CHEMISTRY & PHYSICS:

Fundamental For Our Future

Vision Paper 2025

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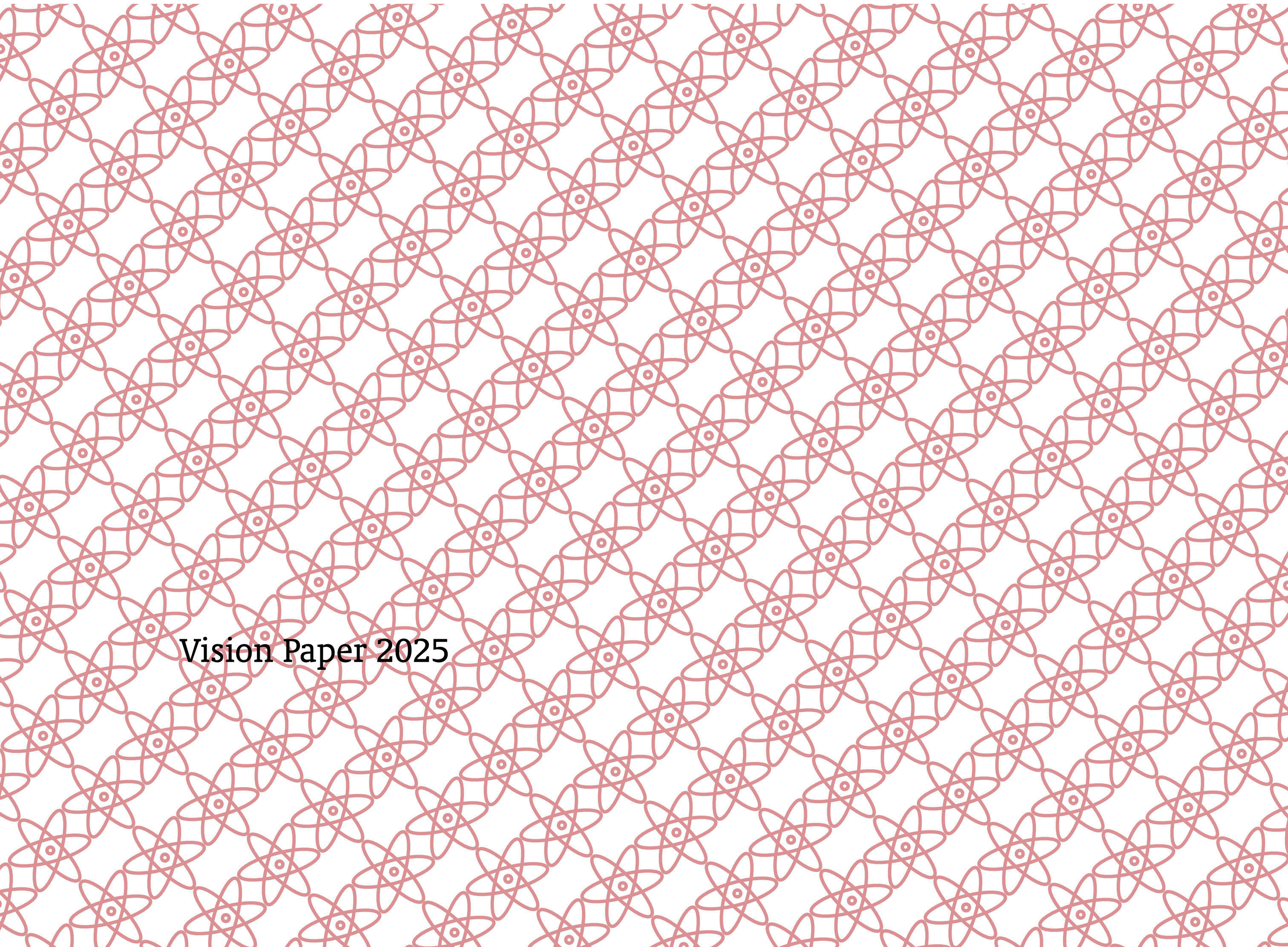

Vision Paper 2025

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1 Physics and Chemistry: bedrock of a knowledge-based society

The Netherlands has the ambition and potential to become one of the top knowledge-based, innovative countries in the world. To realise this ambition, the Netherlands must build on its strong, deep-rooted tradition of excellence in the physical and chemical sciences. Dutch chemists and physicists are punching far above their weight in the global research competition. In the coming years, these disciplines can play three, equally important, key roles within the national and European agendas.

