D. Baird, A. Nordmann & J. Schummer (eds.), *Discovering the Nanoscale*, Amsterdam: IOS Press, 2004.

ISBN: 1-58603-467-7

Unbounded Technologies: Working Through the Technological Reductionism of Nanotechnology

Jan C. SCHMIDT
Center for Interdisciplinary Studies of Technology, University of Darmstadt
schmidt@zit.tu-darmstadt.de

Abstract. It will be shown that the umbrella term "nanotechnology" reveals the endeavor of recent engineering sciences and science-based technologies to find a fundamental technology, in other words: a root or core technology. This is linked to the leading and exciting vision of a specific kind of reductionism, namely *technological reductionism*, which has not yet been perceived by the philosophy of science. Further, it will be illustrated that the quest for a fundamental technology resembles the scientific research program of physics in its goal to find a grand unified theory of everything. Physicists have become pace-setters in research and development of nanotechnology.

1. Introduction

Hitherto, engineering sciences appear to be largely a diverse patchwork consisting of very different areas like civil, electrical, mechanical, material, informational, medical engineering. Classical technologies are bounded technologies which are applied in specific contexts, *e.g.* biomedical technologies in the field of medicine or information technologies in the context of information processing, management and storage. Today, specialization has splintered engineering sciences, and none of the disciplines can master more than a tiny isolated fragment of all problems. During the last 60 years, efforts have been made to bring together the various parts of science-based technologies (*e.g.* the earlier attempts of cybernetics in the 1940's, general systems theory, information theory, solid-state physics; micro systems technology). But an overall progress has not been reached until now. In a pragmatic sense, engineering sciences are sometimes labeled "inter- and transdisciplinary", although this just remains a catchword without a distinctive feature. Further work has to be done in order to establish a "theory of interdisciplinarity" (Schmidt 2003).

The recent development of nanotechnology is an excellent highlight in bridging various engineering sciences (and natural sciences as well). This development is due to the progress in physics, chemistry, and molecular biology as well as in computer sciences and computer technologies. Disciplinary boundaries are being torn down, as "nanotechnology" seems to indicate. In between the disciplines, scientific knowledge "circulates" with high acceleration; an "interference", merging and mixing of disciplines takes place, as Michel Serres stresses (Serres 1992). Today, nanotechnology is just an umbrella term for a wide range of technologies (see Metha 2002). At first glance nothing seems to be new, exciting, or problematic. But the umbrella term does not indicate merely a rhetorical shift or a renaming of well-known technologies without any content or visions of new R&D strategies. In addition, the umbrella term "nanotechnology" reveals the endeavor of recent engineering sciences and science-based technologies to find *a fundamental technology,* in other words: a root or core technology. This is linked to the leading and exciting vision of a specific kind of reductionism, a *technological reductionism* that has not yet been perceived by the philosophy of science. That is my main diagnosis in respect of the development of nanotechnology, as I will go on to explain. In addition, I will show that the quest for a fundamental technology resembles the scientific research program of physics in its goal to find a grand unified theory of everything.

2. Driven by the Frontiers of Natural Sciences and by Application

The "no man's land in between the disciplines" is neglected by the modern sciences, as Norbert Wiener stressed 50 years ago (Wiener 1968, p. 21). So he developed *cybernetics* to fill the gaps between the disciplines, but he did not succeed with his vision to radically change the sciences. Today, something similar is taking place. Although nanotechnology is in its infancy, it has become a popular umbrella term used to describe many types of research or knowledge production where the typical dimensions of the materials used are supposed to be below the microscale, *i.e.*, less than 1000 nanometers. This is, of course, not a definition, but an indication, where we should discuss the question: What is nanotechnology?

Before addressing this crucial question, let us concentrate for a while on the way in which nanotechnology is introduced in public discussion. In fact the core of this new technology is indicated by the dimensions of a particular "universe" and a specific scale of the world, the "nanocosm", accompanied by space- and room-related metaphors. Whereas classical types of technologies are named with reference to specific objects, properties and processes, to definite functions or to areas of application, nanotechnology just refers to the scale of abstract objects. Although engineering sciences are also involved in developing traffic, infrastructural and building technologies, space- and room-related metaphors were not used until today. Key technologies especially were understood solely in a functional way without referring to space. This space-invariance reflects the functional universality and the seeming context-independence of application. By neglecting spatial aspects, the visionaries and lobbyists of high technologies could easily overlook ambivalent social impacts of development, application, and diffusion: social impacts are located in space and time, in other words, within specific contexts.

Though the space-relatedness of nanotechnology and the metaphors of the nanolobbyists might suggest otherwise, nanotechnology represents only a new and more rigorous construction of space-independent technology. The abstract micro- or "nanocosm" of nanotechnology on the one hand and the mesocosm of our day-to-day *Lebenswelt* on the other hand are entirely different. Phenomenologically we do not have access to the "nanocosm" with our senses; technological apparatus and experimental setups are necessary. In this respect, the spatial scale of nanotechnology shows us our spatial limitations and our endeavor to overcome them. Hence, nanotechnology has an implicit anthropological relevance (see Nordmann 2003): the position of humans in the scales of the cosmos is a mere point in between the nano- and macrocosm. But we do not have to remain isolated and epistemological limited in our own mesocosmic world; we may access the "nanocosm", which might be the best cosmos to "live" in. The abstract reality of the "nanocosm" – this is suggested by the visionaries of nanotechnology – seems to be similar to (but better than) our day-to-day-reality in our mesocosms. The cramped conditions of the mesocosms (energy, entropy, information storage, time,...) will be altered and defeated. If the nanocosms will take over and fulfill several functions that today are restricted by the mesocosm, we will get more space and more freedom of action (see Schwarz 2004, this volume).

The reference to an abstract space is intermingled with the lack of semantic specification; the size of objects is a weak basis to define a new type of science or to integrate different disciplines. Similar to its predecessor in the 1990s, microsystems technology, “nanotechnology” (still) lacks content and a core. Like an empty room or a new flat, everyone is invited to furnish, move into, paint or attribute to it whatever he or she wants. The main semantic character of nanotechnology is vague, uncertain, indefinite and indeterminable (see Gamm 2000, p. 275ff). Facts and fiction are merged and cannot be distinguished. It is hard to find scientific disciplines which may not be subsumed under the category “nanotechnology”. In the struggle for financial support, the vagueness seems to be a successful strategy of science policy that is promoted by the visionaries and lobbyists of nanotechnology. At least we have to be aware of the fact that the umbrella term “nanotechnology” could be a mere ideology and a clever strategy of different *scientific communities* to obtain financial support. This was, indeed, the case when James Yorke coined the term “chaos” in 1975 for some deterministic, irregular mathematical properties. “Chaos” became the catchword of dynamical systems theory and nonlinear dynamics, which from then on were called “chaos theory”, accompanied by the interest of the public and the scientific communities. J. Yorke and his group financially survived. But clever umbrella terms and catchwords do not seem to be sufficient for new contents and a homogeneous scientific research program.

