1. INTRODUCTION

AUTHOR: H. Dosch
[Affiliation chapter 12]

1.1. WHAT IS NANOMATERIALS SCIENCE AND NANOTECHNOLOGY?

Nanoscience and nanotechnology are based on the control of the structure and function of materials on the nanometre scale, i.e. on the scale of one billionth of a metre. The gateway to nanoscience and nanotechnology has been opened more than 100 years ago, when W.C. Röntgen discovered the x-rays which allowed us to unravel the nanoscale structure of matter and when Planck, Heisenberg, Schrödinger, and Einstein developed the language of the nanocosmos: quantum mechanics. During the last 100 years, a truly breathtaking scientific and technological development has taken place, which can be illustrated by quoting three scientists:

1900, Ernst Mach: "Atoms cannot be perceived by the senses. They can never be seen or touched, and exist only in our imagination."

1950, Richard Feynman: "The principles of physics do not speak against the possibility of manipulating things atom-by-atom."

2000, Sir Richard Smalley: "Nanotechnology is the art of building devices at the ultimate level of finesse: atom-by-atom."

Nanotechnology is a collective term for a set of technologies, techniques and processes – effectively a new way of thinking – rather than a specific area of science or engineering. Just as electronics and biotechnology have created their own technological revolutions, nanotechnology will have a similar impact; in some areas sooner rather than later. Often referred to as 'convergent technology', nanotechnology is an interdisciplinary ensemble of several fields of the natural sciences that are in themselves highly specialised. The ultimate atom-control of the nanosize and shape as well as of the nanogeometry of novel materials and materials architectures will open up a third dimension on the Periodic Table.

Only few industries will escape the influence of nanotechnology. Faster computers, advanced pharmaceuticals, controlled drug delivery, biocompatible materials, nerve and tissue repair, surface coatings, better skin care and protection, catalysts, sensors, telecommunications, magnetic materials and devices – to name but a few of the areas where nanotechnology will have a major impact. In effect, nanotechnology is a radically new approach to manufacturing. It will affect so many sectors that failure to respond to the challenge will threaten the future competitiveness of a large part of the economy.