Chemistry and physics make a vital contribution to the research-intensive industry in the Netherlands. The high-tech, chemical, and energy sectors of the economy represent the largest share of private research and development, accounting for 75% of the total industrial R&D efforts. These companies also have a very strong international presence. Industry must maintain its leading position by continuous innovation in emerging areas and technologies. Future innovations and productivity demand a leading role of the physics and chemistry research communities to form and grow regional innovation ecosystems of European and global significance.

Society urgently demands new technologies to deal with grand societal challenges such as renewable energy, resource efficiency, climate change, scarcity of materials, and health care. The physical and chemical sciences are indispensable for finding solutions to these problems. At the same time these challenges create exciting new business opportunities that are bound to enhance the future economic competitiveness of the Netherlands.

In terms of research excellence the Netherlands is presently amongst the top-tier countries in physics and chemistry and it is well positioned to make important contributions to the main scientific questions that will shape the coming decades. Maintaining and strengthening this excellence in research and in all levels of education, including a stable financial base, is a key requirement to sharpen the competitive edge and act on new opportunities.

Summarising, the physics and chemistry communities in the Netherlands are in a crucial position to contribute to the future health of our country. They have a unique role vis-à-vis the economic, societal and scientific challenges. However, they can only accomplish these tasks as long as their proven excellence in research, education, and valorisation is strengthened considerably. By fully utilising the potential of public-private partnerships, the Netherlands can build and sustain a leading European, and even global, centre of excellence around these disciplines.

This report outlines a series of measures that are needed to enable these three key roles. The recommendations cover a wide range of aspects from primary schools to innovation hubs, from international students to research facilities. However, they are all connected by the very high international standing of chemistry and physics in the Netherlands. There is every reason to be highly ambitious about the future.

Aim and structure of the report

The aim of this report is to develop a long-term vision for the physical and chemical sciences in the Netherlands. It deliberately addresses a wider circle than the academic community and speaks to broader issues in education and innovation than a narrower research agenda would. In this way, the report hopes to contribute to the upcoming strategic plans of universities and science faculties, research organisations (NWO, FOM), government ministries (Education, Culture & Science and Economic Affairs), and industry. It also explicitly calls upon the chemistry and physics communities to increase their efforts to reach out to society on issues of global challenges, science literacy, K-12 education, gender, and diversity.

This report is not a follow-up of the successful Sector Plan Physics and Chemistry. Such an action plan would require more concrete steps and supporting budgets. It does however aim to lay the groundwork for a sequel, setting the overall direction and terms of references. As its analysis demonstrates, there are compelling reasons for such a determined effort.

In view of its wider aim and time horizon, the report starts from an international and outsider's perspective, it then gradually works its way inwards to an analysis of the current positions of physics and chemistry in the Netherlands, and concludes with the subsequent core recommendations. It starts in Chapter 2 with sketching several overarching global societal and scientific developments that drive worldwide changes in research, education, and innovation. A common thread in these trends is the blurring of boundaries – boundaries between nations, between disciplines, between academia and industry, and between basic research, applied science, and engineering. These trends clearly matter for many fields, but – as argued before – they are particularly relevant for physics and chemistry, since in the Netherlands they play such a key role in addressing global challenges and generating economic growth through innovations.

