

**Wissenschaftsethik und Technikfolgenbeurteilung**  
**Band 27**

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Schriftenreihe der Europäischen Akademie zur Erforschung  
von Folgen wissenschaftlich-technischer Entwicklungen  
Bad Neuenahr-Ahrweiler GmbH  
*herausgegeben von Carl Friedrich Gethmann*

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# Nanotechnology

## Assessment and Perspectives

With 189 Figures

 Springer

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Library of Congress Control Number: 2006921743

ISBN-10 3-540-32819-X Springer Berlin Heidelberg New York  
ISBN-13 978-3-540-32819-3 Springer Berlin Heidelberg New York

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Printed in Germany

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Typesetting: Köllen-Druck+Verlag GmbH, Bonn + Berlin  
Production: PTP-Berlin Protago-TeX-Production GmbH, Berlin  
Cover-Design: deblik, Berlin  
Printed on acid-free paper 62/3141/Yu – 5 4 3 2 1 0



## Europäische Akademie

zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen  
Bad Neuenahr-Ahrweiler GmbH

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*The Europäische Akademie zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen GmbH* is concerned with the scientific study of consequences of scientific and technological advance for the individual and social life and for the natural environment. The Europäische Akademie intends to contribute to a rational way of society of dealing with the consequences of scientific and technological developments. This aim is mainly realised in the development of recommendations for options to act, from the point of view of long-term societal acceptance. The work of the Europäische Akademie mostly takes place in temporary interdisciplinary project groups, whose members are recognised scientists from European universities. Overarching issues, e. g. from the fields of Technology Assessment or Ethic of Science, are dealt with by the staff of the Europäische Akademie.

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### **Acknowledgement**

The project “Nanomaterials, Nanodevices, Nanocomputing. Determination of Present Position and Perspectives” was supported by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung).

## Preface

The Europäische Akademie zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen Bad Neuenahr-Ahrweiler GmbH is concerned with the study of the consequences of scientific and technological advance both for the individual and social human life and for the natural environment. It intends to contribute to finding a rational way for society to deal with the consequences of scientific and technological developments. This aim is mainly realised by proposing recommendations for options of action with long-term social acceptance. The results of the work of the Europäische Akademie is published in the series “Wissenschaftsethik und Technikfolgenbeurteilung” (Ethics of Science and Technology Assessment), Springer Verlag.

This book is dedicated to Nanotechnology, considered by many as a key to the 21<sup>st</sup> century. This fascinating field of research and development is driven by inputs from different academic disciplines. Accordingly, conformal with its acknowledged work principle, the Europäische Akademie set up an interdisciplinary project group of recognised scientists from various European universities and other institutions to tackle the issue. I would like to give my thanks to Professor Dr. Günter Schmid (group chair), Professor Dr. Harald Brune, Professor Dr. Holger Ernst, Professor Dr. Armin Grunwald, Dr. Werner Grünwald, Professor Dr.-Ing. Heinrich Hofmann, Professor Dr. Harald Krug, Professor Dr. Peter Janich, Professor Dr. Marcel Mayor, Professor Dr. Ulrich Simon and Professor Dr. Viola Vogel for their cooperation as well as to Dr.-Ing. Wolfgang Rathgeber for coordinating the project on behalf of the Europäische Akademie and to Dipl.-Chem. Daniel Wyrwa for assisting the group. Special thanks go to Katharina Mader and Friederike Wütscher for the editorial work in preparing the text for print.

Bad Neuenahr-Ahrweiler, January 2006

Carl Friedrich Gethmann

## Foreword

Technological challenges, resulting from political, social, economic or ecological demands, can nowadays only be mastered by a strong integration of different scientific disciplines. This is especially the case in Nanotechnology, where the situation is arbitrarily complex due to the fact that Nanotechnology ranges over all disciplines of natural sciences including medicine and engineering. In nanoscience and -technology the classical differences between physics, chemistry and biology lose their significance, synonymous with a novel view of natural sciences. Nanotechnology is therefore much more than an other kind of discipline, based on nanoscaled products in the sense of a simple continuation of microtechnology. This description is by far too simple. The incredible chances and possibilities offered by Nanotechnology make it indeed the key technology of the new century, as is frequently reported.

