DEFINITION
The field 'nanophysics and nanotechnology' entails research of physical phenomena in structures controlled on a length scale of 1-100 nm, and applications of these phenomena in functional devices. The field now allows the control and study of nanoscale objects and structures, revealing the properties of individual entities therein, e.g. single atoms on a surface, single electrons in a junction, single photons in a nanocavity, single molecules in solution. Driven by scientific curiosity and supported by novel materials and nanofabrication technologies, novel single-X systems are being investigated and regularly new physical phenomena are being discovered.

VISION: MORE COMPLEXITY
In the next ten years, we anticipate the field to increase in complexity in at least three ways.

First, the properties of nanosystems of interest will be increasingly governed by interactions between degrees of freedom (spin, charge, polarization, energy, etc.). No longer will a single degree of freedom be controlled by, e.g., nanogeometry, but the interplay between degrees of freedom will need to be controlled on a wide range of timescales. The increase of the intricacies of future nanosystems will set high demands on nanofabrication technologies and constituent materials. Top-down approaches (optical, e-beam, nanoimprint, scanning probe, etc.) will be combined with self-assembly approaches to control also the smallest length scales (atomic, macromolecular, colloidal).

Secondly, as the role of interactions increases, nanosystems will be probed and controlled to a greater extent by fields (electromagnetic, acoustic, etc.) rather than by direct contact, i.e., mechanical or galvanic. This will have profound consequences for the future toolkit for nanophysics investigations and characterization.

Thirdly, nanoresearch and -applications will occur more and more at the interfaces between physics, technical sciences, chemistry, and biology. In addition to expertise in experimental and theoretical physics, nanophysics research requires expertise in materials science, nanofabrication, and (bio)chemistry. We foresee that the importance of multidisciplinary excellence will continue to increase in the coming years.

DUTCH NANO RESEARCH STRENGTH
Dutch nanophysics research is characterized by a high productivity of excellent quality. The Netherlands houses a large number of nanophysics researchers, many of whom are the recipient of prestigious personal subsidies and prizes. The Dutch universities are active on various aspects of nanophysics/-technology, often organized within dedicated institutes. The FOM Institute AMOLF and interdisciplinary institutes in Twente, Groningen, Nijmegen, Eindhoven, Leiden, Amsterdam (VU, UvA), Delft and Utrecht have sizeable NANO programmes with a strong interplay between theory and experiment. In addition, a large number of nanoscientists are active in a number of large companies and small and medium enterprises (SMEs).
Most nanophysics research themes are pursued at various locations in the Netherlands, often in the context of collaborative, national programmes (FOM, NanoNextNL, Smartmix, etc.). Specific themes are very strong in the Netherlands, e.g. quantum-nano-electronics, functional nanomaterials, nanophotonics, nanofluidics and functional nanocolloids and self-organization. It is essential to maintain and grow the Dutch expertise in nanophysics and nanotechnology.

DEFINITION OF IMPORTANT THEMES

It is useful to make a distinction between research on new concepts, research on new instruments and research on new materials. On the one hand, fundamental questions arise because nanostructures behave fundamentally differently from bulk materials, while on the other hand new scientific questions in this field can be addressed because technological developments make it possible to fabricate, manipulate and study materials on the nanoscale in new ways. All three of these approaches are necessary to contribute to the development of new insights, new functional structures and new devices.

Beyond Moore

The end of Moore’s Law, which describes the exponential progressing miniaturisation of electronics, is in sight. While state-of-the-art (nano)engineering have in the past years effectively postponed this end, the physical universe will finally preclude the exponential trend to continue beyond the scale of one or a few atoms. Actually, well before that ultimate length scale is reached, heat dissipation will already prove to be an insurmountable obstacle in traditional CMOS technology. New technological incentives and accompanying research perspectives have therefore been developed alongside the pursuit of driving CMOS-scaling to the utmost (‘More Moore’). On the one hand, research aims at new platforms (such as molecular platforms and graphene) and concepts (such as spintronics and quantum algorithms) that might follow up silicon-based CMOS, a trend also known as ‘Beyond CMOS’. On the other hand, efforts are made, within a ‘More than Moore’ perspective, to produce completely new functionalities and integration of diverse functionalities on a single chip surface as well as the implementation in new surroundings (e.g. system in foil). Finally, disruptive technologies, based, for example, on neural networks, three-dimensional architectures and interfaces with biological systems, may enable a completely new approach to ICT processes. These developments underline the increase of complexity and multidisciplinarity of future nanoscience.