In Chapter 3 the report moves inwards by highlighting specific scientific challenges within chemistry and physics that drive the international research agenda and where the Netherlands has a strong strategic advantage. These are the fields where the Dutch research community has proven strengths and is in a good position to contribute to future development. To a large extent the choice of these topics aligns with earlier selections made in the Sector Plan and the Royal Netherlands Academy of Arts and Sciences (KNAW) Dutch Research Agenda. However, within chemistry the overlap with the top sector economic policy choices is incomplete, and for physics the overlap with top sectors is haphazard.

After outlining the main societal and scientific trends and the strategic research agenda, Chapter 4 analyses the strengths, weaknesses, opportunities, and threats of chemistry and physics in the Netherlands. This reveals a combination of issues that confronts many academic fields, such as increased international competition and lack of academically trained teachers. Chemistry and physics are particularly vulnerable to these effects given the very strong international research reputation combined with the equally great challenges in attracting future generations of teachers and students.

In Chapter 5 the report concludes with a wide-ranging series of conclusions and recommendations to strengthen research, education and innovation in chemistry and physics. These observations should be considered as a set of guidelines for a follow-up to the Sector Plan. We see an urgent need for such an action plan.

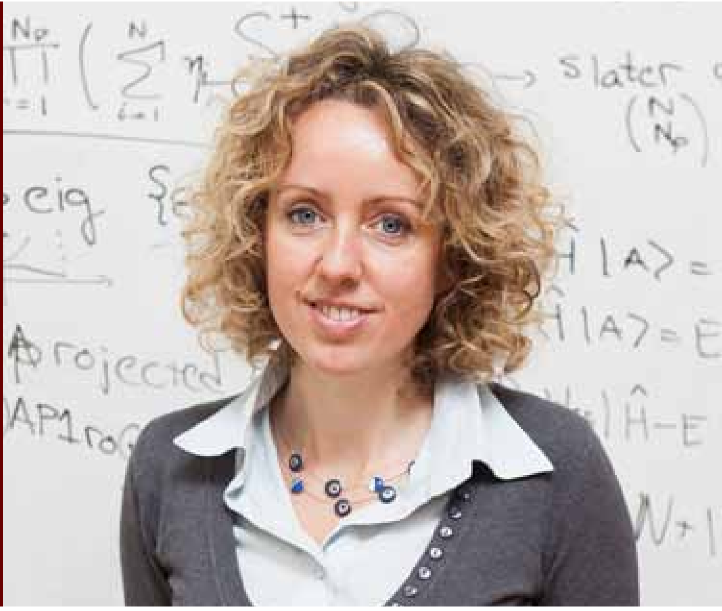
Finally, an obvious point: most of the observations in this report are equally relevant to chemistry and to physics. The two disciplines share many of the advantages and challenges, and some of the most exciting research opportunities lie at their interface. It is therefore apparent that any further action steps preferably should be taken together.

It is my dream that we will understand quantum (many-body) interactions in materials so well that we can engineer new materials to have quasiparticles with unprecedented properties such as non-Abelian statistics for topological computation or macroscopic quantum states at room temperature for dissipationless electron transport.

Alexander Brinkman, University of Twente, Faculty of Science and Technology, Quantum Transport in Matter

I dream of a new era of truly predictive computational chemistry, liberating creativity. Computer simulations will make experimental trial and error unnecessary in discovering sustainable new materials, chemical processes, and designer drugs. Such a breakthrough depends on advances in fundamental, yet-unsolved quantum-mechanical problems that are only apparently abstruse and detached from applications.

Paola Gori-Giorgi, VU University Amsterdam, Dept. of Chemistry and Pharmaceutical Sciences, Theoretical Chemistry



2 Worldwide Trends

This chapter starts the report by describing several long-term and worldwide trends in society and science that will significantly influence the chemical and physical sciences in the coming years and underpin the more specific analysis and conclusions of later chapters.

We distinguish three external trends, which find their origin mostly in larger movements within society: the **Grand Societal Challenges** of sustainable economic development, the emergence of a full **Globalisation of Science** and the transition from private and public R&D centres to **Regional Innovation Ecosystems**.