Faced with the accelerating developments in nanoscience and, in consequence, in nanotechnology, the Europäische Akademie Bad Neuenahr-Ahrweiler GmbH started an initiative with the aim to evaluate the state of the art in nanoscience and nanotechnology, considering not only the natural sciences, but – to the same extent – philosophical, ethical, toxicological and, last but not least, economic aspects. Besides the description of the state of the present situation, the book also considers possible future developments as far as they can be foreseen and gives recommendations to decision makers.

The working group, consisting of internationally acknowledged experts from all fields of nanoscience and -technology, began its activities on 1st July 2003 and organized from this time on monthly working sessions. The project was finished on 31<sup>st</sup> December 2005. On 8<sup>th</sup> October 2004, a Mid-Term Meeting was held in the Academy with prominent representatives of all fields of nanotechnology for getting response and valuable critics on the project at that stage. For this unrenouncable help the group would like to thank Dr. Gerd Bachmann (VDI-Technologiezentrum Düsseldorf), Professor Dr. Peter Bäuerle (Universität Ulm), Professor Dr. Paul Borm (CEL Technohouse, Hogeschool Zuyd), Professor Dr. Harald Fuchs (Universität Münster), Professor Dr. Uwe Hartmann (Universität des Saarlands, Saarbrücken), Professor Dr. Christoph Hubig (Universität Stuttgart), Professor Dr. Martin Möhrle (Universität Bremen), Professor Dr. Reinhard Nesper (ETH Zürich), Professor Dr. Andreas Offenhäuser (Forschungszentrum

Jülich), Dr. Markus Pridöhl (Degussa AG, Hanau), and Dr. Eberhard Seitz (Forschungszentrum Jülich).

Personally, I am anxious to thank the members of the working group for the enthusiastic cooperation over two and a half years, the valuable contributions during the numerous intense discussions, the patience, and the absolute will to bring this difficult task to a successful end. Special thanks go to Dipl.-Kfm. Nils Omland (WHU Koblenz) for his assessment of patent data used in this study.

The group's work was exemplarily supported by the co-workers and members of the Europäische Akademie, among numerous others especially Mrs. Margret Pauels, Dr.-Ing. Wolfgang Rathgeber and Dr. Gerd Hanekamp. Their overwhelming hospitality contributed substantially to the effective study progress. The excellent working atmosphere caused regular anticipation of the next meeting by each group member.

Essen, December 2005

Günter Schmid

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The main interest of his current research are the possible health effects of metals and metal compounds, polybrominated hydrocarbons and ultrafine particles/nanomaterials. Furthermore, the establishment of new in vitro cell models for screening of toxic effects is one of the principle tasks.

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## Appraisal and Recommendations

By meeting at the nanoscale, the differences between classical disciplines, from physics via chemistry to biology, from engineering to medicine, are disappearing. Due to this merger of disciplines, our approaches to science and technology are fundamentally changing. The newly created knowledge base and resulting technological advances will revolutionize many sectors of our society. Consequently, the challenges and opportunities are multidimensional: scientific, technical, economical, cultural, ethical, educational and risk related.

### *Scientific and Technical Needs*

Research and development at the nanoscale will be key drivers to innovation and ultimately economic vitality. Central to such innovations are (a) nanotools to explore, analyze and manipulate at the nanoscale, (b) molecular assembly processes to construct novel materials and devices from nanoscale building blocks, (c) new concepts for information technology, (d) technologies to interface biological and synthetic systems and finally, the creation of a new knowledge base that will lead to major innovations in biological sciences and medicine.