The space-related metaphors of nanotechnology turn into an ideology by suggesting that the nanocosm has to be conquered like a country or a white region on the map. The conquest visions and metaphors of nanotechnology have been around for many years. The physicist Richard Feynman was supposedly the first person to speak about the idea of nanotechnology in 1959. He drew a map with a white unexplored region: “There’s Plenty of Room at the Bottom” (Feynman 1959/2003). Hence, the room awaits scientific conquerors. In a speech to the American Physical Society, he proposed that tiny machines could be programmed to replicate themselves at one half their original sizes. He suggested that it would be possible to manipulate individual atoms and molecules to form exactly the products desired. Today, this vision is indirectly adopted by the NSF slogan “shaping the world atom by atom”. According to Feynman, “The principles of physics [...] do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big. [...] But it is interesting that it would be, in principle, possible for a physicist to synthesize any chemical substance that the chemist writes down [...]: put the atoms down [here] [...] and to do things on an atomic level. [...] [This is a] development which I think cannot be avoided” (Feynman 1959/2003). But Feynman’s vision was not only the *bottom-up* strategy of “shaping and maneuvering the world atom by atom” in order to create new chemical substances, but also the miniaturization of well-known mesocosmic entities and artefacts *top-down*. At the end of his speech, Feynman issued a challenge to everyone: “It is my intention to offer a prize of $1,000 to the first guy who can take the information of the page of a book and put it on an area 1/25,000 smaller [...] in such manner that it can be read by an electron microscope. And I want to offer another prize to the first guy who makes an operational electric motor which is…only 1/64 inch cube. I do not expect that such prizes will have to wait long for claimants” (Feynman 1959/2003). The vision of Feynman combines “cross-disciplinary” chemical engineering, mechanical construction, information processing, data storage, electroengineering, electrooptics, and others. Equivalent names for nanotechnology include molecular manufacturing, molecular fabrication, mechanosynthesis or chemosynthesis.

The objects nanotechnology tries to handle are mainly concentrated on the interdisciplinary borders between physics, chemistry, molecular biology – and engineering sciences. The scientific ambition is to link and to unify quantum mechanics, solid-state physics, inorganic chemistry, and molecular biology. These issues are, however, not new, but more or less classical. They are unsolved until today, when even in physics a unified theory merging quantum mechanics with macroscopic phenomena and with a complex system is not established. In statistical mechanics, important theoretical entities of phenomenological thermodynamics like entropy are not explained in a satisfactory way. These theoretical gaps seem to reflect that nature is ontologically multi-tiered and coarse-grained. But the visionaries of nanotechnology fail to notice the state of the art in physics. They just orient themselves toward the heuristic objective of physics, which is mainly the quest for a fundamental theory of everything.

The vision of an extremely tiny technology was first raised not by an engineer, but by a physicist, Richard Feynman, who founded quantumelectrodynamics (QED) and worked on macroeffects like suprafluidity. This does not seem to be a pure coincidence. Particle, high energy and nuclear physicists are used to preparing "nature" on the nanoscale. Their day-to-day experimental (technological) preparation has certainly influenced Feynman to expect and to predict the global success of nanotechnology. Physicists in the 20th century have always engaged in "nanoscience" (without naming this "nanophysics" or "nanotechnology") and they advanced the "nano-methodology" in particle physics as well as in solid-state physics. To a certain extent, these aspects are a line of arguments against the hypothesis that nanoscience and nanotechnology are (in fact) a radically new type of science and technology. They base on the advancements of physics: Indispensable physical instruments in the rise of nanotechnology are scanning tunneling microscopy (STM) and the atomic force microscope (AFM), which stem from developments in the early 1980s. Nanoscience and nanotechnology are highly dependent on the advancements of instruments in the realm of physics. They are mainly driven by methodological improvements in the horizon of physics.

We should be aware of the fact that it is not engineers, but natural scientists who proclaim an advancement of nanotechnology – and they are working as natural scientists on topics which are relevant for the future of technology and hence, as they themselves state, for the future of society. Today, technology is even more science-based than in the 19th century, whereas – conversely – natural science is based on technological apparatus. The diagnosis of a "hybrid" consisting of science, engineering, and technology – an intermingled "technoscience" as pointed out by Bruno Latour and Donna Haraway – seems to be plausible (Latour 1987; Haraway 1995). The question of whether this indicates a "new production of knowledge", as some sociologists have stated (Gibbons *et al.* 1994), cannot be answered just by referring to societal aspects whilst inner-scientific aspects and the inner-scientific evolutionary processes (like the paradigm of physics in the quest for unification and the leading research program) are mainly excluded. It is not at all obvious that the facts in the advancements in science and technology justify the diagnosis that we are entering into a radically new era or a new paradigm, as the nanolobbyists proclaim. And Martin Carrier stressed that technology or policy-related scientific research ("Mode-II-Production of Knowledge", Gibbons *et al.* 1994) is by no means historically novel (see Carrier 2001, p. 25f). Phenomenological thermodynamics and hydrodynamics in physics are developed in close relation to technological applications and industrial innovations. The discussion about "*finalizing* scientific research programs" shows that the merging of science, technology, society, and politics has always been around, especially in the 19th and 20th century (Böhme *et al.* 1974). Nanotechnology, of course, is a new summit and it accelerates this merging process. What seems to be a qualitatively new step are its visions, particularly its *technological reductionism*. Even if we may (and can) not argue that the recent facts justify the diagnosis of a radical new era, the visions are a sufficient indicator for this diagnosis which should the analyzed seriously. Often, visions (science-fiction and "Leitbilder") turn to facts; visions may open road-maps to reality (see Nordmann 2003).