These external trends are complemented with three internal ones that are mostly based on scientific and technological developments that cut across all sciences: the increased focus on **Information and Big Data**, the exploding ability to **Design beyond Nature**, and the emergence of exciting research and technology challenges at the interfaces of **Multi-Disciplines and Engineering**.

2.1 Grand Societal Challenges

In the coming decades our society will be confronted with enormous technological global challenges related to sustainable development of our planet, appropriately summarised by 'avoiding the unmanageable and managing the unavoidable'. Chemistry and physics will be increasingly asked to deliver solutions for these challenges, such as energy transition, climate change, scarcity of materials, and health care, while simultaneously providing innovative business opportunities.

By 2025 the world will be on its way to a fundamental transition from fossil to alternative energy. Global energy use will have increased substantially while oil production will be close to its peak, leading to intense competition for existing energy resources, which overlap in part with materials resources. This will lead to strong demands for renewable energy sources and storage technology, hydrogen, fuel cells, and smart grids. An emerging bio-based economy will thrive on new catalytic processes converting biomass to valuable raw materials.

To cope with these global challenges we need fundamental breakthroughs in science, engineering, and technology. Physics and chemistry will play a key role in many areas. In the technological push to an energy transition, new mechanisms and smart materials are needed to harvest sunlight and increase energy efficiencies. In the long run fusion reactors may play a role. Future health care demands will require both the development of new advanced instrumentation and materials, and the push for a bottom-up, quantitative understanding of the principles of life, leading to improved early diagnosis and treatment of disease. An increase in healthy life span will outweigh the threats of an ageing population. Renewable, smart materials by design will increasingly impact the sustainable production of food and other products. Similarly, water management, the security of ICT, and transportation all pose fundamental problems that will need to be solved with sustainable solutions.

Global challenges will also be more leading for business development, since governments and markets will increasingly demand sustainable processes and products. At the same time it is important to manage short-term expectations, particularly in politics and from the general public. Fundamental transitions, such as the one from fossil to renewable energy sources and from classical health care to increasing healthy life span, historically come with a costly and lengthy infrastructure overhaul and rollouts can be slow. Breakthrough science and technologies would speed up such transformations, but still require a sustained effort over many decades including long-term investments in human capital and infrastructure.

2.2 Globalisation of Research and Education

We live in a rapidly globalising world and several drivers make the globalisation even more pronounced in science. The physical and chemical sciences are by nature international, but the coming decade will see the development of a fully integrated global scientific community and infrastructure. The worldwide recruitment of students, postdocs, and senior scientists will transform higher education into a global market. Research funding is shifting from national funding bodies to European funding institutions, catalysing national and international cooperation, and leading to global research infrastructures such as the existing European particle physics laboratory CERN, synchrotron centres such as ESRF, and neutron centres such as ISIS.

Scientists operate in international networks, choosing collaborations with strong groups from all over the world. This globalisation will be boosted by the spectacular growth of science in emerging countries, opening vast talent pools, particularly in India and China who by 2025 will have doubled their scientific output. The recruitment of scientific brainpower will happen at increasingly larger scales. This trend is already clearly visible in the recruitment of PhD students, postdocs, and staff, but will also increasingly encompass BSc and MSc programmes. By 2025 it is estimated that more than 600,000 Chinese students and 300,000 Indian students will study abroad. The crucial question will be who can attract and retain the most talented students, teachers, and researchers. The emergence of a global higher education market will be strengthened by the growth of MOOCs (massive open online courses). Within this process of globalisation European institutions have traditionally lagged behind the top American universities. The developments are so rapid that it is difficult to sketch the outcomes. It is clear however that increased global competition will lead to stronger differentiation in size, financial power, and attractiveness of universities and research institutes.