*Nanotools:* The improvement of existing and the development of new tools is of decisive importance for any kind of techniques, however, it is the more the case for Nanotechnology. The state of the art in Nanotechnology could only be reached by fundamentally new tools. Analytic tools are the driving forces in Nanotechnology. For instance, without the development of scanning tunnelling microscopy (STM) and subsequently a dozen or more other scanning probe techniques, Nanoscience and -technology on the present level are unthinkable. Improved spectroscopic tools have become as important as modern high resolution electron microscopic devices allowing us the observation of biosystems in unexpected details. Modern nanotools in bio-nanotechnology will allow us to quantitatively understand how cells work. Intensive further research and development of nanotools is an unrenounceable condition for further progress in Nanoscience and -technology.

*Molecular assembly:* The assembling strategies are in part inspired by natural processes, from where we can learn how molecular systems interact in a pre-

dictable way in order to generate manifold structures and functionalities which range from simple control and molecular recognition to complex properties. Hence, future research should not only be focused on the duplication of biotic design principles, but nature's strategies shall inspire new solutions how to engineer at the nanoscale. Technologically relevant problems that could be addressed by bioinspired approaches include the self-assembly of three-dimensional electronic circuits or the development of new concepts of information technology beyond optics and solid state electronics. Going beyond biology, self-assembly strategies further need to be combined with micro- and nanofabrication tools which will ultimately result in materials and devices with integrated nanoengineered building blocks. A particular challenge in assembling nanoscale building blocks is to generate functions that go beyond the capabilities of the individual building blocks. Research on this topic has to aim at the development of quantitative and synthetic molecular construction techniques that lead to novel physical, chemical and biological functions. This will enable to combine the complex functionalities of large organic or bioorganic molecules with the size specific properties of inorganic nanoscaled objects following reliable design rules resulting in new emerging systems and properties.

*Information technology:* Information technology and enhanced miniaturization will profit from the understanding of nature's design and system's integration principles. Future nanoelectronics will essentially depend on the development of design rules for the set-up of complex architectures compatible with scalable technologies for the synthesis of the respective building blocks. This will by far exceed the present day paradigm of information exchange, since three-dimensional architectures will enable fundamentally new logical concepts. Furthermore, quantitative simulations and model building, as well as the integration of the myriad of digital information require major computational efforts.

*Interfacing biology with engineered systems:* Of particular interest is the interface between synthetic and living systems. Interfacing living cells with engineered nanosystems is needed for many biomedical applications, from tissue engineering, drug delivery to sensors implanted within human tissues to obtain real-time information on biological processes and functions. Considering the cost explosion of the health care sector, microfabricated platforms with integrated nanoscale systems are needed to build portable devices at low cost to analyze samples from body fluids and gases without major time delays.

*Nanotechnology in biosciences and medicine:* Today's medicine is often focused on developing therapies for preexisting diseases, often treating symptoms rather than curing the disease. In part, this is due to the lack of a comprehensive understanding of how cells work and how cell functions are regulated. Advances in Nanotechnology provide new tools to bring about

major changes leading to a transitioning of biology into a quantitative science. This includes how cellular building blocks are chemically modified typically in a spatiotemporal dependency, how they facilitate and interact in signaling pathways and other cellular processes, and how these building blocks are assembled and disassembled into larger functional units. Deciphering the hierarchical architecture of molecular networks and understanding the regulation is needed for the comprehension of biological systems on the nanometer scale. The technological advances will come from various disciplines and include the development of new nanoscale probes and imaging techniques in combination with intelligent computational tools to analyze molecular events in living cells with high spatial and temporal resolution. They will be complemented by new devices for in- and ex-vivo sensing and diagnostics. The goal is to ultimately derive the engineering principles that control and regulate cellular functions, from growth, differentiation, motility, contractility, to apoptosis. The biggest longterm pay-off for society might come from the early detection of diseases and their more effective treatment.