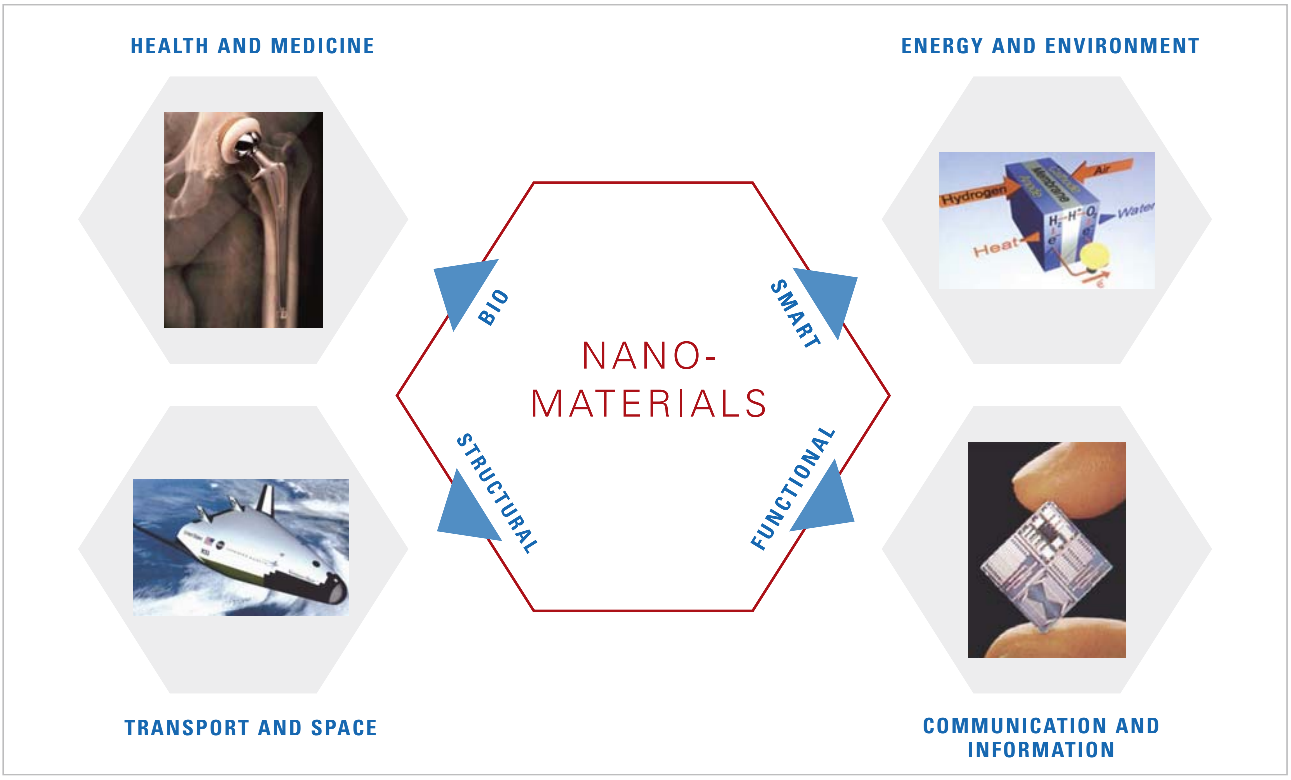

Fig. 1.1: The impact of nanomaterials in industry and society.

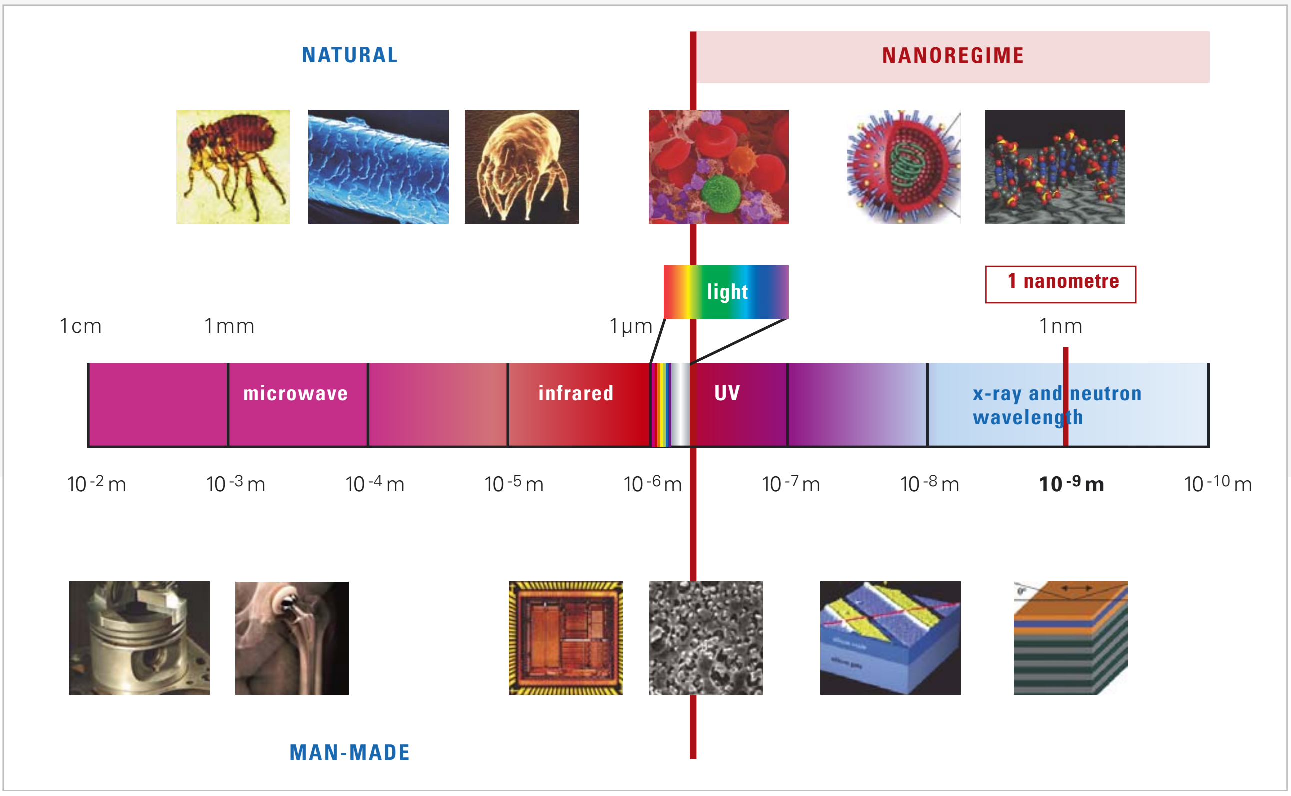

Fig. 1.2: Typical length scales in current and future technologies.