The increasing complexity and multi-disciplinarity of much pioneering research leads to the need for larger teams and larger shared facilities. Globalisation is therefore driving fundamental changes in the funding landscape, shifting initiatives away from universities and national agencies to international and even worldwide funding sources. The European Union will strengthen its role with the Horizon2020 programme. Some research instruments have become so complex and costly that no single country can afford them, culminating in global research infrastructures, such as CERN, the International Thermonuclear Experimental Reactor (ITER) and synchrotron facilities (ESRF). Chemistry research also uses increasingly complex and expensive equipment (NMR, free-electron lasers, sequencing and screening facilities). This leads to a de facto worldwide programme for certain areas of research. To deal with the challenges of globalisation, an increasing number of research fields, including many in the physical sciences, are establishing coordinated roadmaps or global research strategies, such as the priority list of large-scale infrastructures maintained by the European Strategy Forum on Research Infrastructures (ESFRI).

To fully benefit from these global developments a country needs to have a qualitatively excellent local base with sufficient quantitative strength. The Netherlands is well-positioned to explore its inherent strengths – compact, well organised, with a very good average level of education and research – and develop models to participate internationally at the highest levels. One model is to use strong national organisations and networks to influence higher level, international consortia and agencies to obtain a maximal multiplier. Highly organised fields such as astronomy and high-energy physics are already successful here; other physical and chemical sciences are in an outstanding position to benefit from these international developments.

2.3 Regional Innovation Ecosystems

The pipeline from science to innovation is changing dramatically. Time scales are getting shorter. The role the major industrial research labs have played in the previous century is diminishing rapidly, and may be replaced by open innovation ecosystems focused around a few hotspots worldwide in which academic institutions collaborate with large and small companies. This changing environment has a profound impact on how science should be organised to maintain a high impact in innovation. Academic science has to become more active in 'use-inspired research'. Universities, government, and companies must define long-term roadmaps, identify areas where further research is needed, and be willing to support it for many years. The Netherlands could be one of those open innovation ecosystem hotspots.

The time between invention and market penetration of technology continues to shrink. Whereas it took 100 years for the train to be accepted in the early 1800s, 50 years for the automobile in the early 1900s and 20 years for the PC in the 1970s, it nowadays takes only a few years for a major invention, such as the smartphone, to be launched onto the market. Large industrial laboratories, such as BASF (1880), General Electric Research Laboratory (1900), Koninklijke/Shell-Laboratorium Amsterdam (1914), Philips Nat Lab (1914), Bell Labs (1925), and IBM's Thomas J. Watson Research Center (1945) have previously played a major role in global innovation. The role of these big industrial laboratories has changed significantly over the last decades; they have decreased in size and are far less involved in basic science. Companies are less vertically integrated (science - applied research - development). Instead we have seen the emergence of innovative regions. Prominent international examples of such systems are Silicon Valley in California, the Boston Area, Waterloo in Canada, and Grenoble High Tech Campus. Brainport Eindhoven is an important Dutch example of an international innovation region. These innovation ecosystems are formed by complementary small and large-scale companies and always include important academic institutions. This trend opens up new perspectives for technology institutes in the field of chemistry and physics, such as TNO, ECN, and DLO.

The change from a single company laboratory to a regional ecosystem affects the type and process of innovation. The traditional single company laboratories in physics pursued long-term inventions such as long-distance telephone networks, semiconductor electronics, satellites, and the laser. In chemistry, the traditional laboratories dominated catalysis, performance materials and colloids. Dutch big pharma companies have pursued vaccine development and hormone manipulation.

The development of new, cheap, active and selective catalysts for important chemical transformations is crucial to solve global sustainability and energy production issues. My dream, in this perspective, is to couple (metalloradical) catalysis to electrochemical or photochemical 'uphill reactions' so to produce fuels and other valuable chemicals. Hopefully this will gradually make mankind independent from fossil feedstocks.

Bas de Bruin, University of Amsterdam, van 't Hoff Institute for Molecular Sciences (HIMS), Bio-inspired Sustainable Catalysis

My dream is to unite the art and science of chemical assembly in water via a profound understanding and exquisite control over assembly pathways.

Ilja Voets, Eindhoven University of Technology, Institute for Complex Molecular Systems

Innovation ecosystems, on the other hand, do not have a single management and their innovation paths are characterised by flexibility and short-term goals. This trend includes a shift from a closed innovation model, with all relevant disciplines in house, often covering science as well as engineering, to a much more open innovation model that makes use of a supply chain for specific knowledge and manufacturing.