### ***Commercial Needs***

The patent analyses have shown that Europe is lagging behind Japan and the US in many fields of Nanotechnology. This finding could result from different perceptions about the effectiveness of patents as an important instrument for the creation of competitive advantages. Managers and policy makers must understand that professional intellectual property management is essential for the successful commercialization of Nanotechnology. Policy makers can give support by 1) creating a strong and attractive intellectual property regime, and 2) by providing the right intellectual property infrastructure at research institutions:

A strong intellectual property regime makes it possible for inventors to get an effective patent protection in all fields of Nanotechnology. Inventors can only leverage the advantages of patents (e.g., by means of licensing or the exclusive offering of products) in the field of Nanotechnology, if patent protection is legally strong. The attractiveness of patent protection is further impacted by the efficiency (time and money) of the patenting process at the various patent offices. The European patent system is not favorable to inventors, start-up firms and SMEs, because a common European patent does not exist and the costs of obtaining a European patent are too high, especially compared to the US. This institutional obstacle puts European inventors in an unfavorable position when it comes to protecting and commercializing new discoveries in the field of Nanotechnology.

Patents are an important instrument for knowledge protection and the creation of competitive advantages in many industries. Empirical research suggests that professional patent management and a strong portfolio of

high-quality patents are important drivers of business performance in high-tech industries (Ernst et al. 2005; Shane 2001). These findings should raise the awareness of the value of intellectual property among scientists and managers and must lead to initiatives to improve patent management in firms and research institutions. Professional patent management especially requires the establishment of the right organizational structures and the corresponding processes to handle patent-related matters in the R&D process. Start-up firms, SMEs and research institutions should benchmark their patenting activities against existing best practices in order to increase the proficiency of their patent management (Ernst et al. 2005).

The relatively low patenting activity in Europe should not be viewed as an indicator of inferior research performance. The analysis of scientific Nanotechnology publications clearly revealed that European scientists produce the most scientific publications in many fields of Nanotechnology. This finding leads to the conclusion that Europe faces the problem of transferring research results consequently and effectively into development and subsequently into commercial applications. European research institutions must therefore increase their willingness and their possibilities to move research results into the subsequent development of new products. This requires a change in culture, incentives and structures in many research institutions. A critical aspect in this regard is that it takes good management to turn research results into a successful new product (Brockhoff 1999; Hauschildt 2004). A scientist may not have the motivation or the capabilities to build up a management team or to found a start-up to commercialize research results. To avoid this pitfall, the formation of cross-disciplinary teams (esp. scientists and business people) at research institutions must be encouraged in order to successfully found and to spin-off start-up firms. New forms of collaborations between established firms and research institutions should be established in order to get market feedback early in the research and development process and to foster the knowledge transfer from research institutions into firms. Finally, the establishment of professional and capable technology transfer centers at research institutions, as e.g. in the US, can further improve the transfer of Nanotechnology from research into commercial applications.

### ***Societal and Ethical Aspects***

The further development of Nanotechnology should be accompanied by continuous research on the impact on environment and health as well as on ethical and political questions associated with possible risks, but also in view of the expected benefits.

Currently, classical risk assessment is – according to knowledge gaps concerning hazards resulting from nanoparticles – not applicable in the field of Nanotechnology. Quantitative measures of the probability of damage and of the extent of possible hazards are not yet available. Insofar it is not surprising

that lively discussions about the applicability of the “strict precautionary principle” take place in the industrialized countries. According to our analysis and to the review of the state of the art in toxicological research on nanoparticles given above we do not see a “reasonable concern” which would legitimate hard measures, like a moratorium, but with respect to responsibly dealing with artificially designed, new nanoparticles specific caution is required. Such particles should be handled analogously to *new* chemicals even in case that the chemical composition is well-known beyond the nano character. Dealing with new nanoparticles is still based on a case by case approach because established nomenclature and classification schemes are not well-prepared to be applied to nano-particles. Beyond risk management and regulation the level of public risk communication has to be observed carefully because irritations in this communication could have dramatic impact on public acceptance and political judgment. It is necessary to distinguish between scientifically assessed risks and the public perception of risk, which has to be taken seriously even in case that it seems to be inadequate against the results of scientific risk assessment.

Knowledge about risks includes knowledge about the validity and the limits of that knowledge. Communicative and participative instruments of technology assessment could help improving mutual understanding and public risk assessment. Scientists should not leave these discussions to the mass media and politicians but should engage themselves in those debates.

