risks. In both cases these dangers would be linked to the extreme minuteness and to the reactivity of these products. They may enter biotic systems deeply and irreversibly, affecting life functions not positively but deranging or destroying them with lethal effects. Compared to previous conventional macroscopic technologies, nanotechnology relates differently to nature inasmuch as it can affect the functionality of natural systems on the smallest scale.

Nanotechnology, however, does not only create an artificial world that is distinct from nature. It also relates to natural processes and materials in a new way.[1] In this respect it is difficult to separate it from nature. Here, too, I would like to give some examples.

- There is hope that the development of nanotechnology may not only permit the production of artificial made-to-measure materials, but also improve conditions for the perfect artificial reproduction of substances that can only be derived from nature through difficult procedures.
- In the bottom-up-production of materials, nanotechnology already uses techniques of self-organization – which are similar to processes that appear in nature (*e.g.* the spontaneous creation of GaAs-quantum points).
- On the product level, there are nanotechnological systems in which objects of biotic origin are used. Since the functions of such objects are partly independent of their origins, the characterization with which we began is a problematic basis for distinguishing between nature and

> nanotechnology. DNA-molecules, for example, are utilized in electronic components. Other nano-products are to have new kinds of biocompatible (*e.g.* coatings of artificial joints) or bioanalogue (*e.g.* hydrophobe) features.

Nanotechnological products and techniques that are closely related or even identical to natural materials and processes may cause just as much harm to nature as those that are clearly distinct from nature. For instance, the degree to which an artificially produced substance is life threatening is not clearly related to the degree of its structural similarity to natural substances. To mention another example, the introduction of artificially produced nature-identical substances into natural cycles can lead to considerable interferences of these cycles. But despite justified objections to the use of the model of nature as a point of orientation, there is still hope that the dangers of nanotechnology could be reduced by an increasing proximity to nature.

The practical relevance of the dangers to life processes that might emerge from nanotechnology constitute probably the most important motivation for investigating the relationship between nanotechnology and nature. But, with respect to a technology that permits the synthetic production of nature-identical objects and that is able on demand to execute minute changes in nature on the molecular scale, the question of its relationship to nature emerges also in theoretical terms. Is it at all possible to distinguish between nature and technology if nature has already become technologically malleable at the level of molecules? Can nature – if it is distinguishable from technology at all – set limits to technology? Against the background of Western culture, where nature is conceived through its opposition to technology, the importance of these problems cannot be overestimated. While technology as a human creation is regarded as completely transparent, a separate reality is ascribed to nature. The contrast between technology and nature is to be considered most obvious in the case of living nature – organisms are paradigmatic of a nature not produced by human beings. Up to now, the concept of nature has had a central function in shaping the Western worldview, which would be undermined if it became impossible to maintain its difference from technology.

But can these questions be answered if the relationship between nanotechnology and nature is itself manifold? One could be tempted to assume that a restriction of the term nanotechnology would lead to a more unequivocal statement. But this suggestion is rendered implausible by the fact that nanotechnological research is still in its early stages. According to the unanimous judgment of its analysts, most disciplines of nanotechnology have not yet reached the stage of producing functioning technology, but are still researching their object fields.[2] There are endeavors underway in various disciplines to shed light on the scarcely analyzed structures of the nanoworld.

Thus, a specification of this term would only conditionally restrict the variety of disciplines belonging to it. Nor is a reduction of the scope of the concept of nature likely to clarify the different ways in which nano-objects are related to nature. The concept of nature that I proposed earlier corresponds – as I aim to show – to the common and justifiably used conception of nature in nanotechnology. It allows different relations to nanotechnology in general and in specific areas. Therefore, I would argue that under the present circumstances the relationship between nanotechnological and natural objects cannot be described in uniform terms.

But the diversity of the relations between nanotechnology and nature does not necessarily imply a diversity of the criteria for describing these relations. Rather, I would assume that the various relations can be characterized by a single set of criteria that make it possible to give initial answers to the aforementioned questions. In so doing, one cannot rely on the philosophical discussion of nanotechnology, which until now has been poorly developed.[3] The proposed concept of nature forms a proper starting point, as it makes it possible to develop two basic criteria for characterizing the relationship between nanotechnology and nature.