Universities can play an important role within these larger ecosystems. Since the importance of the sciences for innovation remains high, this changing environment can lead to new models for the organisation of research. This will require increased flexibility from the chemistry and physics communities, combining for example innovation projects with shorter time scales and curiosity-driven research with longer timescales. Integration within the ecosystem can be promoted by the mutual use of facilities, exchange of staff, and common short-term research projects. To make these measures attractive for academic staff, the academic institutes can open up towards a broad range of research profiles contributing to teaching, research and innovation.

The entrepreneurship among university staff has definitely increased, and starting a small company has become increasingly common for university staff. Yet, the support for smaller start-up companies is not very extensive. Most of the universities have technology valorisation centres that provide initial support and infrastructure but this is not enough to sustain small start-ups. However, there is limited funding for start-ups after the incubator stage and limited management support for the transition from a science lab to a business.

Although the large multinationals still operate factories in the Netherlands, and the bulk chemical industry still provides the majority of revenue, their level of fundamental innovation research has decreased. It is important to realise that the field of chemistry is much broader than the area covered by the Top Sector Chemistry, and even that of the Sector Plan Chemistry and Physics. Even more than innovation within existing industry, start-ups may well be a main driver for future innovation, and hence for fundamental research programmes.

2.4 Information and Big Data

Turning now to general trends within science, information is becoming a leading principle. New measurement techniques, data- and text-mining are generating ever-increasing amounts of information. This requires and allows completely new analysis strategies. In all areas of science and society, there will be a need for innovative technologies and algorithms to interpret these huge quantities of data. At the same time, new types of information processing, such as quantum computing and simulation, will vastly enhance our computational power leading to the ability to predict the behaviour of highly complex systems and solve fundamental problems that are beyond the realm of current digital computers.

Rapidly improving measurement, imaging, and sequencing instruments go hand in hand with the generation of vast amounts of data, including those from ‘-omics’ approaches, such as the genome-wide studies into the biomolecules of a cell, tissue, or organism. Increasingly precise data sets are becoming available that quantitatively characterise the properties and dynamics of ever more complex systems, including life itself. The resulting large data files will need to be analysed with modern computer technologies and new data analysis strategies, such as multidimensional crossing of whole genome databases, searches for the organising principles from correlations without using a-priori hypotheses, and algorithms that derive predictive power from inherently noisy data sets. Computational analysis provides a new scientific methodology for such cases.

Entirely new methods will be developed to process information. An important example is to use the laws of quantum mechanics as principles for data processing. This will result in quantum computing and simulation as a fundamentally new computing paradigm. The resulting quantum computer, probably available in 2025, will be able to address many problems that cannot be solved with classical computers. For example, a quantum computer is the best machine to understand the fundaments of quantum mechanics itself.

The vast improvement in computational power that will undoubtedly become available will be transformative in our approach towards developing new materials for scientific and industrial applications, taking us away from classical trial-and-error methodology. It will tremendously impact our ability to simulate and predict the behaviour of complex systems, allowing us, for example, to combat microorganisms more effectively and to design personalised medical treatment for individual patients based on their genetic make-up. We will learn important lessons from the brain and the living cell, which themselves can be considered information-processing machines, and whose computational principles are only starting to be uncovered.

2.5 Design Beyond Nature

Out of all possible forms of matter only a small fraction has been realized in nature. The chemical and physical sciences, traditionally concerned with understanding and manipulating natural phenomena and systems, are rapidly evolving their ability to create and investigate non-natural systems, building on the tradition to synthesise molecules. In the future we will design and synthesise more and more sophisticated molecules and materials with new and improved functionalities, with breakthrough applications in for example energy and health, and also in integrated circuits with natural systems. Conversely, the re-creation of complex natural systems such as living cells will provide a decisive route to their fundamental understanding.