## **Education**

Education in the field of Nanotechnology is established on the level of bachelor, master and doctoral schools at only a few places. The reason for this can be found in the fact that Nanotechnology is a young research field with a very high degree of interdisciplinarity. Therefore, the content of teaching is not well defined and a job description for a nanoscientists or an engineer in Nanotechnology is also missing. Because the content of teaching depends very often on the background of the institute or department responsible for the courses, curricula focused on Nanoscience like physics of small systems, or on nanostructured materials and finally such that try to fulfil the demand for an interdisciplinary program in Nanotechnology are offered. The latter have the difficult problem to select the right courses as well as the right level of difficulty and of being too large and, because of time limitations, too superficial.

## **Recommendations**

1. The project group defines Nanotechnology based on effects and functions independently of any longitudinal measure. Size is relevant only derivatively and thus is not addressed in the definition. It is recom-

- mended that this definition as Nanotechnology in the narrower sense be used to specify the field. This narrowing of the scope is not supposed to preclude priority settings in research funding (s. chapter 2).
2. *Funding in Nanotechnology in Europe is mainly restricted to top-down target oriented programs. However, diversity of research approaches is a crucial requirement for knowledge creation and innovation. Therefore, funding priority should be given to basic research on a broad level and basic knowledge has to be better transferred by engineering science and technology into products.* This step has not yet been taken over by most of the industrial partners and the gap between basic research and application is still existing for many of those nanosystems with new functions. *It is therefore recommended to strengthen the efforts of transient research in this field and to encourage industry to better close the information gap between basis and practice (see chapter 3).*
  3. *It is also recommended to encourage the change in culture and incentives at universities and research institutions which are dealing with Nanotechnology versus new forms of collaboration to stimulate the transfer between scientific institutions and facilitate the contact to the industry (s. also chapter 4).*
  4. Materials (section 3.1) and their specific properties in the nanoregime create novel applications preferentially in the field of information storage systems (section 3.2), in biology and in medicine (section 3.3). The research in each of these fields needs profound knowledge of the experts, but for applying the materials an interdisciplinary knowledge exchange is indispensable. *It is recommended to create a pool of experts from the different branches who are acquainted with research and development and the industrial needs to support decision makers in politics and enterprises.* This kind of proceeding could also be developed for other potential fields of application (s. section 3.4) and *would help (s. recommendation 2) to close the gap between basic research and industry.*
  5. Many more of the inventions and innovations which have been and will be made in Nanoscience and Nanotechnology have to be patented to secure the intellectual properties of the inventor, the university and/or the industry. *As in Nanotechnology patents already have to be applied in the early stage of research and development, it is therefore recommended to establish a more attractive European Intellectual Property regime in order to foster the commercialization of Nanotechnology inventions and to improve the competitive position of European inventors and firms (s. chapter 4).* In regard to recommendation 2 it is also recommended to encourage and facilitate a professional Intellectual Property Management at universities and research institutions to support researchers in their business venture to transfer knowledge into application.
  6. There is a tendency to reduce research activities at the universities. This is problematic for two reasons: Firstly, excellence in teaching is tightly cou-

- pled with excellence in research. Secondly, diversity in basic research originates mainly from universities. Consequently, politics must provide sustainable strengthening of research capabilities at the universities (s. chapter 7).
7. The many and engaged debates about societal and moral aspects of Nanotechnology show a high degree of uneasiness among the population. Possibly adverse effects of nanotechnological products are presently discussed in the public mostly on the basis of speculations and many of these debates are very emotional and not based on facts. It is therefore recommended to identify risks in studies performed in related institutions and to place future debates on “facts and figures” so that society is informed in a transparent and understandable way by experts who are trained for this (s. also recommendations 8–10).
  8. Knowledge on the behavior of nanomaterials in living organisms and in the environment is largely missing. Research is now starting only at selected institutes and rarely as a combined activity between materials and bio-, medical research. *It is recommended to foster a common research based on similar standards so that results can be compared and industry can use the recommendations in their production of Nanotechnology based products. Regulations have to be reconsidered according to the outcome of research (s. chapter 5).*
  9. *ELSI (Ethical, Legal and Social Implications) activities should be specifically dedicated to recognisable ethical concern in specific areas of nanotechnological advance (chance/risk considerations, enhancement of human performance) and should be a parallel research activity to basic, materials/engineering research, industrial application and the medical observation of Nanotechnology risks (s. chapter 6).*
  10. The future of education in Nanoscience and Nanotechnology depends on the acceptance of Nanotechnology in the industrial environment. The more research activities can be transferred into products and the daily life, the more a profound education in all fields of Nanotechnology will be required. *It is recommended at this stage to educate students in one of the established domains like physics, chemistry, biology or engineering and to superimpose in a second stage the truly multidisciplinary education in Nanotechnology, for example at the master level or in graduate schools. In a parallel step, it is recommended to improve the continuous education of engineers, medical doctors and other people dealing with Nanotechnology so that nanomaterials are used in an adequate way without any healthy risks and by exploiting all the new and interesting functions of these materials (s. chapter 7).*