- First, the concept of nature as that which is not produced by human beings suggests a criterion for distinguishing between natural and artificial nanotechnological objects (Section 3).
- Secondly, this concept of nature makes it possible to formulate a criterion for delimiting the scope of nanotechnology (Section 4).

The most important point in the discussion of the relationship between nanotechnology and nature is the contrast between nanotechnology and living nature. None of the known laws of nature excludes the possibility that life could in the future be produced artificially by means of nanotechnology. If the difference between the objects of nanotechnology and those of living nature were to be dissolved, it would be the most fundamental conceivable change in the relationship between nanotechnology and nature (Section 5).

Before I expound these criteria, I would like to elucidate the concept of nanotechnology with which I began in order to clarify what aspects of it enter into a relationship with nature.

2. On the definition of nanotechnology

The initial understanding of nanotechnology is only a part of a definition proposed by Mihail C. Roco, according to which nanotechnological materials and systems have the following 'key properties': "they have at least one dimension of about one to 100 nanometers, they are designed through processes that exhibit fundamental control of the physical and chemical attributes of molecular-scale structures, and they can be combined to form larger structures" (Stix 2001, p. 9).[4]

Nanotechnology is the application of scientific knowledge for the purpose of producing such materials and systems. In the present phase of investigating elementary conditions of production, technological and basic scientific research are merging. Wherever I do not explicitly differentiate between nanotechnology and nanoscience, the term 'nanotechnology' includes nanoscience.

I want to adopt Roco's definition and make two additions. The first concerns the origin and purpose of nanotechnology. Nanotechnology is – as all technology – a human affair. In this respect, the relation of nanotechnology to nature is reduced to the relation of human beings and their actions to nature. As a human affair, nanotechnology is a cultural-historical phenomenon that uses appropriate and knowledge-based ability in pursuance of objectives. The concept of nanotechnology can only be used in an analogous or metaphoric manner to describe non-human nature; strictly speaking, there are no nanotechnological processes or products in nature. The next section, however, will give some examples that show why not all nanotechnologists would agree with this view.

My second addition concerns the relation of nanotechnology to other technologies. By 'fundamental control' of attributes, I understand a realization of desired attributes that goes beyond the manipulation of already existing attributes. Here the definition distinguishes nanotechnology from gene- and biotechnology (which frequently deal with objects of a size above nanoscale).[5] The attributes of gene- and biotechnological objects are not produced but, rather, modified by exerting influence. Without this distinction between disciplines, it would be impossible to differentiate between the transfer directions of nanotechnology and biotechnology.

The definition does not rule out that biotic materials or living beings could be produced in the future by means of nanotechnology, nor does it deny the already existing transitions and contacts between nano-, gene- and biotechnology. Its application to current technological possibilities leads, however, to a division into the mainly abiotic products of nanotechnology on the one hand, and the mainly biotic products of gene- and biotechnology on the other. In this respect, current nanotechnology is clearly distinct from a nature that includes living beings.

3. Nature as that which is not produced by human action

As in the natural sciences and in most other technological fields, fundamental categories like the concept of nature are not a subject of discussion in nanotechnology. When they are explicitly used, it is normally only in publications that address a broader audience or the audience of other disciplines – and therefore somewhat vaguely. The concept of nature takes on various meanings in these contexts, which I assume are also relevant in scientific practice. I have chosen three representative and electronically accessible publications as examples and scanned them for appearances of the term 'nature': the brochure *Nanotechnology. Shaping the World Atom by Atom*, published by the National Science and Technology Council (NSTC) in the US in 1999; the volume *Understanding Nanotechnology*, compiled by the journal *Scientific American* in 2001; and the *Springer Handbook of Nanotechnology*, published by B. Bhushan in 2004.