The chosen approach is referred to as ‘Beyond Moore’. This theme targets new concepts for chip-based structures and devices with electronic, magnetic and optical functionalities. The approach includes research into new platform concepts such as lasers based on nanothreads, LED’s based on plasmons, displays based on carbon nanotubes, molecules as the basis for electronics and the use of (nanostructured) graphene. On top of that, attention is paid to completely new concepts, for example, those based on the application of charge or energy quanta, spin polarised currents, nuclear spins or molecules in new ways of data storage and processing, quantum entanglement in optical or electronic logic, and new frequency regimes (THz-radiation) for imaging.

These new developments are, in most cases, founded on completely different physical concepts and classes of material than ‘Moore’ technology. In particular, the useful exploitation of the interactions between several different degrees of freedom will greatly expand the application potential, while requiring new investigations of the underlying physics.
Firstly, the theme 'Beyond Moore' aims at nanoscale optical and electronic phenomena with applications in lighting, displays, data storage, lithography, sensors, actuators and 'nano-energy'. This theme capitalises on existing fortes in the Netherlands in the field of fundamental nanophotonic and nano-electronic studies. Secondly, this theme aims at new concepts for molecular scale devices and integrated circuits. It also builds on the Dutch strengths in the field of optical and electronic phenomena in organic materials and graphene. Glimmering at its horizon are new molecular memories, more complex bio-electronic integration and also the application of molecular machines. Thirdly, GHz/THz electron and spin dynamics are targeted. Building on the rising fundamental knowledge in several Dutch research groups, spin-electronics and quantum simulation computing are a long-term prospect with immense potential.

Nano-instrumentation

The Dutch physics community holds a strong position when it comes to developing novel instrumentation. These instruments enable the study, imaging, and fabrication of materials at the nanoscale.

Nano-instrumentation in itself is a challenging proposition because of the inherent size of the entity to be investigated or fabricated. For the nanofabrication the challenge is obvious: for sculpting matter on length scales approaching the atomic one, atomic/molecular control is required. As the length scales decrease, the role of thermodynamics increases. This is particularly true for so-called chemistry-inspired bottom-up techniques. While the CMOS-based industry has come a long way, developments away from CMOS (see 'Beyond Moore') will have a profound impact on commercial nanofabrication instruments, like ASML's wafer steppers. The challenge of nanoscale investigations comes in two parts. Firstly, the entity to be investigated is small so the typical signal-to-background (STB) of measurements is low. In some cases, e.g. in a scanning probe microscopy experiment, the STB is excellent, but only a small fraction of a larger structure is imaged. Secondly, as the entity to be investigated is small, it is very easy to perturb the phenomenon of interest by the measurement itself. It is a large challenge to translate solutions found in a research setting to a commercial setting, where high throughput and reproducibility are at a premium. In the near future these challenges will grow further as more than one degree of freedom need to be controlled.

The Dutch community has a strong background in imaging-technology on the nanoscale. Improving microscopes to obtain higher resolution and speed, to operate them less destructively, more user-friendly, under a wider range of conditions and in a combination with other imaging modalities, has two advantages. It not only facilitates researchers to be the first with a new discovery, it also leads to valorization when these instruments can be sold commercially. The same holds for the development of lithography machines, novel (photon) detectors, the manipulation and growth of materials, such as in pulsed layer deposition, atomic layer deposition, etc., as well as quantitative measurements of composition, physical properties and organization of nanostructures.

Advances in nano-instrumentation will also have immediate impact in other disciplines like biology, engineering, chemistry and astronomy.