# 1 Introduction and Summaries

## 1.1 Introduction

Since Nanotechnology is considered a key to the 21<sup>st</sup> century, its promises have been assessed by various scientific communities. By meeting at the nanoscale, various disciplines, from physics via chemistry to biology, from engineering to medicine contribute synergetically to the newly created knowledge base and the resulting technological advances. Considering that large societal sectors will be impacted, the unique aspect of this 2-year study was to assess Nanotechnology from various interrelated perspectives: scientific progress, industrial relevance, economic potential, educational needs, potential adverse health effects, and philosophical aspects.

The goal of this study is to derive recommendations which consider the large range of societal implications reflecting the different views in an integrative manner. The study attempts to link previously isolated statements, bundling the various concepts and giving unified recommendations to decision makers in relevant society sectors as politics, economy and research. Special attention was given to the European situation with respect to commercial consequences, an aspect that turned out to have serious consequences.

The world is facing major challenges that cannot be sufficiently addressed by current technologies. These challenges include environmental protection, exploding health care expenses, as well as energy and resource limitations. While the large range of emerging nanotechnologies will not bring universal solutions, as sometimes misleadingly expressed in the public, Nanotechnology will most likely make essential contributions to addressing those challenges. In contrast, being of enormous societal relevance, Nanotechnology and its consequences are also subject of intense public debate. Fuelled by fears, anti-“Nano” campaigns and calls for a moratorium on any kind of Nano research are getting started. An early fact-based debate and risk assessment will enable society to get involved in addressing relevant questions and concerns, helping to avoid mistakes committed with the treatment of nuclear energy or genetically modified organisms, where lack of adequate public communication has led to broad front rejection of these technologies. Neither must risks be denied, nor must chances be overestimated – otherwise much harm could be done. An honest and transparent discussion is the basis for widespread acceptance of any new technology.

The Europäische Akademie GmbH has adopted the aim of discussing matters of technology assessment rationally, seeking an independent discourse with society. In accordance with the insight that technology assessment should be carried out in an interdisciplinary way, the group consists of chemists, physicists, engineers, biologists, toxicologists, philosophers and economists. Its scheme of work was to lead a dialogue across the borders of the disciplines. While desirable in any scientific endeavour, this way of operating was *essential* for the assessment of Nanotechnology where the traditional borderlines between established disciplines are disappearing.

The group's starting point was first to ask which properties and functions of materials are changing at the nanoscale in accordance with our definition (s. chapter 2) and then how those unique properties can be exploited for technological applications as summarized in table 3.1. Due to the endless range of potential applications, we then focused on emerging technologies in information storage (table 3.2) and major biomedical challenges (table 3.3). These tables served as a basis to organize our chapters, to highlight relevant technologies and comment on their respective relevance. The consequences following from these considerations are reflected in our recommendations. This structural organization is unique and gives fundamentally new insights into the treated matter. The book's overall setup becomes apparent by the summaries in the next subchapters.