1.2. NEW MATERIALS FOR NEW TECHNOLOGIES

Advanced materials are a prerequisite for all major research and development areas and for all key technologies ranging from information and communication, health and medicine, energy and environment, to transport and space exploration. Sophisticated materials and materials systems with novel properties and unheard of performance will have to be conceived and designed in the decades to come. This will be imperative if the European high-tech industry is to remain competitive and if a high standard of living is to be guaranteed for the European citizen in the 21st century.

The development of the materials of tomorrow will make increased use of new nanoscience concepts, i.e. the design of artificial material structures within the ultimate limit – atom control. New nanofunctions will be created by the control of size and shape of the nanoparticles as well as by the controlled interactions between them across tailored interfaces. In this way, future materials research will open up a new dimension in the periodic table allowing new materials functions beyond the properties tagged by nature to the elements. These future visions of nanomaterials science bearing on the virtually infinite possible materials combinations and on the resulting emergent phenomena have been anticipated by Richard Feynman's "There is plenty of room at the bottom" and Phil W. Anderson's "More is different".

It is expected that new nanomaterials will find their way into almost all future technologies: New nanoparticle-reinforced and light-weight materials will be used for transport technologies; new storage media based on nanolayers and quantum dots will revolutionise information

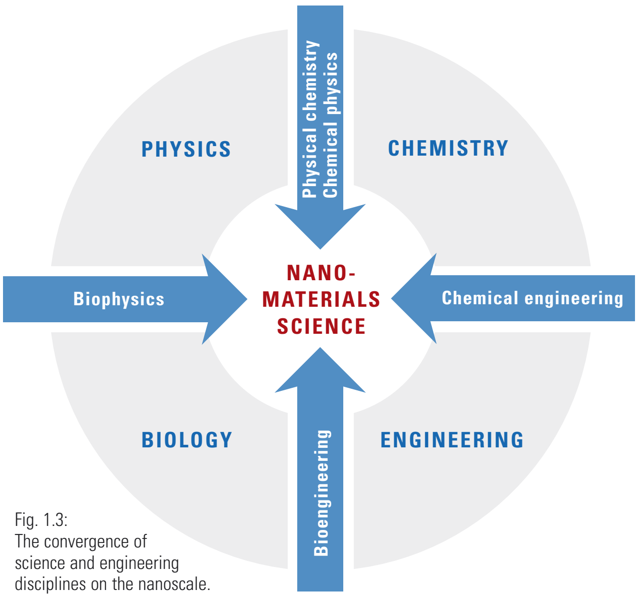

Fig. 1.3: The convergence of science and engineering disciplines on the nanoscale.

technology; new materials based on nanoparticles will be employed in catalytic reactors; new pharmaceutical nanomaterials will serve in drug delivery, and new charge separation materials will enhance the performance of future batteries and fuel cells, to name but a few examples of new applications.

Future nanotechnology will be enabled by enhancing fundamental research in the critical areas of nanomaterials synthesis, nanomaterials analysis, and nanomaterials modelling. In all these areas there are major challenges to be met and barriers to be overcome. More specifically, it is necessary that we:

- Achieve a much better control of the size and shape of the primary nanoparticles in order to exploit their full potential ("precision synthesis");
- Develop a new level of analytical capability for the in-situ and destruction-free characterisation of nanomaterials and nanodevices under the relevant operating conditions as well as with the highest resolution and sensitivity;
- Develop a detailed microscopic understanding of how a given artificial nanoarchitecture and its properties are related.

The development of new nanomaterials will no longer be limited by our resources, but instead by our knowledge. The design of such "knowledge-based materials" requires new concepts which will *inter alia* be based on two interdisciplinary strategies:

• **"Interdisciplinarity I":** The expert input from the field of physics, chemistry, engineering, and biology is required. This poses a challenge both for future research structures, as well as for the future training of young scientists who not only have to remain experts in their own field, but must also improve their literacy in neighbouring fields.