A pioneer (and a lobbyist) of nanotechnology in the early 1970's was Eric Drexler, who was involved in genetic engineering (see, *e.g.*, Drexler 1990). Drexler was convinced that the same principles behind the manipulation of DNA molecules could be applied to other molecules. Drexler was probably one of first people, besides N. Taniguchi, to use the phrase "nanotechnology" in order to describe the process of precise molecular placement one atom at a time. In his papers and books, Drexler stressed three concepts which are fundamental to his vision of nanotechnology: assemblers/disassemblers, replicators, and nanocomputers. Assemblers are macroscopic pumps to carry out mechanical actions, *i.e.* to put things together; disassemblers take things apart; replicators are copying mechanisms; nanocomputers give instructions to the other parts, *i.e.* to assemblers, disassemblers, and replicators (Drexler 1990). Although it was Drexler's objective to shape the term "nanotechnology", he merely described the functional frame of molecular fabrication without any hint to objects, methods, goals, implementations, and social diffusion.

So we can sum up that, in the large, nanoscience and nanotechnology have their roots in traditional disciplines like physics and chemistry. This comprises three aspects: Firstly, the visions ("shaping the world atom by atom") and *Leitbilder* arise in the realm of physics and chemistry. Secondly, the theoretical scientific basis lies in the area of physics, chemistry and in between. Thirdly, the instruments and experimental methodology necessary for nanotechnology (like Scanning Tunneling Microscopy or the AFM), are based on frontier advancements in physics and chemistry. Hence, gaining an understanding of nanotechnology may be possible by concentrating on the visions and *Leitbilder*, theories and methods primarily established in physics and chemistry – of course without neglecting the increasing power and influence of a globalized economy and an accelerated capitalism.

One main objective of physics and chemistry is the unification project in the metaphysical, epistemological and methodological sense. My line of argument will show that this successful unification strategy and reductionist metaphysics are grasped and extended by the visionaries of nanotechnology.

3. Nanotechnological Unification Project: Convergence and Reductionism

Nanotechnology, this is my main thesis, aims to be a fundamental technology ("root technology") with hegemonic tendencies: Nanotechnology presents itself as *the* basis for all other technologies. The objective of this new fundamental technology seems to be the general foundation of science-based technologies. Similar to classical-modern physics and the unifying attempt to converge the four main forces to obtain a "theory of everything", nanotechnology follows a unification program – here a unification program of engineering sciences – in order to eliminate the patchwork of various bounded technologies which are restricted in application. So nanotechnology is not at all a scale-restricted technology; it is not just another step towards miniaturization. Probably, G. Stix is right in emphasizing that "nanotechnology is all the range" (Stix 2001, p. 32). Hence, "nanotechnology" is not only an umbrella term for a variety of technologies, but, in addition, a strategic vision for a science-based unification research and development program of engineering sciences itself. Nanotechnology indicates the attempts of unifying engineering sciences. Some details:

Essential criteria for a technology being a "fundamental technology" can be derived from the quest for a fundamental theory in theoretical physics where at least some theories are converging. A fundamental theory and the unity of physics are mainly synonyms (see Weizsäcker 1974). A necessary condition for the unity of physics in the epistemological sense is a convergence of the four main theories. However, the heuristic concept of the unity of physics may be extended to the unity of technologies. In the case of technologies and engineering sciences one has to show that a unity of technologies exists and that one "mother technology" enables all other "daughter technologies", *i.e.* the mother technology incorporates all daughter technologies, as in physics, where quantum mechanics claims (misleadingly) to ground the predicates of classical mechanics.[1] This is what I will name "*technological reductionism*" or "*reductionism of technology*".[2] This kind of reductionism

– and the inverse path, that of technological constructionism – has to be further specified. The technological reductionism of engineering sciences is the metaphysical core of the heterogeneous and diverse fields of the umbrella phrase "nanotechnology", covering electron-beam and ion-beam fabrication, molecular-beam epitaxy, nanoimprint lithography, projection electron microscopy, atom-by-atom manipulation, quantum-effect electronics, semiconductor technology, spintronics and microelectromechanical systems.

Arguments for my thesis, that nanotechnology aims to be *the* fundamental technology with imperialistic tendencies, are given by the US National Science Foundation (NSF) itself (Roco & Bainbridge 2002). The NSF states that technologies like nanotechnology (also: biotechnology, information technology and cognitive sciences) are not only "key technologies" but also "converging". The NSF speaks of "Converging Technologies for Improving Human Performance" explicitly in terms of "Unifying Science and Converging Technologies" (*ibid.*, p. x). This is based on the traditional metaphysical claim of the unity of nature, revealing an implicit Platonism and showing, beyond Plato, a strong naturalism in the field of nature and of technologies (*ibid.*, pp. ix, 32):[3]

> In the early decades of the 21st century, concentrated efforts can unify science based on the unity of nature, thereby advancing the combination of nanotechnology, biotechnology, information technology, and new technologies based on cognitive sciences. [...] Converging technologies could achieve a tremendous improvement in human abilities, societal outcomes, the nation's productivity, and the quality of life. [...] The phrase 'convergent technologies' refers to the synergistic combination of four major 'NBIC' (*nano-bio-info-cogno*) provinces of science and technology, each of which is currently progressing at a rapid rate. [...]
>
> Convergence means more than simply coordination of projects and groups talking to one another along the way. It is imperative to integrate what is happening.

The unity and convergence metaphors are linked with catchwords like "holism" and "synergism", as stated by the NSF: "Converging of the sciences can initiate a new renaissance, embodying a holistic view of technology based on transformative tools, the mathematics of complex systems, and unified cause-and-effect understanding of the physical world from the nanoscale to the planetary scale" (*ibid.*, p. x). "A trend towards unifying knowledge by combining natural sciences, social sciences, and humanities using cause-and-effect explanation has already begun" (*ibid.*, p. 13). The traditional naturalistic view of a continuous causality and a causal nexus of nature is renewed by the NSF in order to highlight the epistemological and technological possibility and importance of unification: It is "possible to develop a predictive science of society". (*ibid.*, p. 22) "The sciences [...] have reached a watershed at which they must unify if they are to continue to advance rapidly" (*ibid.*, p. x). To illustrate this, a strange (piece of) poetry is placed in the NSF report (*ibid.*, p. 13):

> If the Cognitive Scientists can think it
> the Nano people can build it
> the Bio people can implement it, and
> the IT people can monitor and control it

Obviously, this could and would imply a circle in argument, in the sense that the IT people would control what the cognitive scientists think. More radically: the IT people would control the cognitive scientist, and so on. So the naturalistic causal nexus seems to "operate" without any influence of any human agent, like the Laplacian Demon in the 19th century.