“What I cannot create I do not understand” was the text found on the blackboard of Nobel Prize winner Richard Feynman at the time of his death. The ultimate control and understanding of matter over wide parameter ranges also provides new windows on tackling big outstanding questions in physics, chemistry, and biology. Designer matter leads to an accelerating feedback cycle between understanding and the creation of ever more intricate systems.

A combination of unprecedented control and manufacturing techniques allows us to structure and create new (meta-)materials over a large range of scales. This development will vastly increase the range of phenomena that chemists and physicists can study and understand, including known states of matter under new conditions and behaviour of molecules over time in a living person. Even the idea of making synthetic cells or designing new, industrially useful forms of living systems is no longer science fiction.

Creating this wealth of new materials, devices and living systems is likely to lead to a bigger revolution than the introduction of plastics. The design of such systems can be used to address major issues in the global societal challenges, such as in energy, health, and sustainability. These systems will also provide major new business opportunities, even with as yet non-existent products in so far non-existent markets.

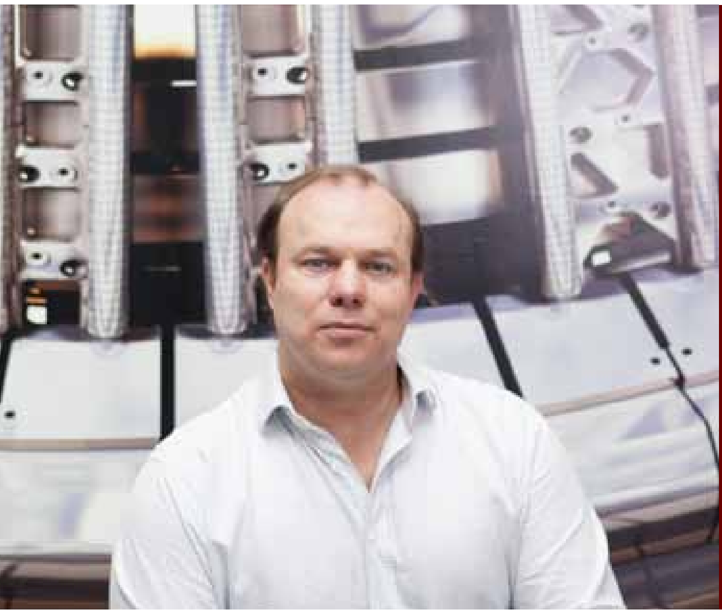
2.6 Multi-Disciplines and Engineering

The importance of a multidisciplinary approach in addressing the grand societal challenges cannot be overestimated. The greatest scientific and technological successes of the past decennia, including 'one giant leap for mankind', resulted from a close collaboration between various scientific disciplines. Many future innovations and solutions for grand societal challenges will rely on knowledge developed across and between disciplines. The disregard of traditional disciplinary boundaries is increasingly successful in stimulating scientific creativity, which is needed to drive these scientific and technological innovations, and in opening up avenues for paradigm shifts and new breakthroughs in our knowledge. In line with this development, industry is increasingly looking for an academic environment that can address complex, multidisciplinary problems.

Physicists and chemists approach complex problems by collaborating with materials scientists, computer scientists, biologists, chemical engineers, and others. Each approaches challenges from different angles, leading to unexpected insights and new inspiration for fundamental science and innovation in technology and health care. Connecting fundamental sciences and engineering is becoming ever more important, particularly in the design and development of advanced instrumentation and devices. Both of these play a key role in many applications for society as well as in fundamental research all across physics and chemistry.

Internationally, multi-disciplinary research innovation ecosystems are emerging rapidly. When facilitating and encouraging scientists from different disciplines to work together, entirely new (interdisciplinary) methods and approaches are being found to work on grand societal challenges. The research lines in these clusters may be long-term, but well-functioning multidisciplinary teams may also be flexible enough to quickly follow-up on the latest breakthroughs in complex research topics, or quickly developing industrial and societal needs.