An adjectival and a substantival usage can be differentiated as the two primary meanings in these texts. These also correspond to the two meanings of nature given in *The New Oxford Dictionary of English* (without being labeled as such). The adjectival usage describes "the basic or inherent features of something, especially when seen as characteristic of it". A typical example is, for instance, "the wave nature of electrons" (NSTC 1999, p. 1) or "the cyclic nature of this process" (Bhushan 2004, p. 156). Since this meaning does not refer to specific properties and can only be understood contextually, I will ignore it here.

The substantival usage is divided into an extensional and an intensional meaning. Both can also be found in *The New Oxford Dictionary of English*, although they are not labeled as such. In its extensional meaning, nature refers to "the phenomena of the physical world collectively […] as opposed to humans or human creations"; in its intensional meaning, it is "the physical force regarded as causing and regulating these phenomena". The extension demarcates the scope of the concept negatively – namely, through the contrast to human action. The intension, on the other hand, cites properties – such as a physical force – by way of a positive characterization.[6]

A typical example of the extensional understanding is the reference, which appears in all three publications, to "nature's own nanotechnology, which emerged billions of years ago when molecules began organizing into the complex structures that could support life" (NSTC 1999, p. 1; similarly, *Scientific American* 2001, p. 9; Bhushan 2004, p. 2). This understanding gives rise to a distinction between natural and synthetic objects. Hence, we learn, for example, "that nature constructs its objects" (Bhushan 2004, p. 246), or that an artificially established function is "unprecedented in nature"

(Bhushan 2004, p. 283). The intensional usages differ from the aforementioned encyclopedic notion in that the characteristics given also include human action and their products. Thus, the NSTC brochure quotes from Richard Feynman's famous speech 'There is Plenty of Room at the Bottom' (1959): "But we must always accept some atomic arrangement that nature gives us" (NSTC 1999, p. 4). In the same vein, Michael L. Roukes refers to the concept of nature by stating, "Nature has already set the rules for us" (Scientific American 2001, p. 32).

These examples are the product of an intuitive technological understanding of nature, according to which nature is a resource for the realization of human purposes. With respect to conceptual precision – which, admittedly, is not decisive in the context of these publications – it leaves much to be desired. Part of the terminological haziness is also due to the ambiguity of the concept of technology, which is not consistently opposed to that of nature but, rather, partly transferred to natural processes. Furthermore, relations between intensional and extensional meanings of nature are not taken into account, and there is no criterion for distinguishing between natural and artificial objects. These desiderata can be attained by specifying more precisely the concept of nature I proposed earlier.

The concept of nature that I am going to elaborate follows the intuitive understanding of nature by assuming a positive characterization not of nature, but of human purposes: nature is that which is not made by human action. This concept is distinct from traditional definitions, which attribute positive attributes to nature – such as self-movement in Aristotle, or expansion in Descartes.[7] I use the expression 'not made by human action' in a narrow and in a broad sense. While the narrow sense refers to objects whose existence does not originate in human action, the broad sense describes the empirical content of laws of nature – which is not at humans' disposal[8] – and thus comprehends predetermined conditions to which human action is subjected. In this section I focus on the narrow, in the next section on the broad sense.

In view of the sophistication of today's technology, scientific methods are required to determine whether an object owes its existence to human action. Thus, I would like to introduce an epistemic criterion according to which an object is natural if it is impossible with all scientific methods available at a given time to detect that it was produced by human action; alternatively, an object is to be defined as artificial if it can be scientifically demonstrated that it was produced by human action. This criterion makes the distinction between natural and artificial objects an empirical matter, subject to experimental methods of assessing the naturalness of technological products – similar to the Turing-test of artificial intelligence.[9] An artificially produced object would therefore belong to nature if all scientific methods available at a given time could not succeed in distinguishing it from an identical natural object. This application of the criterion presumes of course all knowledge about existing natural objects.[10]