Nanoscale metamaterials

This theme entails the study of the physics of materials that gain controllable properties through their nanogeometry. Sometimes the term metamaterials is associated only with optical properties. Here, we refer to metamaterials in the broader sense, namely materials in which
nanostructuring leads to novel optical, electrical, magnetic, mechanical, biological etc. properties. The materials are built from nanoscale building blocks, such as inorganic solids, macromolecules (e.g. synthetic polymers and biopolymers), colloidal nanoparticles, and lipid vesicles.

The design toolbox of nanoscale metamaterials is rapidly increasing and sophisticated hybrid constructs are being realized, e.g. plasmonic nanoparticles combined with biopolymer origami. The systems are fabricated mostly by combining self-assembly approaches (atomic, macromolecular, colloidal) with top-down approaches (optical, e-beam, nano-imprint, scanning probe, etc.). The materials can have spectacular physical properties and novel functionalities, as single objects (e.g. in a nanochannel or a nanopore) and within ensembles (e.g. as interacting colloids). Nanostructuring ‘traditional’ condensed matter systems leads to a variety of novel electric and magnetic phenomena due to bandstructure modification and the increased role of interfaces, as is reflected by the expanding field of topological insulators. The resulting systems invariably have a multi-scale character, on one end showing the behavior of the individual nanoscale building blocks and on the other end showing the behavior of the total system. The scientific challenges for the nanophysicist are to measure the physical properties of the systems (in isolation and within device environments), to understand their behavior (optical, electrical, magnetic, mechanical, biological, etc.), and to reveal the scaling laws that will enable the design of novel nano-based metamaterials and metamaterial functionalities in the future. The nanoscientist builds and studies the metamaterials with a bottom-up approach, starting from the single constituent components. This field of research therefore requires effective collaborations between physicists and (bio)chemists for the realization and study of the new materials systems.

We expect that nanoscale metamaterials will enable completely new nano-based devices, with novel interactions between different degrees of freedom (electronic, optical, magnetic, mechanical, biochemical). Developments in nanoscale metamaterials are also important for the field of nanomedicine, where probing and controlling is generally done by fields (electromagnetic, acoustic, etc.) which interact with the biology via sophisticated nanomaterials systems such as functional nanoparticles and vesicles.

**INFRASTRUCTURE**

In order to maintain the Dutch leading position in nanophysics research it is crucial to keep the relevant research infrastructure up-to-date. Two developments are essential. First, cutting-edge fabrication, manipulation and analysis instruments need to be accessible to the Dutch nanoresearchers. A good example of this kind is NanoLabNL. Second, the prevalence of nanoscale building blocks and on the other end showing the behavior of the total system. The scientific challenges for the nanophysicist are to measure the physical properties of the systems (in isolation and within device environments), to understand their behavior (optical, electrical, magnetic, mechanical, biological, etc.), and to reveal the scaling laws that will enable the design of novel nano-based metamaterials and metamaterial functionalities in the future. The nanoscientist builds and studies the metamaterials with a bottom-up approach, starting from the single constituent components. This field of research therefore requires effective collaborations between physicists and (bio)chemists for the realization and study of the new materials systems.

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INNOVATION

One of the key driving forces for nanophysics research is the small intellectual gap between research that is at the forefront of fundamental physics on the one hand and applications on the other. Most if not all nanophysics research has an obvious application potential, although the application horizon can vary. Application areas that have already been identified are (green) ICT, energy, health, food, environment and safety, either through functional devices or smart materials. Many companies active in the Netherlands have a current or potential interest in nanophysics research. In addition to the well-known multinationals, a number of SMEs, amongst which several academic spin-offs, invest in nano-activities.

As a consequence, nanophysics is ideally positioned for the realization of public-private collaborations, e.g., through the Industrial Partnership Programmes of FOM. The 'NANO-werkgemeenschapscommissie' considers it the challenge for FOM to ensure on the one hand a proper valorization of nanophysics research, while on the other hand preserving the existing research excellence with respect to the fundamental and more forward-looking aspects; aspects that are easily overlooked in complementary EZ and EU programmes.

The valorization of novel nano instrumentation poses its own set of challenges. The development of new instrumentation requires a high level of technical support. New, small spin-off companies based on instrumentation lean more heavily on the expertise of the research group, and less on patents than valorization in general. This complicates the company formation process for those universities which restrict the involvement of the group-leaders as cofounder or shareholder in a spin-off company.