There exist numerous other reports on Nanotechnology. These reports, however, stretch different aspects of Nanotechnology and take approaches that are not comparable to ours. Usually, they follow a descriptivistic line, not questioning the label "Nano" attributed to various fields of science and technology by various actors, and examine typical or exemplary application areas and related societal implications (Paschen et al. 2004). This conception is adequate for giving a survey of Nanotechnology in a wider sense. In contrast to that, we introduce our own definition and concentrate on Nanotechnology in a stricter sense. This enables us to set an orientation mark throughout the whole book.

There are topics we did not consider in our study. For example, Intellectual Property (IP) problems of Nanotechnology have not been treated due to the fact that the corresponding legal questions remain unsettled so far. Besides, they are not of decisive importance for the ends of this study. However, the authors are aware that this topic will play a significant role in the further commercial development of Nanotechnology. Neither were the juridical aspects of risk management treated in chapter 5 due to size limitations. Also, the tables of chapter 3 may miss some entries. This is either because we do not know them – due to conscious or unconscious lack of knowledge – or because we feel that they will not play a significant role in the further development of Nanotechnology. Besides, this work was not driven by an encyclopaedical impetus. We just tried to discuss subjects we consider representative for this fascinating field of science. Hopefully, this will contribute to a clearer picture of what Nanotechnology is today and what it could or should be tomorrow.

## 1.2 Summaries

### **Chapter 1: Introduction and Summaries**

The general idea of the study was a multi-perspective treatment of Nanotechnology leading to integrated acting recommendations. Public perception of Nanotechnology with its hopes and fears entails the goal of a transparent technology discussion which is based on facts. Technology Assessment (TA) can be carried out in a variety of ways. The approach of the Europäische Akademie zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen Bad Neuenahr-Ahrweiler GmbH (European Academy for the Study of Consequences of Scientific and Technological Advance) is an interdisciplinary treatment by experts from different science branches. The way of work and the methodology of the project group “Nanomaterials, Nanodevices, Nanocomputing. Determination of Present Position and Perspectives” determine the structure and contents of this book. No claim for completeness is stated, instead only selected aspects of Nanotechnology of exemplary character are treated.

### **Chapter 2: Nanotechnology and Philosophy of Science**

Theory of science reflects research practice of sciences and their results with the aim of critically checking subjects and methods (technical laboratory methods as well as term and theory formation procedures) relatively to the claims and aims of the researchers. Questions of different subject determinations of the nano domain, of measurement techniques in the nanoscale (against the background of historical controversies), different forms of (constructive or empirical) progress and the principle of methodical order for the orientation of theory along laboratory techniques have to be treated as well as aspects of discovery, invention and application, which can be judged as researchers' actions following purposes and means. Known distinctions include the ones between nature and technology or between top-down and bottom-up approaches. Conclusions with respect to the understanding of traditional disciplines and of new microscopy techniques arise. Further conclusions refer epistemically to the character of Nanotechnology as paradigm change, ethically to the acceptability of research consequences and side effects, and politically to the question where research aims and purposes come from.

On the basis of these considerations, the authors suggest a new, recursive definition of Nanotechnology: *Nanotechnology comprises the emerging applications of Nanoscience. Nanoscience is dealing with functional systems either based on the use of sub-units with specific size-dependent properties or of individual or combined functionalized subunits.*

Conceptually different from Nanotechnology as defined above are *scaling effects*, where laws that already hold in the macroscopic world are just trans-

formed to other size scales by miniaturization of existing structures. Nevertheless, many of these effects are designated as Nanotechnology in common language use and play an important role. Thus, some of them are mentioned in the course of the book. The authors of this study agree that lateral dimensions between 1 and 100 nm can be a good indicator of Nanotechnology, but decided not to include this size specification in their definition to stress the decisive importance of specific size-dependent properties.