I want to elucidate this criterion by appealing to some examples: according to this criterion, the atoms dealt with in nanotechnology are natural if they stem from natural substances or if it becomes impossible scientifically to ascertain their artificial origin. Insofar as natural substances are designed differently in nanotechnology than in nature, nanotechnological products are always hybrids of nature and art. The criterion does not challenge the naturalness of an object merely if it is influenced by human action. Thus, atoms do not lose their naturalness because they must first be isolated in order to be assembled in a different pattern. As for this assemblage, it is possible to distinguish several ways in which an influence can artificially be exerted. A weak form of influence would be to create the appropriate conditions under which a process of synthesis would run independently. Processes of self-organization in the production of quantum points are a good example of this form of influence.[11] Production that requires a special operation at each step represents a stronger form of influence. This applies, for example, to the movement of atoms, which M. Eigler used in 1989 to produce the IBM-logo in nanoscale.

The criterion can be applied to all of the examples that I mentioned earlier in order to illustrate the difficulty of distinguishing between natural and artificial objects. According to the criterion, if nanotechnology succeeds in constructing perfect replicas of naturally existing molecules, they should be considered natural the moment when their artificial origin ceases to be demonstrable (*e.g.* when mingled with the corresponding natural molecules). Each component of self-organizational processes that are used in the production of nano products and each property of completed nano products can be assessed to determine whether it is natural or artificial. Nonetheless, the application of the criterion is not unproblematic. Artificial properties may, for instance, unknowingly be added to a substance when it is extracted from its natural environment.

It may appear odd that nanotechnological objects, *e.g.* synthetic molecules, should lose their artificial character the moment they cease to be (scientifically) distinguishable from natural objects. However, this not only corresponds to traditional concepts of nature[12] and to current linguistic conventions in nanotechnology (as discussed above), but also reveals the point where the distinction between human-made products and nature becomes senseless.

I suspect, though, that most nanotechnological objects are still distinguishable from natural objects and will continue to be in the near future. I see three reasons why the artificial character of nanotechnological objects should remain apparent for the time being. First of all, the focal point of nanotechnology is to produce artificial objects that are more useful for human purposes than natural ones. Since these objects are intended to differ in their effects from natural objects, they can be expected to remain distinguishable from them. Secondly, the scientific methods of revealing an object's artificial origin are so sophisticated that they would probably still be able to identify an artificial object even if it were very similar (not identical) to equivalent natural objects. Thirdly, there is still a clear difference between nanotechnological and natural processes, as I shall illustrate in Section 5, where I discuss the example of living nature

This epistemic criterion builds upon the narrow understanding of nature as that which is not produced by human action. It inquires into the genesis of any produced object, but unfolds its efficacy only when it becomes problematic to ascertain an object's artificial origin. Nanotechnological objects provide characteristic examples. By having the greatest possible influence on the properties of its materials, nanotechnology can blur the traces of its interventions to the most comprehensive extent.

4. The lawfulness of nature in the nano world

In this section, I will return to the broad sense of the term 'nature'. It does not necessarily refer to the genesis of objects, but generally to those regular properties that are beyond human influence, and which sciences express as laws. Natural laws represent the universally valid expression of the conjunction of conditions under which an event or a state regularly obtains.

As revisable, mostly mathematical constructions, natural laws are human-made. True observational statements, however, which are predicted by these laws and constitute their empirical content, refer to the natural prerequisites of human action. Hence, their truth does not depend on the specific experimental conditions under which the corresponding phenomena are produced or discovered. The empirical content of the laws of nature delimits the scope within which nanotechnology can unfold its potential.[13]

Between nature in this sense and nanotechnology, there is a certain tension, which has recently been the subject of discussions about the potential of human constructions on the nanoscale. Particularly at issue are physical and chemical laws, which must be taken into account in planning nanotechnological constructs. In the following, I will focus on physical laws, which *present* plans have to take into consideration. In the next section I will move to discussions of technological constructs (*e.g.* Eric Drexler's assemblers) whose *future* conditions of realization are controversial.