I will proceed one step further, beyond the symmetry of "NBIC (*nano-bio-info-cogno*)", and concentrate on nanotechnology. Nanotechnology seems to be, more or less, *the* fundamental basis for the unity of technologies because the abstract nanoscale is where the convergence of the four technologies is supposed to take place: "Convergence of diverse technologies is *based on material unity at nanoscale* and on technological integration from that scale. The building blocks of matter that are fundamental to all sciences originate at nanoscale" (*ibid.*, p. ix). The unity of science itself, the unification of engineering sciences and technologies, is said to take place on the nanoscale. In the very small and abstract world of the nanocosm, everything seems to converge. Convergence is *the* pacemaker to unity; unity is the final point. The final point is the point of total control – it is the point of Archimedes. So it is not only a metaphysical unity of the (given) nature ("ontology"), a unity of knowledge and explanation about nature and about technologies ("epistemology") or a unity of methods ("methodology"), but a unity referring to preparation, manipulation, acting in nature; it is a unity of technology, a unity of *technoscience* itself (see Latour 1987).

A common paradigm is stressed by the nanolobbyists and nanovisionaries: In terms of traditional epistemology, this is a classical reductionist strategy. It is not only a reductionism of science, but a *reductionism of technology*, which links knowledge, action and application. It is not solely a reductionism in the scope of truth production, theories and propositions (representation), but of knowledge production in the horizon of application and intervening (see Hacking 1996). The philosophy of science has not yet developed an approach and access to this new type of reductionism. The NSF criticizes all positions which do not support an overall reductionism:

> Some partisans for independence of biology, psychology, and the social sciences have argued against 'reductionism', asserting that their fields had discovered autonomous truths that should not be reduced to the laws of other sciences. But such a discipline-centric outlook is self-defeating, because as this report makes clear, through recognizing their connections with each other, all the sciences can progress more effectively. [Roco & Bainbridge 2002, p. 13]

Hence, fundamental technologies are conveyed by a technological reductionism based on the metaphysical unity paradigm of (the given and constructed) reality – and a linear optimism about scientific progress.

In reductionist approaches, explanation has been defined as the subsumption of new phenomena under well-known general laws (Rule 5 in Descartes 1979, p. 379). According to Hempel and Oppenheim, to Nagel, Popper and Scheibe this is called the deductive-nomological (DN-) scheme of explanation (see Hempel and Oppenheim 1948, Scheibe 1997) or the "covering law model". It is implicit in the convergence and unification program of the theories of physics (reductionism of explanation). In physics, three of four fundamental theories converge to a new "theory of everything"; in engineering science, a convergence of the four "NBIC (*nano-bio-info-cogno*)" technologies is stated by the NSF.[4] Now, the theoretical strategy of explanation is partly interlaced with experimental or methodological reductionism. Reality is experimentally torn to pieces and the pieces are isolated from each other in order to gain deeper insight into the structure of matter (reductionism of experimental setups, reductionist and analytical methodology, even in "holistic" quantum physics). Implicitly, most scientists assume the *smaller* the entities of nature are, the *deeper* is the synthetic understanding of nature in general and the *more fundamental* is the explanation. Hence, it is assumed that understanding the microcosm implies understanding in a synthetic way the whole cosmos, but not vice versa (viability of the *bottom-up* strategy of explanation). The (metaphysical) claim necessary to argue for this epistemological statement is ontological reductionism, linked with naturalism. Further details in the debate on reductionism will be skipped here; different other aspects of a metaphysical, an epistemological or a methodological reductionism could be analytically distinguished. This has been done by philosophers several times. But philosophy of science has not yet grasped the *technological reductionism* which is apparently present in (the program and metaphors of) nanotechnology.[5]

What is *technological reductionism* in detail? Let us specify some aspects. *First,* in general, technological reductionists assume the possibility and effectiveness of shaping the world atom-by-atom. The world can be effectively shaped, manipulated and controlled by shaping atoms and molecules. This is an ontological claim and a perfect *bottom-up* methodology. Apparently, shaping the "bottom", the nanocosm, will imply an intentional shaping of the meso-, macro- and megacosm. Hence technological reductionists debase other scales of acting in the world, like the micro-, meso-, macro- or megacosm. These scales are *not* relevant for general control of the world. The meso-, macro- or megacosm do *not* possess own strong supervenient properties which can*not* be manipulated by the nanocosm (see Beckermann 2001, p. 203ff). This is, of course, a strong claim and reveals the straight naturalistic viewpoint which is based on the (classical) conviction of a continuous cause-and-effect nexus of the world, especially a naturalistic line from the nanocosm to the macrocosm. The phrase "shaping the world atom-by-atom" neglects classical engineering sciences (research and development) on scales of the micro-, meso-, macro- or megacosmos and just focuses on the nanocosm. Technological reductionism is anti-pluralistic, and is not based in a structural science ("Strukturwissenschaft": Weizsäcker 1974, p. 22f). The NSF states: "The traditional tool kit of engineering methods will be of limited utility in some of the most important areas of technological convergence" (Roco & Bainbridge 2002, p. 11). This indicates that engineering sciences are in (a state of) transition, from bounded to fundamental nano-engineering sciences.

Second, to give some more formal details, nanoengineering sciences suggest a monocausal (epistemological) dependence structure of knowledge, action, and manipulation in the scope of technological reductionism, without emergent properties which cannot be controlled from the nanocosm. Technology t_1 is said to be reduced to technology t_2 if, and only if, the advancement of t_2 is fundamental to the advancement of t_1. In other words: The development of t_2 is the bottleneck (and the necessary condition) for the development of t_1. Technological reductionism does not only claim a reductionism of explanation, but (also) a reductionism of research and development activities, of technical handling, control, and intervention.[6] In order to promote the daughter technology t_1, one mainly has to enhance research in the field of technology t_2. It does not mean that technology t_1 and t_2 are identical, but that a monocausal dependence exists. Progress of technology t_1 monocausally depends on technology t_2. This new kind of reductionism is a way to give substance to catchwords like "key technology", "enabling technology", and "nanotechnology", which I have renamed "fundamental technology" in order to highlight the parallelism to the ambitions of (classical-modern) physics.

Third, there is also a more societal understanding of "fundamental technology". The *more fundamental* a type of technology is, the *more dominant* it obviously is in our day-to-day life, the *more* it becomes an implicit circular of our society, the *more* traditional distinctions (nature vs. technology, technology vs. culture, politics, ethics) are dissolved. Fundamental technologies are those technologies which constitute, like other mass media, a "medium of society" (Gamm 2000, p. 275ff); they are the nexus of knowledge circulation (Serres 1992). They cannot be defined solely as artifacts, instruments or processes. An external position of mere observation cannot be captured. Fundamental technologies are wherever we are, like the blood in our body.