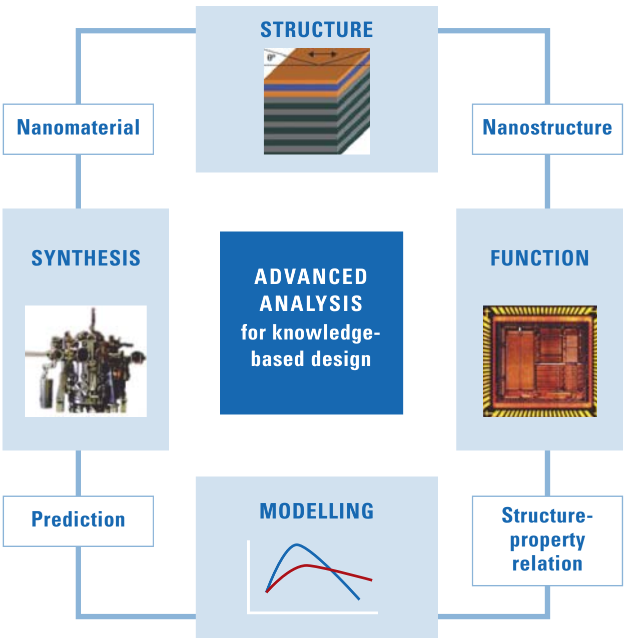

Fig.1.4: Role of advanced analysis for nanomaterials science and nanotechnology.

• **"Interdisciplinarity II":** It is mandatory that the experts in materials synthesis collaborate intimately with the experts in materials analysis, materials functions and with experts in materials modelling. It is only with the detailed knowledge of the microscopic structure of the grown nanomaterial at hand that a microscopic structure-function relationship can be obtained. This knowledge can then be cast into theoretical models which carry sufficient predictive power to modify the synthesis parameter in the most promising direction.

It is apparent that our future capabilities in nanomaterials analysis will play a key role for the advancement of nanomaterials and nanotechnology. New types of interdisciplinary materials science centres must include a new level of analytical capability. Such new "Science Centres" will integrate new nanomaterials synthesis capabilities with an in-situ and non-destructive analytical infrastructure of the function, performance, and failure behaviour of nanomaterials and nanodevices as well as with the necessary computing capacities.

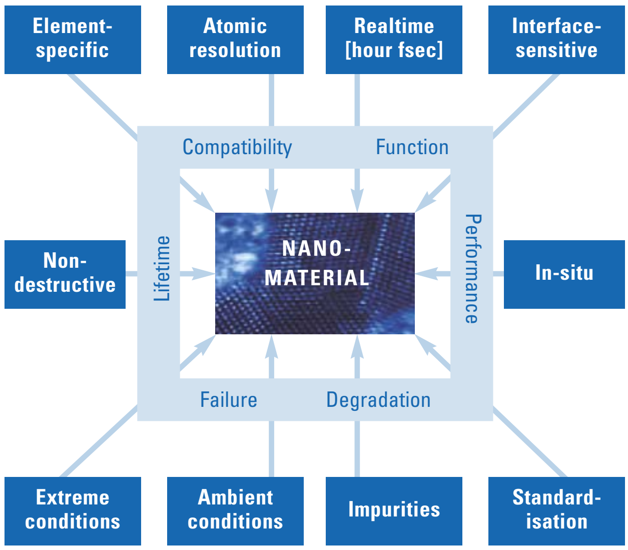

Fig.1.5: Future analytical need for the development of nanomaterials.

1.3. FUTURE ANALYTICAL CHALLENGES

The advanced analysis of nanomaterials is the future enabling technology for the development of novel materials and nanodevices. Detailed knowledge of the chemical, electronic, and magnetic structure of nanomaterials is a prerequisite to tailor their functions in a controlled way, and to develop microscopic models with predictive power. This includes subtle structural details, such as strain profiles across interfaces with picometre resolution, impurities and composition variations with single atom detection capabilities, or the precise separation of spin and orbit contributions to a local magnetic moment. In the next two decades, the need from nanoscience and nanotechnology to obtain these important microscopic insights into their nanomaterials

and -devices in-situ, in a non-destructive way and under industrially and environmentally relevant conditions will increase exponentially.

While the traditional analytical tools of the materials scientist, i.e. transmission electron microscopy together with routine spectroscopy and routine x-ray and neutron diffraction (i.e. power diffraction and small angle scattering) have been very efficient for traditional materials research, these tools cannot meet the aforementioned challenges of tomorrow's nanomaterials design.