A large portion of the current projects in nanotechnology are designed to advance the miniaturization of technology. This tendency is especially strong in electronics (Fahrner 2003, p. 1-3). Nanotechnological constructions are to reproduce traditional electronic components (switches, diodes, transistors, *etc.*) on a nanoscale. One main goal of this effort is to open up new dimensions of data processing, namely through the storage of large amounts of data in the smallest possible space (*e.g.* the British Library in a sugar cube). These plans are countered by the assertion that new laws have to be expected at the nano level, which emerge from the fact that this field lies between the atomic and subatomic quantum phenomena on the one hand, and the continuous phenomena of systems with large numbers of atoms on the other. Because of the intermediary position of the nanoscale, it is also called 'mesoworld'. In this world, not only known quantum phenomena appear (*e.g.* the uncertainty principle or the tunnel effect), but also the known phenomena of continuum physics (*e.g.* heat flow). There are even some new regularities that emerge, like the quantization of electrical and thermal conductance. The quantization of electrical conductance has already turned out to be a fundamental feature of the smallest structures of conductors. The quantum nature of heat flow was first observed in 2000 in narrow silicon nitride bridges, constituting a fundamental lower limit of this flow in minute objects that can conduct heat (Roukes 2001a, 2001b).

These phenomena restrict technology's ability to maneuver on the nanoscale (Fogelberg & Glimell 2003, p. 18. The question whether a quantized current flow is technologically utilizable remains problematic; the quantum nature of heat flow could hinder the necessary cooling of electronic and mechanical nano building components. Roukes comments on the novel regularities discovered in the mesoworld as follows: "The nanoworld is often portrayed by novelists, futurists and the popular press as a place of infinite possibilities. But this domain is not some ultra miniature version of the Wild West. *Not* everything goes there; there are *laws*" (Roukes 2001a, p. 26).

Corresponding to the tension between nature as the lawful constitution of reality and nanotechnology, there is a conflict between scientists' interest in knowledge and engineers' interest in applications. Roukes represents the scientific position, stating that understanding laws is a precondition for technological applications: "Much exotic territory awaits exploration. As we delve into it, we will uncover a panoply of phenomena that we must understand before practical nanotechnology will become possible" (Roukes 2001a, p. 21). Engineering technology, in contrast, is less interested in the clarification of lawful coherence than in its utilization for technological purposes. P. Chaudhari of IBM Watson Research expresses this position by stating the following: "The engineers were not so much concerned with understanding the laws of nature but rather in using them to build something useful for mankind" (Chaudhari 2001, p. 78).

5. The relationship between living nature and nanotechnology

Up to the present, living nature has been considered the epitome of that which is not human-made. As much as the organic structures of living beings have been changed through human intervention, human beings have not yet succeeded in producing life itself. Life processes occur in dimensions that are so complex and minute as to be only conditionally accessible. At this level, nanotechnology promises to open up new opportunities. It is among the disciplines that develop means to create life artificially – be it as a reconstruction of existing forms of life or as a construction of a differently designed artificial form of life.

Against this background, it is striking that not only current nanotechnological research but also the most boldly futuristic visions of nanotechnology are confined to non-living constructions. Correspondingly, artificial life is mentioned neither in Eric Drexler's futurist books (Drexler 1986, Drexler *et al*. 1991) nor in connection with nanotechnology in the optimistic report *Converging Technologies for Improving Human Performance* (Roco & Bainbridge 2002).

In my view, the restriction of nanotechnology – both in current practice and in futuristic visions – to the construction of non-living systems reflects a gap between technological and biological objects, which also exists at the nano level. Following Stuemper-Jansen 1994, I have compiled some of the characteristic differences between technological and biological systems in Table 1. I want to underscore the abilities of organisms to self-replicate and to self-repair, which have not even begun to be realized in abiotic technological systems. Moreover, whereas metabolic processes in living organisms produce energy by degrading endogenous substances, technological systems depend upon energy usually supplied from outside. The comparatively low efficiency of technological systems makes it necessary that they be cooled.