### ***Chapter 3: Fields of Research and Technology***

In chapter 3 all physical, chemical, material, and biological effects and connections, summarized in tables 3.1-3.3, are discussed and assessed in appropriate length. From these texts result the recommendations presented in "Appraisal and Recommendations". The explanations concerning table 3.1 are dealing with the detected nano-effects in agreement with the definition in chapter 2, resulting from the combination of physical and chemical properties. Important developments in this sense are, for instance, high-strained and transparent ceramics based on nanoscopic building blocks. Other forward-looking developments are linked with quantum size effects. Table 3.1 also contains molecular units that are either functionalized units by themselves like molecular magnets or that are used as building blocks for the construction of more complex systems from which, for instance, molecular motors, machines or switches can be developed. Also the so-called supramolecular chemistry offers great opportunities to generate nanoscaled systems with hitherto unknown properties.

The evaluation of the effects captured in table 3.2 is of special future relevance, since they all open novel opportunities on the field of data storage and future computer generations, respectively. There exist already technologies in the test phase, for instance the Millipede system. Others, like the quantum dot computer or even the quantum computer are still in the state of fundamental research. This is also valid for storage capable and switchable molecular systems or optical computing. Further developments of the Atomic Force Microscopy (AFM) promise numerous applications. Examples are the Magnetic Force Microscopy (MFM) and the Magnetic Resonance Force Microscopy (MRFM), promising candidates for the optimization and practical applications of nano-sized magnetic systems. Scanning-Near-Field Optical Microscopy (SNOM) and Scanning-Near-Field Magneto-Optical Microscopy (SNMOM) represent new optical procedures with a dispersion below the wavelength of light.

The consequences from table 3 reflect the possibilities for the use of biosystems in combination with artificial building blocks. These lead to completely new approaches in medicine, whereby the further development of nano-tools is of considerable importance. The dominating tendency in the living nature for self-assembling can be utilized to transfer artificial nano-building blocks with biomolecular units into novel hybrid systems. The interaction of nanoparticles with biosystems also gives rise to critically

assess toxicological aspects. Here, transport mechanisms through living systems play a dominant role. A better understanding of transport mechanisms will help to reliably assess the health risks originating from nanoparticles.

In contrast to the strict scientific definition in chapter 2, the expression “Nanotechnology” is commonly also used for proceedings which would be better described by “Scaling Effects”. It is the matter of size-dependent behaviour that develops continuously from microscopic to nanoscopic dimensions without coming to a significant change of properties at a distinct dimension. Possibly, in the nanometer regime the phenomena may become stronger or even weaker. Examples of successful scaling effects are, for instance, the self-cleaning (Lotus effect) or the antireflection behaviour (moth eye effect) of micro-/nanostructured surfaces. In order to take these developments into account, some relevant examples are listed at the end of the chapter, but are not part of the tables and the related texts.

#### ***Chapter 4: Commercial Perspectives of Nanotechnology***

Technological and economic opportunities in the field of Nanotechnology are assessed based on the analysis of patent data. Such patent data analyses are an adequate approach to analyze development trends in the field of Nanotechnology. Patents have been found to correlate significantly with the level of R&D expenditures and the probability for successfully commercializing these R&D results. There are different tools and methods for the assessment of patent data. The meaningfulness of information gained hereby depends largely on the specific analytical tool used for the examination. Multiple indicators for analyzing the patenting behavior of inventors, companies, regions, countries etc. exist. Such patenting indicators and portfolio illustrations are used for the presentation of the results gained by the study.

The patent analyses differentiate according to the specific sub-fields of Nanotechnology as defined and explained in the previous chapters of this book. The patent analyses are based on the number of patent families filed between 1983 and 2002 in the major industrialized countries in the field of Nanotechnology. The patent analyses indicate the importance, the growth dynamic and the patent position of European inventors relative to other countries for each sub-field of Nanotechnology.

One important result of the patent analyses is that Europe’s patent position is weaker compared to the USA and also Japan in many fields of Nanotechnology. Especially the USA have a dominating patent position in almost every field of Nanotechnology. Europe should therefore take initiatives to improve its patent position. This includes in particular strengthening basic research in Nanotechnology to create long-term and sustainable competitive advantage; increasing the awareness of the value of intellectual property rights for creating a competitive advantage and for attracting venture funding for Nanotechnology enterprises; establishing an attractive European Intellectual Property regime for inventors and entrepreneurs; introducing