Fourth, furthermore, technological reductionism merges and mixes scientific realism and constructivism of the very small, insofar as representation and intervening are both the core of technological reductionism. Technological reductionism does not only have its root in scientific realism, but merges and mixes realism and constructivism: it is a "pragmatic constructo-realism".[7]

To sum up: Although, at first glance, "nanotechnology" just seems to be heterogeneous, diverse and pluralistic, *i.e.*, only loosely connected by the umbrella term, technological reductionism is anti-pluralistic in its core. "Nanotechnology" may be interpreted as an overall research and development program of the *technosciences* which is based on a strong technological reductionism. For understanding nanotechnology, philosophy of science should address the core of nanotechnology, *i.e.*, its technological reductionism.

4. Epistemological Limits of the Technological Reductionism

Is the overall reductionism of the nanotechnological research program justified? – It is hard to see how the research program could succeed as stated by the nanolobbyists. By looking closer at reductionist strategies one has to be aware that even in recent physics we do not have a nice hierarchically ordered theoretical frame or a final unified theory of everything (TOE). The unification strategy is successful to a certain extent but has not reached its goal of a theory of everything until now. This, of course, is just an argument derived by referring to the status quo of physics. It is not a general argument which shows that the unification strategy of physics and of nanotechnology will fail in the future. Let us strengthen our argument that nanotechnology overestimates the possibilities of technological reductionism and present some principal and major limits.

The reductionist *bottom-up* methodology is and will be successful for the development of specific materials, instruments, properties, processes such as superconductivity or some quantum computing, but not in general. Many doubt the thesis of nanotechnological visionaries that nature can be constructed atom-by-atom. The constraints of physics and chemistry are too severe. In particular, I would advance here the following line of argument: If nanotechnological visionaries recognize as one of their fundamental theories dynamical systems theory, including nonlinear dynamics, chaos theory, and theories of self organization – and sometimes they claim that they do – they would be aware of the limits of all reductionist strategies and hence of the epistemological limits of technological manipulation.[8] I am therefore inviting nanovisionaries to identify and to learn from the limits of physics.

First, we have to consider the instabilities in nature and in the objects of engineering sciences. The origin of nonlinear physics and chaos theory is an impartial criticism of classical modern physics and its leading paradigms of ontological and epistemological reductionism (see Schmidt 2001). One important lesson of the new physics for all mathematical and engineering sciences known today is the fundamental role of nonlinearity and instability in nature and in technical apparatuses. If nature and technological objects are governed by nonlinearity, they can be structurally and dynamically unstable; flipping points, bifurcations, and chaos can occur – with small changes in initial conditions producing large effects in the overall dynamics (sensitivity, "butterfly effect"). According to M.L. Roukes, a physicist working on nanosystems, instability of nature challenges the nanotechnological *bottom-up* strategy and limits technological control of the tiny objects and the (seemingly continuous) path from the nanocosm to the macrocosm: the smaller the objects are, the more unstable they can behave, the more the nanoeffects may be amplified into the mesocosm without control. Perturbations on the nanoscale cannot be handled and controlled in all details. "The instability may pose a real disadvantage for various types of futuristic electromechanical signal-processing application" (Roukes 2001, p. 37). A second limitation is given by the laws of physics, namely the fundamental threshold for the minimum operating power: the random thermal vibrations and fluctuations of a device impose a "noise floor" below which real signals become hard to discern. – Briefly stated, nonlinear physics and chaos theory question (a) the classical modern understanding of experimental repeatability and hence the methodology of experimental and technological preparation in general, (b) the computability and predictability of the future and therefore access to its, (c) mathematical modeling and in consequence the empirical testability of models in experiments. Such severe methodological criticism challenges the common understanding of science (see Schmidt 2001, p. 276f) and restricts the ways of preparation and construction of certain aspects of reality. Hence technological interventions are restricted.

Second, the focus of interest: One main difference between classical-modern reductionist physics and new nonlinear physics lies in their respective methodologies, *i.e.*, in the approach to their objects. Classical-modern physics assumes relevant epistemic aspects for understanding nature to be located primarily in the nano- or microcosm; on the other hand, new nonlinear physics and chaos theory focus on objects of medium scale, the mesocosm, with their own properties. The scope of interest and inquiry is broadened towards mesocosmic objects, the phenomena and appearances therein, – contrary to the nanotechnological vision. For instance, fractal geometry, a daughter theory of nonlinear dynamics, investigates nonlinear processes, pattern formation and structure building of plants and animals, as well as of fluids, gases, and solid states. Fractal geometry does not aim to understand the "genetics" of a plant but to describe the morphologic structure and the pattern formation process. Contextualized modeling and simulation become the core of the scientific methodology of new physics. The perspective of a moderate epistemological functionalism, but not a fundamentalism or a foundationalism of engineering sciences seems to be evident. – In contrast to the nanotechnological paradigm, "there is plenty of room in *medium scale*": the dimension of the mesocosm is not neglected by nonlinear physics. Yet, we do not understand processes on the mesoscale like tool processing machines, railway dynamics, mechanical production processes, or building construction. We do not know how to handle these processes in detail. Further work has to be done on this scale of the classical engineering sciences. Of course, they are linked with computer science to a certain extent, but they will not be dissolved in or reduced to computer science. Technological reductionism seems to be the wrong answer to a strange question: Which kind of engineering science is of major importance and has to be financially supported? Nonlinear physics advances a pluralistic image of natural and engineering sciences.

Third, methodological and "manipulogical" issues: Two intermingled problems and limits have to be taken into account within the nanotechnological *bottom-up* strategy, as Richard Smalley points out (Smalley 2001). Smalley calls one the "fat finger problem" and the other the "sticky finger problem". Because the "fingers" of a manipulator arm and technical apparatus must themselves be made of atoms, they have a certain irreducible size. In many applications the fingers of manipulation are far too "fat". Furthermore, the atoms which should be shaped by nanotechnology will also be too sticky: the atoms of the manipulator arm will adhere to the atom that is being moved. It will often be impossible to release this nanostructure in precisely the right spot. – So there is no isolation and no definite border between the surroundings on the one hand and the object to be shaped on the other hand. Thus emerges in the nanocosm a kind of holism, based on instabilities, classical and quantum effects.

Fourth, limits of explanation and prediction: Complex nonlinear phenomena resist reductionist strategies of explanation: an a priori subsumption of phenomena under well-known unified laws is not possible, which can be concluded from the criticism mentioned above. Understanding reality requires a phenomenological process and the occurrence of pattern formation. Fractal geometry describes these processes in a phenomenological-morphological way but does not explain it based on "genetic" aspects, according to the reductionist scheme of nomological explanation. In consequence, the meanings of scientific "truth" and knowledge change. Since understanding is required for shaping and manipulation, this limit to explanation challenges nanotechnological strategies of understanding what it wants to construct. As weaker types of explanations are coming up, these imply limitations of prediction, and hence of acting and of shaping the world.