Eric Drexler believes that the difference between living nature and non-living nanotechnology originates from the fact that living nature must submit to the struggle for survival even at the lowest level of the generation of its products. He quotes Ralph Merkle approvingly: "It's both uneconomical and more difficult to design a self-replicating system that manufactures every part it needs from naturally occurring compounds. Bacteria do this, but in the process they have to synthesize all twenty amino acids and many other compounds, using elaborate enzyme systems tailored specifically for the purpose. For bacteria facing a hostile world, the ability to adapt and respond to a changing environment is worth almost any cost, for lacking this ability they would be wiped out" (Drexler *et al*. 1991). Under the conditions of the struggle for survival, organisms have developed an adaptability, which is normally not inherent in technologically produced systems designed to serve human purposes. As Merkle – referring to the example of machines – puts it: "The machines made by human beings bear little resemblance with living systems, and this is most likely to be true for molecular production systems. […] Machines do not have this marvelous adaptability of living systems" (Merkle 2001, p. 184).

Table 1:
Characteristic differences between technological and biological systems

	Typical realization in technological systems	Typical realization in biological systems
production process	- top-down (bottom-up, self-organization only in nano- and biotechnology) - technological methods for large amounts	- bottom-up, self-organization processes (incl. self-replication and self-repair) - slow growth of functional units on the molecular level, connection to larger systems
controllability	- possible only in small parts at atomic or molecular levels or as statistical ensembles	- by means of numerous specialized systems combining in a network on the molecular level
materials	- generalized building set (wide range of elements and compounds with various properties)	- flexible basic building set (few classes of bio-materials, optimized for various functions)
energy input	- high (often in high temperature range), comparatively low efficiency, loss through cooling	- low (highly efficient transformation chain with chemical substrates, but therefore also with molecular by-products)
environmental sustainability	- frequently problematic	- bio-degradable products, usually unproblematic under natural conditions
durability, stability, changeability	- technological solutions over a broad scale of environmental conditions (*T*, *p*, *pH*, *etc.*) - usually stable long-term; but, no self-repair, inflexible	- comparatively susceptible - but: renewable, flexible, able to regenerate, natural degradation processes, self-correcting

As a property that distinguishes organic beings from nanotechnological products, adaptability is one example of the application of the epistemic criterion for distinguishing between natural and artificial objects. For the time being, the lack of adaptability of the latter attests to a human origin. Nanotechnological development of adaptable products, *e.g.* the context-dependant adaptation of a substance's surface properties, constitutes a step toward dissolving the difference between nature and technology.

The difference between living nature and non-living nanotechnology has also provided the backdrop for a controversy in the past few years, mainly between Richard E. Smalley and Eric Drexler, regarding the future possibilities of technology on a nanoscale. The subject of the argument has been, above all, the question to what extent nanotechnological production will be possible without reference to already existing biological processes. Drexler follows Richard Feynman's program, according to which nanotechnology is "fundamentally mechanical, not biological" (Drexler 2003). Drexler's plans envision computer-programmed robots on a nanoscale, so-called assemblers, that assemble single molecules with atomic precision in order to produce themselves or other objects. Smalley, on the other hand, considers such nano-scale mechanical self-replication and production of objects to be physically impossible. According to Smalley, moving single molecules does not suffice to produce stable chemical compounds. In his opinion, the entire reaction scale has to be controlled. For this purpose even the smallest robot would be too big (Smalley 2001, Whitesides 2001, Jones 1995). Moreover, the molecules to be moved would adhere to the arms of the robots (Smalley 2001, 2003). Smalley concludes that "such a nanobot will never become more than a futurist's daydream" (Smalley 2001).[14]

Smalley's arguments illustrate the application of the second criterion, which refers to natural laws. This criterion is not conducive to distinguishing among objects, but it defines the scope that natural laws set for potential nanotechnological object design. In Smalley's view, the production of nanobots contradicts physical laws and is therefore impossible.