FOM's nanophysics/-technology advisory committee stresses the importance of nanoresearch making an impact in industry and society. A number of the research themes enumerated above have a link with industry, because in some areas a strong Dutch industry already exists (imaging, fabrication). In other areas, where Dutch industry is conservative or absent, new spin-off companies will be an important vehicle for innovation. Nano-activities have many links with important societal issues in the field of energy, health and environment. Special care should be taken on how nanophysics can actively contribute to the risk-assessment of nanomaterials. To increase the impact of nanoresearch in these areas it is important that it is performed in strong interaction with players in these fields.

(INTERNATIONAL) EMBEDDING

In recent years FOM has, together with NanoNed and STW, generated a national Strategic Research Agenda (SRA) for the period 2010-2020. This SRA has been established in interaction with top researchers and industrial partners. One of the immediate results was the NanoNextNL programme in which more than 130 partners, from academia and industry, collaborate within ten themes on micro- and nanotechnology research. Nanoresearch forms an important aspect of the three TU collaborations (UT, TU/e, TUD). The Leiden-Delft collaboration was recently awarded a Zwaartekracht grant by NWO for the investigation of the 'Frontiers of Nano'. Related to the topic of Nanoscale Metamaterials, the Eindhoven-Nijmegen-Groningen collaboration was awarded a Zwaartekracht grant for the investigation of 'Functional Molecular Systems'. Many aspects of nanophysics are important to the Dutch 'Topsectorenbeleid'. Nanoresearch is present in two ways. Firstly, nanoresearch forms an integral part of the HTSM Topsector, and to a lesser extent of the sectors Energy, Agri-Food, Chemistry and Water. Secondly, the Roadmap Nanotechnology is drawn up to intersect the various sectors.
European initiatives, such as Horizon2020 and Nanofutures have significant nano-agendas. As such they provide opportunities to strengthen international research collaborations and provide additional funding for excellent Dutch nanophysics research. Of course the more open EU instruments like ERC, Marie-Curie and Future and Emerging Technologies also offer potential for nanoresearch. Actively helping researchers to identify which funding opportunities will aid their research and in influencing the contents of future European initiatives, becomes increasingly more important.

With respect to EU instruments (Horizon2020, including large initiatives like the FET Flagship Graphene) it is important that FOM, in collaboration with other Dutch research councils, safeguards open competition funding for excellent nanoresearch with a mid- to long-term application horizon, where the Netherlands currently has an outstanding international position. Clearly, nanoresearch also offers unique opportunities for more short-term applications. These should be exploited, in the context of the more application-driven parts of the Dutch 'Topsectorenbeleid', Horizon2020 and the EU Nanofutures Roadmap, to increase the nanoresearch effort rather, than reallocating funds from fundamental towards applied research.

MOVING NANOPHYSICS FORWARD

The community and associated research councils should continue to build on the existing strength in the field. The field will continue to be driven by scientific curiosity, but the increasingly successful applications of nanotechnology have created a new dynamics in which possible applications of new ideas are more easily explored. To maintain and grow the Dutch excellence in nanophysics and technology requires nurturing the curiosity and, in parallel, making continued efforts to bridge the gap between fundamental and applied research.

The NANO Committee feels that, in light of the growing influence of nanophysics on society as a whole, all diverse societal groups should be represented in the research community. Diversity, in particular gender diversity, is of crucial importance, especially in this rapidly developing field.

Given the anticipated future of the field this will involve spotting opportunities and nurturing multidisciplinary excellence, which should be pursued on a NWO wide level. Because of the large impact of nanoscience on other disciplines, special care should be taken to not only transfer these technologies, but invest in long-term collaborations or joint programmes between the NWO divisions. The NANO Committee does however feel that curiosity-driven research should not be hampered by requiring (in cash) matching by industry for NWO-wide nanoscience programmes.

Because of the high quality of Dutch nanoresearchers, catalyzing the connections to European initiatives, such as Flagship initiatives, continued support for nanophysics in the widest sense, and continued investments in research infrastructure, will have a large return on investment.