Fifth, the world is a constructo-realistic patchwork: Given and designed nature is not to be described as an invariant material block (see Cartwright 1999) but rather as a dynamically unstable, open process. New patterns and structures emerge from lower levels of complexity in unpredictable ways. Unpredictability on the one hand and technological construction on the other hand, contradict each other. Nature and technology, as N. Cartwright puts it, is "a patchwork, not a pyramid" (Cartwright 1999, p. 1f). If reality is indeed a "patchwork", the technological reductionism that is based on the classical metaphysical assumption of a naturalistic, continuous cause-and-effect nexus of the world is a prejudice that cannot be justified reference to the natural sciences.

These arguments challenge and question the visions of the nanolobbyists, *i.e.*, their technological reductionism. A necessary condition for the scientific foundation of the nanotechnological research program is the success of reductionism in the realm of physics. But this remains a visionary dream (Weinberg 1996). Thus nanotechnology may be successful to a certain extent, in specific contexts of application. A global technological reductionism and fundamentalism, however, remains a utopia. This utopia is not a very new one, it traces back to F. Bacon and the founders of modern sciences in the 17th century.

5. Tracing Back the Roots of Technological Reductionism: Renewing and Extending the Baconian Project

F. Bacon is probably the founder of the technological reductionism. He proclaimed that science is an instrument to extend the power of man as far as possible (see Bacon 1959; Bacon 1990). Knowledge is power! Nature should be hunted by sciences like an animal in order to unveil her secrets; nature was for man to milk. Indeed, this view of nature had become dominant in the concept of modern science and put into practice within its experimental and technological framework. Nature was thought to be an enemy which has to be tamed and brought under control. In contrast to the Aristotelian understanding of nature, nothing was simply given, everything seemed to be subject to technological manipulation. *Homo Sapiens* became *Homo Faber,* and further aspires to become *Techno S@piens* today. An institutionalization of science in scientific communities, like the Royal Society, London, was supposed to establish and guarantee a program of scientific discoveries, technological inventions and innovations. Science-based technological progress became identified with social and human progress (see Böhme 1993). This identification was doubted from the 1960's until the middle of the 1990's, but evidently just for this short era. In the late 1990's technological optimism was back in science and politics: the Baconian Project seems to provide the underlying ethos of scientists and engineers working in the fields of nanotechnology.

The visions of a science-based technological shaping and manipulation of the world are not very new ones. They are rooted in the history of our culture. In the empiricist tradition David Hume confirms the Baconian Project. "The only immediate utility of all science is to teach us how to control and regulate further events [in nature]" (Hume 1990, p. 76). Immanuel Kant linked the manipulation and construction of nature on the one hand with understanding on the other hand: We understand nature only as far as we can constitute and construct her (Kant 1989, p. 25f). So the phrase "shaping the world atom by atom" is an extrapolation and a new summit of the Baconian Project since the 17th century. Representing and intervening are, as stated by Ian Hacking, twin sisters (Hacking 1996). Science and modern technology have always been merged as *technosciences* (see Latour 1987). The *more* one knows about nature in the scope of a science-based reductionist methodology, the *more effectively* one can act, intervene, and manipulate. Although in the 19th century technology became science-based in general, the 21st century will probably be the century of the emergence of fundamental engineering sciences and an overall technological reductionism.

In line with a general technological optimism the physicist Michio Kaku states today: "For most of human history, we could only watch, like bystanders, the beautiful dance of Nature. But today, we are on the cusp of an epoch-making transition, from being passive observers of Nature to being active choreographers of Nature. The Age of Discovery in science is coming to a close, opening up an Age of Mastery" (Kaku 1998, p. 17). Nanotechnology is the tip of the Baconian iceberg which is not yet recognized in the ocean of scientific propositions and scientific practice by most philosophers of science.

Until today, Bacon's Project has not been realized and put into practice to its full extent. Bacon speaks in favor of a science-based reductionist "technological foundation", a foundation for acting in and manipulating the world. The NSF's phrases resemble Bacon's words: "If we make the correct decisions and investments today, many of these visions could be addressed within 20 years' time. Moving forward simultaneously along many of these paths could achieve an age of innovation and prosperity that would be a turning point in the evolution of human society" (Roco & Bainbridge 2002, p. x). The emergence of the new nanoscience-based innovations has renewed the convictions of "Nova Atlantis" to support not only scientific explorations and "truth" production but also discoveries, inventions, and innovations (see Bacon 1959, 1990).

Bacon was convinced that only an institutionalized research and development strategy could guarantee inventions and innovations. Nanoscience and the developments in nanotechnology are expensive R&D. They require cooperation between universities, governments, and industry, for example "private public partnerships". These projects are called "megascience" (Ahluwalia 1994). Megascience projects are defined as those undertaken primarily for the production of knowledge in the horizon of application, where a classical distinction between fundamental and applied science is no longer plausible. They require formal management structures and resources that cannot be provided by a single agency, university, firm, or country. Other examples are the Human Genome Project or ITER's tokamak fusion reactor. In order to get support from the public and to legitimate expensive R&D investments, Eric Drexler founded in the 1980's the "Foresight Institute", which is dedicated to the education of the public to help prepare society for the anticipated "technological advances" that the implementation of nanotechnology is thought to bring.

In the course of these institutional developments, the understanding of "technologies" may change from artifacts and procedures to media (see Gamm 2000, p. 275f). Technology is everywhere, it has become the "blood of society". The distinction between nature and technology, between man and machinery, which is still present in our day-to-day life, seems to be dissolving steadily. The dissolution of the traditional culturally leading differences reveals a paradigm of a total and fundamental technology: Everything will be shaped, designed and controlled within the limits of the laws of nature. This is pure Baconianism. But, it remains a question of politics and subpolitics whether we will accept this dissolution of our cultural distinctions. Normative and ethical aspects are arising within new types of politics like nature-politics, bio-politics or of "nano-politics", which may become established and should be reflected upon philosophically.