Smalley believes that the fabrication of products on a nanoscale would require "something very much like an enzyme". "Any such system will need a liquid medium. For the enzymes we know about, that liquid will have to be water, and the types of things that can be synthesized with water around cannot be much broader than the meat and bone of biology" (Smalley 2003). According to Smalley, the limits posed by natural laws compel nanotechnology to orient itself toward the model of existing biological systems. George M. Whitesides sees a larger scope for nanotechnology. He, too, assumes that there is presently a difference between biological and nanotechnological systems, and considers the realization of Drexler's assembler vision impossible. In his view, only two possibilities remain for the production of nanomachines. "The first is to take existing nanomachines – those present in the cell – and learn from them. [...] The second is to start from scratch and independently to develop fundamental new types of nanosystems. [...] It will be a marvelous challenge to see if we can outdesign evolution. It would be a staggering accomplishment to mimic the simplest living cell" (Whitesides 2001). However, since this approach is much more difficult than the first one, he considers it unlikely to be implemented. Therefore, it also seems reasonable to him for nanotechnology to assume the model of existing biotic nature.

The controversy among Drexler, Smalley, and Whiteside illustrates two positions with respect to the divergent directions in which nanotechnology may be developed in the future: Nanotechnology could develop independently or follow the model of nature. The first way would mean the creation of an increasingly artificial world apart from nature; the second a new dimension of connection between technology and nature. Both scenarios would clearly be distinct from the traditional relationship between macroscopic technology and nature. The latter is characterized by the fact that while it admits of a distinction between technology and nature, it also interrelates the two. In the future, either the element of interrelation, with increasing artificiality, or that of distinguishability, with the establishment of a new dimension of connection between nanotechnology and nature, may become less relevant.

6. Conclusion

I have defined nanotechnology as a human affair. The human origin of nanotechnological methods clearly distinguishes them from nature insofar as nature is not produced by human action. But this distinction does not necessarily apply to the relationship between nanotechnological and natural objects. Nanotechnological objects are designed to serve human purposes. Nanotechnologically produced substances, which are appropriate as industrial materials, are just as unlikely to be found in nature as nanoelectrical switches and nanomechanical gears. On the other hand, nanotechnology offers unique ways of using natural processes and re-building natural objects, or of substituting equivalent alternatives. Large molecules can be assembled from naturally occurring atoms in such a way that they become indistinguishable from molecules of natural origin. Since both of these aspects presently play a role in the relationship between nanotechnology and nature, this relationship cannot be characterized uniformly.

The multifariousness of the relationship between nanotechnology and nature, however, does not prevent the application of uniform criteria for characterizing it. In order to show this, I considered a conception of nature that is common among nanotechnologists. This notion conceives of nature as that which is not made by human action. I distinguished two senses of this concept. While the narrow sense refers to objects that do not originate in human action, the broad sense describes the empirical content of laws of nature, which is not at humans' disposal.

Building upon the narrow sense, I proposed an epistemic criterion according to which an object is natural if it is impossible – using all available scientific methods at a given time – to ascertain that it was produced by human action. This criterion makes it possible to distinguish – analogously to the Turing-test of artificial intelligence – between natural and artificial components of most nanotechnological processes and products. Given the multifariousness of the relationship between nanotechnology and nature, there are cases where it becomes problematic to distinguish between the two. I assume, however, that these cases are exceptions. Nanotechnological objects are mostly hybrids of nature and art; only in a few cases would they be said to be wholly natural because their artificial origin could no longer be confirmed.[15]

The broad sense of the concept of nature led to a criterion for the scope of current and future nanotechnology. Whatever the future development of the relationship between nanotechnology and nature might be, nanotechnology will be subject to a reality that is structured by the laws of nature. The empirical content of laws refers to that which precedes human action. Nature in this sense is already relevant for nanotechnology, because present developmental prospects depend on the still poorly researched laws of the mesoscale between quantized and continuous phenomena. It is possible that a more precise determination of these laws may considerably restrict technology on a mesoscale. Just as there are areas in the macroscopic world that are rather unsuitable for human life (such as mountains, icy or sandy deserts, deep seas *etc.*), the mesoscale could turn out to be an area whose structures are only conditionally useful for technological purposes.