1.4. THE EUROPEAN SYNCHROTRON RADIATION AND NEUTRON FACILITIES

The European Synchrotron Radiation and Neutron Facilities provide an exquisite analytical potential for the detailed analysis of nanomaterials. Starting as research laboratories pioneering the use of neutrons and synchrotron radiation, they have developed into dedicated, user-friendly facilities offering their clever analytical solutions to external research groups.

X-rays and neutrons are generally known to be bulk-sensitive techniques that provide "average structural information" for a given material. However, sophisticated new concepts, developed at these facilities in the past twenty years, have completely changed this situation. New diffraction and spectroscopy schemes, new focusing optics, new imaging and microscopy concepts having been worked out along with the development of more brilliant and more powerful sources now allow for a revolutionary new analytical access to nanomaterials.

Europe's synchrotron radiation and neutron facilities have developed a European network simultaneously ensuring synergetic development of key technologies for the future demands in advanced analysis as well as a coordinated user service.

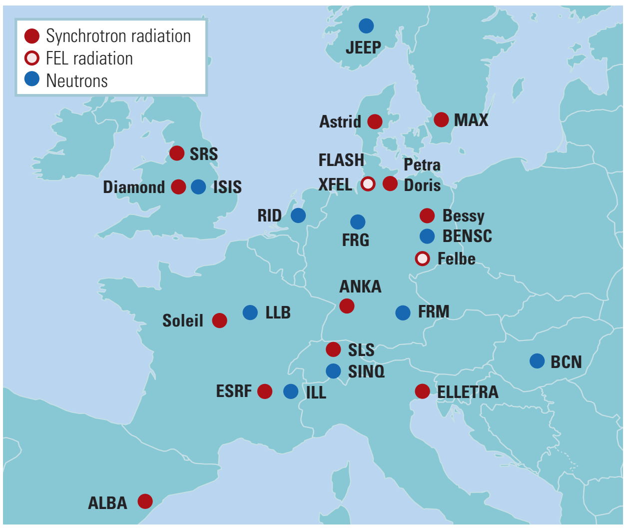

Fig. 1.6: European research infrastructure for the fine analysis of matter.

1.5. GENNESYS: A NEW NANOMATERIALS STRATEGY FOR EUROPE

In the last two decades, the synchrotron x-ray radiation and neutron facilities in Europe have developed a highly sophisticated and reliable analytical technology which carries the potential to meet the future analytical challenges for the development of new nanomaterials and the advancement of nanotechnology. It is thus rather surprising that the two scientific communities, the nanomaterials laboratories on the hand and the large scale facilities on the other hand, have developed rather independently and are thus largely unaware of each other's existence.

At present, the materials science and synchrotron radiation and neutron communities carry out research virtually separately. Synchrotron radiation and neutron facilities have developed revolutionary new ideas and experimental schemes to characterise nanomaterials, nanophenomena, and nanoprocesses in a most sophisticated manner, but they are largely unaware of the trends and needs in the nanolaboratories. Likewise, most of the nanomaterials and nanotechnology scientists have only little information on and limited knowledge about the enormous analytical potential provided by the synchrotron radiation and neutron facilities and its use for solving their problems. It is apparent that this fragmentation of efforts has to be overcome, if Europe wants to stay competitive with the nanoscience and nanotechnology development in the USA and in Asia. It will become an important task of European science policy to set up efficient European research structures leveraging the current and future potential of the European large scale facilities for synchrotron radiation and neutron science for the development of nanomaterials and nanotechnology.

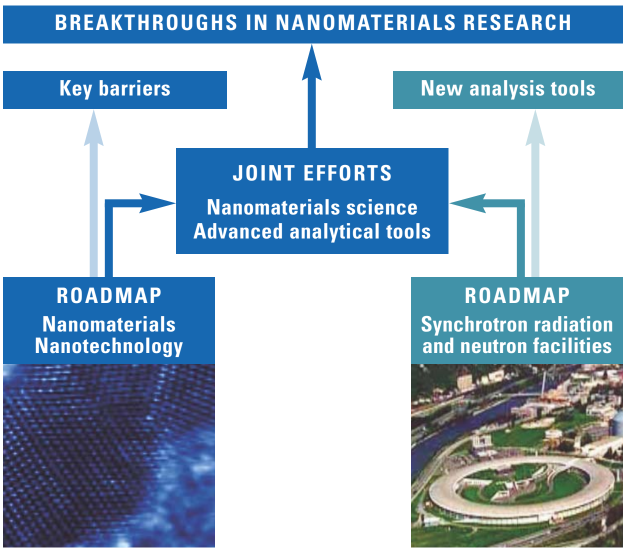

Fig. 1.7: The GENNESYS objective.