For the philosophy of science it remains a challenge to critically show that the vision of a totally shaped world overestimates the power of science and the power of men. Technology may be everywhere (Gamm 2000, p. 275ff) and the Aristotelian understanding of nature may be dissolved in a fundamental technology with its technological reductionism. But technology cannot be shaped and controlled everywhere. The boomerang effects of technology within society have been perceived and reflected upon since the beginning of the ecological crisis in the early 1960s. So it is surprising that the Baconian Project and its linear technological optimism are renewed by nanotechnology. The cultural and political progress of the last 40 years with its perception and recognition of the societal ambivalence of science and technology seems evidently to be retracted.

6. Technology Assessment as Vision Assessment

How to cope with nanotechnology and the technological reductionism within society? Technology assessment (TA) provides fruitful and, to a certain extent, successful tools for the societal shaping of technologies (Grunwald 2000). Procedures of perception, assessment, decision-making, management, and controlling have been developed during the last 35 years. But often TA comes too late to gain influence on the processes of technological advancement and societal diffusion; the speed of technological innovation grows rapidly; often concepts of co-evolution of TA and technological innovation have not been applied. Although nanotechnology as a technology is in its infancy, the leading goals, visions, *Leitbilder*, and metaphors are well known and fully established. Even if burdened with religious aspects and dreams of Baconian prosperity, visions are pathways to reality. They often turn from mere thoughts and abstract ideals to road maps for constructing and shaping reality. A leading magnet and a powerful *Leitbild* ("vision") is technological reductionism, linked with the nanotechnological shaping metaphor, the "shaping of the world atom-by-atom".

For the megascience "nanotechnology" a prospective Technology Assessment (TA) should not be restricted solely to assessing the technological artifacts and procedures and, in the end, the diffusion into society. A co-evolution should take place. Technology Assessment may include *Vision Assessment* (VA), in other words: an assessment of *Leitbilder* (Dierkes *et al.* 1992). An extended understanding of shaping technology covers a shaping of visions as well as a shaping of technical apparatus, technical procedures and societal diffusion: the way one thinks and talks, the way one might act and behave. The methodological philosophy of science and the science-related constructivism of the school of *Erlangen* (Lorenzen, Mittelstrass, Janich, and others) have shown the crucial role of terms, languages, and prototheories in the advancements of science. This could be transferred to the development and societal shaping of technologies, insofar as technologies are science-based. This extension of TA to Vision Assessment is controversial. Sometimes it is doubted that visions play any relevant role in the process of technological invention and innovation. Other critics may raise the objection that visions are too vague to be a fundament for rationally assessing prospective technological advancements; this is the position of those representing "Rational Technology Assessment" (see Grunwald 1998). Some critics believe that in the period in which *Leitbilder* still play a leading role it is far too early to say anything about a new technology, its chances and limits. And some natural scientists and engineers suspect a renewing of the *Two Culture* dichotomy: they fear that social sciences and humanities will dominate the shaping of technology, but without any inner knowledge about natural and engineering sciences and technologies.

But all of this would be a misunderstanding of the framing concept of Vision Assessment. By introducing Vision Assessment to the scope of Technology Assessment, the technological core of new technologies in the TA concept are not neglected or excluded. Vision Assessment stresses the relevance of soft aspects for the development, the diffusion and the use of new technologies, in the sense of Ernst Cassirer when he spoke about "symbolics and symbolism of technology" (Cassirer 1985). So two aspects may be distinguished within the framework of an extended TA: (a) Science and technology promote not only successful, but ambivalent knowledge about modifying, manipulating and designing nature. (b) Science and technology are interlaced with ideas, interpretations and thoughts. They create (and demolish) *Weltanschauungen*, cultural symbols and ideals by obtaining fascinating insight into structures, forces, and evolutionary processes of nature and technology. Scientific methodology is often thought to be culturally leading, as are its implicit norms and guiding values, its experimental setups and laboratory practice, its way of thinking and asking, its criteria for testing – and its pre-definitions and assumptions about nature, and hence the constitution of nature and technology in the scientific process.

TA of nanotechnology may be aware of the fact that nanotechnology has material and process, as well as social, symbolic, and anthropological components – and that its visions and *Leitbilder* may constitute the reality of the present and the future. So the core of nanotechnology, its technological reductionism, should be assessed. This extended approach opens the TA (of nanotechnology) to plural perspectives about the central questions: What are the central struggles and issues we have to resolve in society? What do we want to know? What can we realize? And: How do we want to live? Technological advancement, controlled and managed by an extended TA, would then become more problem- and purpose-centered than in the past. And corridors of (rational) decision-making about visions may be (re-)opened by a public debate on the future of our societies.

7. Conclusion

Let me summarize some of the fragments presented here: *First*, the driving forces, metaphysical backgrounds, leading metaphors and visions of nanotechnology have been developed in the horizon of physics (and chemistry). *Second*, the vision of nanotechnology is based on a convergence and unification program, revealing a new type of reductionism, *i.e.*, technological reductionism, which has not yet been recognized by the philosophy of science. *Third*, technological reductionism can be illustrated by the visions of the NSF, the metaphor of shaping atom-by-atom. *Fourth*, this reductionism is based on the naturalistic viewpoint of a closed causal reality and a cause-and-effect nexus of the world. *Fifth*, technological reductionism and the reductionism of the unification project of physics are somewhat similar. *Sixth*, I have sketched some arguments against technological reductionism by referring to recent physics of complex systems, nonlinear dynamics and chaos theory. *Seventh*, I added some remarks on the Baconian program which comes to a new summit in the context of nanotechnology, although it might fail. Conceptions of technology may shift from artifacts and procedures to media. *Eighth*, Technology Assessment of nanotechnology should encompass, as I have normatively stressed, concepts of Vision Assessment, especially to assess technological reductionism, and also the driving forces, the visions and desired states of a society of the future. *Technological reductionism* should be assessed in the horizon of our knowledge society. Further work needs to be done by the philosophy of science and cultural studies of technology to analyze it.

Notes

1 To a certain extend this standard conviction of the “covering law model” is misleading because many parts of the theories are incommensurable, as Thomas Kuhn and others have already shown.

2 Contrary to the rhetoric of the nanolobbyists, not a holistic (or system theoretical) but a reductionist metaphysics about reality is heuristically leading.

3 The founder of the modern philosophy of technology, E. Kapp, advanced a naturalistic understanding of technologies. Similar aspects can be found in the anthropology of A. Gehlen.

4 This suggests that he number “four” is the magic number of unification projects in physics as well as in technology.

5 I do not ask here whether technological reductionism is justified.

6 Action theoretical specifications are necessary.

7 The concept of constructo-realism has not been worked out yet.

8 So the NBIC-report lacks of two related inconsistencies, one concerning holism and reductionism, a second one between referring to “complex systems” and shaping the world from the bottom up.