The relationship between the two criteria can be formulated in the following way: While the narrow sense of the concept of nature permits the determination of variable demarcations between natural and artificial properties in nanotechnology, the broad sense denotes invariable properties of nature, which are preconditions for nanotechnology. The first criterion deals with the dynamic boundaries of the natural world, the second with the static limits imposed by nature. The one describes what is possible within the scope of the other.

An important example to which both criteria can be applied is the relationship between nanotechnology and living nature, which I discussed in the last section. Currently, life is the part of nature most distinct from technology in general. The possibility that nanotechnology may in the future produce artificial life, similar to or distinct from existing living nature, cannot in principle be ruled out. The present discussion of future possibilities indicates that technology on a nanoscale will probably be modeled after living nature in order to have the best possible conditions for producing artificial products to serve human purposes.

Acknowledgments

My thanks to the two anonymous referees for their useful comments, as well as to Katja Plaisant and John Michael for their translation.

Notes

1 "Nanotechnology […] can be oriented either to reproduce natural things or processes, exhibiting different features, or to produce new objects or materials" (Negrotti 2002, p. 4).

2 *E.g.* Siegel *et al*. 1999, p. 11-12, Stix 2001, Jopp 2004, p. 36.

3 The philosophical discussion focuses mainly on issues of ethics, without making a problem out of the relationship between nanotechnology and nature. *Cf.* the Nano-STS Bibliography of University of South Carolina (www.cla.sc.edu/cpecs/nirt/bibliography.html), which "includes scholarly publications in the history, philosophy, and sociology of nanoscience and technology", as well as Baird et al. 2004. One exception is Lee 1999, who grounded the distinction between the natural and the artificial upon an ontological basis and defended it against the nanotechnological possibility of its nearly complete effacement. Schiemann 2004 provides a philosophical discussion of the concept of nature, wherein he makes reference to the public presentation of nanotechnology.

4 The currently relevant definitions of nanotechnology are discussed at length in Schmidt *et al*. 2003.

5 Biotechnology means in general the technical utilization of advances in the methods and instruments of the biological sciences. Genetechnology can be understood as a subarea of biotechnology and molecular biology.

6 The term 'extension' means the object class that a concept refers to, 'intension' means the class of features that appear in a complete conjunctive definition of a concept. *Cf.* Schiemann 2005 for a more specific definition of the extensional and intensional senses of the concept of nature.

7 Historically, the definition of 'nature' as that which is not produded by humans first became significant in the 19th century. Mill 1874 was particularly influential. For a more recent formulation, see Passmore 1974.

8 The extension of the term 'nature' in the narrow sense can be defined either intensionally by the property of not being produced by human action, or extensionally by listing the objects to which it refers. In its broad sense, it can be defined only

intensionally by the empirical content of the laws of nature, which refer to reality in its entirety (the extension in the broad sense).

[9] The Turing-test investigates the ability of computers to imitate human intelligence: a person interviews two invisible objects, one of which is a human being, the other a computer. The person is to determine whether there are specific differences in the respective answers.

[10] The criterion must be supplemented to make sure that synthetic molecules produced on earth would not cease to be considered artificial in the unlikely event that they were found to exist extra-terrestrially.

[11] Wevers and Wechsler 2002, p. 11.

[12] For Aristotle, for instance, certain parts of a sick human body take on natural status the moment they are healed. According to Aristotle, medical treatment of diseases is actually technological. Physicians are technicians, who produce artificial states in the body that lead to health and thus back to nature (*cf.* Schiemann 2005).

[13] The relation of the broad sense of the concept of nature to the narrow sense, which is only defined negatively by reference to human action (*cf.* Section 3) is of tensional character inasmuch as the lawful structure of nature can be understood as a positive (scientific) characterization of nature. Laws, however, can always be formulated in negation (*cf.* Popper 1935, p. 39), in which case nature emerges as a limit to possible human actions. One example is the theorem of energy conservation, taken as a postulate of the impossibility of constructing perpetual motion machines of the first kind.

[14] Jones 1995, provides an additional argument, related to the concept of entropy.

[15] As long as nanotechnology does not use atoms made of non-natural elementary particles, its products will not be completely artificial.

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