The Grand European Initiative on Nanoscience and Nanotechnology using Neutron and Synchrotron Radiation Sources (GENNESYS) has been initiated to achieve this goal and to develop new European research strategies to facilitate joint efforts between the nanomaterials science and the European large-scale facilities for the advanced analysis of materials in order to overcome the key barriers in the development of nanomaterials and nanotechnology that are already visible on the horizon.

This White Paper gives a condensed report on the major findings, conclusions and recommendations of the GENNESYS project for the various fields of nanoscience and nanotechnology. Several general problems have been disclosed by the GENNESYS task forces in current materials science efforts:

- **Lack of public awareness:** While all future technologies rely on the precise and dependable performance of specialised materials, the role of materials science is often not appreciated by the public because its activities generally take place in the background.

- **Fragmentation of materials research efforts:** Materials science in Europe is severely fragmented, as research is often performed within isolated and subcritical efforts.

- **Communication gap between nanomaterials science and large-scale facilities:** Nanomaterials research is frequently based solely on lab-based research tools and researchers are generally unaware, or cannot access the enormous potential of neutron and synchrotron characterisation techniques. In turn, the management of neutron and synchrotron x-ray radiation facilities only have rather fragile information on the actual and future analytical needs in nanomaterials research.

- **"Horizontal challenges meet vertical structures":** Nanomaterials research is an interdisciplinary ("horizontal") effort integrating the traditional branches of natural sciences and engineering and, in the future, integrating nanolabs and large-scale facilities. In the meantime, national and European funding structures have, however, developed along the traditional ("vertical") lines.

It is hoped that the roadmaps presented in this GENNESYS White Paper will provide a point of reference for policymakers as well as the operators of large-scale facilities. It is envisaged that GENNESYS will serve as a novel and world-wide unique platform for scientists to foster future collaborative, cross-disciplinary research and development, and to stimulate growth in the commercial exploitation of nanomaterials science and technology in Europe.

GENNESYS strives to integrate nanomaterials research, nanomaterials industry, and the European research infrastructure (synchrotron x-ray radiation and neutron facilities) in overcoming the key barriers in the development of new materials for future technologies.

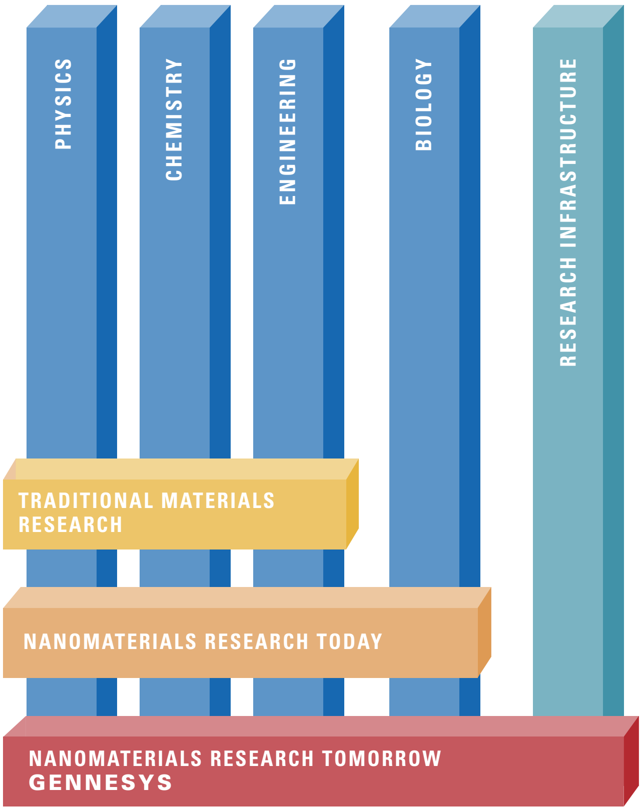

Fig. 1.8: The envisaged future GENNESYS platform.