References

Ahluwalia, P.: 1994, *Big Science in Canada: Resource Book for Science and Technology Consultations*, Ottawa: Industry Canada.

Bacon, F.: 1959, *Neu-Atlantis* (1627), Berlin: Akademie Verlag.

Bacon, F.: 1950, *Neues Organon*, Hamburg: Meiner.

Beckermann, A.: 2001, *Analytische Einführung in die Philosophie des Geistes*, Berlin/New York: de Gruyter.

BMBF: 2001, *Strategische Neuausrichtung der Forschung: Nanotechnologie in Deutschland*, Bonn/Berlin.

Böhme, G.; van den Daele, W. & Krohn, W.: 1974, 'Die Finalisierung der Wissenschaft', in: Diederich, W. (ed.): *Theorien der Wissenschaftsgeschichte*, Frankfurt: Suhrkamp, p. 276ff.

Böhme, G.: 1993, *Am Ende des Baconschen Zeitalters*, Frankfurt: Suhrkamp.

Carrier, M.: 2001, 'Business as Usual: On the Prospect of Normality in Scientific Research', in: Decker, M. (ed.), *Interdisciplinarity in Technology Assesment*; Berlin: Springer, pp. 25-31.

Cartwright, N.: 1999: *The dappled world: a study of the boundaries of science*, Cambridge: Cambridge University Press.

Cassirer, E.: 1985, *Symbol, Technik, Sprache*, Hamburg: Meiner.

Crandall, B.C. (ed.): 2000, *Nanotechnology. Molecular Speculations on Global Abundance*, Cambridge, MA: MIT Press.

Descartes, R.: 1979, *Regeln zur Ausrichtung der Erkenntniskraft*, Hamburg: Meiner.

Dierkes, M., Hoffmann, U. & Marz, L.: 1992, *Leitbild und Technik. Zur Entstehung und Steuerung technischer Innovationen*, Berlin: Sigma.

Drexler, K.E.: 1990, *Engines of Creation: The Coming Era of Nanotechnology*, Great Britain: Fourth Estate Limited.

Drexler, K.E.: 1992, *Nanosystems: Molecular Machinery, Manufacturing, and Computation*, New York: John Wiley & Sons.

Feynman, R.E.: 1959/2003, 'There's Plenty of Room at the Bottom', available at: http://www.zyvex.com/nanotech/Feynman.html.

Gamm, G.: 2000, *Nicht nichts. Studien zu einer Semantik des Unbestimmten*, Frankfurt: Surhkamp.

Gibbons, M. *et al.*: 1994, *The New Production of Knowledge*, London: Sage.

Grunwald, A. (ed.): 1998, *Rationale Technikfolgenbeurteilung. Konzeption und methodische Grundlagen*, Berlin: Springer.

Grunwald, A.: 2000, *Technik für die Gesellschaft von morgen. Möglichkeiten und Grenzen gesellschaftlicher Technikgestaltung*, Frankfurt: Campus.

Haraway, D.: 1995, *Die Neuerfindung der Natur*, Frankfurt: Campus.

Hume, D.: 1990, *Enquiries Concerning Human Understanding*, Oxford: Oxford University Press.

Kaku, M.: 1998, *Zukunftsvisionen. Wie Wissenschaft und Technik des 21. Jahrhunderts unser Leben revolutionieren*, München: Lichtenberg.

Kant, I.: 1989, *Kritik der reinen Vernunft*, Stuttgart: Reclam.

Klein, J.T.: 2001, 'The Discourse of Transdisciplinarity: An expanding global field', in: Klein, J.T. *et al.*, *Transdisciplinarity: Joint Problem Solving among Science, Technology, and society*, Basel: Birkhauser, pp. 35-44.

Latour, B.: 1987/1999, *Science in Action*, Cambridge: Harvard University Press.

Mehta, M.D.: 2002, 'Nanoscience and Nanotechnology: Assessing the Nature of Innovation in these Fields', *Bulletin of Science, Technology & Society*, **22**, no. 4, 269-273.

Nordmann, A.: 2003, 'Shaping the World Atom by Atom: Eine nanowissenschaftliche WeltBildanalyse', in: Grunwald, A. (ed.), *Technikgestaltung*, Berlin: Springer, p. 191-199.

Roco, M.C., Bainbridge, W.S. (eds.): 2002, *Converging Technologies for Improving Human Performance. Nanotechnology, Biotechnology, Information Technology, and Cognitive Science*, Arlington/Virginia: National Science Foundation.

Roco, M.C., Williams, S., Alivisatos, P.: 1999, *Nanotechnology Research Directions, IWGN Workshop Report. Vision for Nanotechnology Research and Development in the Next Decade*, Washington: NSF/CT.

Ropohl, G.: 1999, *Technologische Aufklärung*, Frankfurt: Suhrkamp.

Roukes, M.L.: 2001, 'Unten gibt's noch viel Platz', *Spektrum der Wissenschaft Spezial (Nanotechnologie)*, **2**, pp. 32-39.

Scheibe, E.: 1997, *Die Reduktion physikalischer Theorien*, Berlin: Springer.

Schmidt, J.C.: 2001, 'Was umfaßt heute Physik? Aspekte einer nachmodernen Physik', *Philosophia Naturalis*, **38**, 271-297.

Schmidt, J.C.: 2003, 'Wundstelle der Wissenschaft. Wege durch den Dschungel der Interdisziplinarität', *Scheidewege*, **33**, 169-189.

Schwarz, A.E.: 2004, 'Shrinking the 'Ecological Footprint' with NanoTechnoScience?', in: D. Baird, A. Nordmann & J. Schummer (eds.), *Discovering the Nanoscale*, Amsterdam: IOS Press, pp. 203-208 (this volume).

Serres, M.: 1992, *Hermes II.: Interferenz*, Berlin: Merve.

Smalley, R.E.: 2001, 'Chemie, Liebe und dicke Finger', *Spektrum der Wissenschaft Spezial (Nanotechnologie)*, **2**, p. 66-67.

Stix, G.: 2001, 'Little Big Science', *Scientific American*, **9**, 32ff.

Strand, R.: 2002, 'The Idea of Post-Normal Science', Lecture at University of South Carolina/Columbia, Nov. (draft).

Weizsäcker, C.F. v.: 1974, *Die Einheit der Natur*, München: dtv.

Weizsäcker, C.F. v.: 1985, *Aufbau der Physik*, München: Hanser.

Wiener, N.: 1968, *Kybernetik. Regelung und Nachrichtenübertragung in Lebewesen und Maschine*, Hamburg: Rowohlt.