The marvels and benefits of multi- and interdisciplinary work should not diminish the strength of the disciplines and their identity. High-quality teaching of chemistry, physics, and the bordering disciplines will secure fostering the talents for a high-quality multidisciplinary future that will have a decisive impact on solutions for grand societal challenges, and will provide many opportunities for industrial innovations that will affect our lives and our economy.



Mankind will have created a sun on earth: ITER. Piping-hot plasmas, self-heated by nuclear fusion, will be operated in close proximity to stability margins. State-of-the-art control systems will allow for the real-time optimization of the plasma efficiency, the safe exhaust of heat and particles, and the active detection and suppression of instabilities.

Marco de Baar, NWO/FOM-institute DIFFER,
Fusion Research

In 2025 I want 10% of the world's energy to be supplied by solar, which requires a 100-fold increase over today's capacity. We can achieve this by understanding solar conversion at the nanoscale and applying this knowledge to new technologies. It's time to start the next industrial revolution.

Erik Garnett, FOM Institute AMOLF,
Nanoscale Solar Cells

3 Research Agenda for Chemistry and Physics

In this chapter the main ingredients are presented for a long-term research agenda for physics and chemistry in the Netherlands. The form we have chosen is to imagine what can be potentially achieved by the year 2025. This vision of the future should generate enthusiasm for the phenomenal research opportunities in the coming decade. Clearly such a vision is always open to debate and full of uncertainties. Undoubtedly there will be unexpected challenges and breakthroughs that will drastically change the path forward, perhaps opening up completely new vistas. A healthy bottom-up research culture anticipates and encourages such developments, and is ready to act on them.

Within the international physics and chemistry communities there is considerable consensus on the fundamental frontiers that need to be explored and pushed forward the coming decade. From these a number of challenges have been identified that are particularly relevant for the Netherlands, and in which Dutch science has the track record, expertise, stature, and capacity to play a world-leading role. In all these areas pioneering researchers and research groups currently are active in the Netherlands. These grand science challenges, ranging from Life to Universe, are largely in line with the focus areas previously selected in the Sector Plan[1], and the relevant key questions of the KNAW Dutch Research Agenda[2].

3.1 The Chemistry and Physics of Life and Health

The coming decades will see many fundamental breakthroughs in our understanding of living systems, including humans. Physics and chemistry, through all their sub-disciplines, will contribute to many of these breakthroughs in essential ways. Reductionist biochemical, biophysical, and structural studies will continue to advance our understanding of the properties and functioning of biological macromolecules (e.g. Nobel Prize in Chemistry 2012). Advanced instrumentation such as nanoscale imaging will continue to be developed at a rapid pace, tremendously adding to the volume of information that will become available on the dynamic properties of individual components in the cell. The integration of physics, chemistry, (systems) biology, and mathematical modelling approaches will provide insights into the dynamics of interactions between all molecules in the cell, allowing us to elucidate the design principles and function of each molecular structure and pathway in the cell. We anticipate great progress in understanding the complex interactions between individual cells that lead to highly organised tissues – the ultimate example being the exquisite information-processing machine that is the brain.

The fundamental understanding of the way life functions will open up new targets for molecular therapies, including new antibiotics and antivirals. Academia will feed drug development pipelines through the design of novel assays and compound scaffolds for high-throughput screening. Rapid DNA-sequencing methods, which already are becoming available, will allow rapid genetic profiling of individual patients. This, combined with single-cell protein analysis in a lab-on-a-chip environment, will allow the design of personalised treatment.

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[1] *De perfecte Chemie tussen onderwijs en onderzoek*, Regiegroep Chemie, 6 juni 2007 en *Fysica voor de toekomst. Toekomst voor de fysica, Commissie ad hoc* Sectorplan Natuurkunde, 6 juni 2007

[2] *De Nederlandse Wetenschapsagenda*, Peter Vermij (eindred.), Koninklijke Nederlandse Akademie van Wetenschappen, 2011

The lessons physics and chemistry can learn from the way life works will be just as important. Bioengineering will create a vast amount of bio-related or bio-inspired structures and materials that capture the essential multi-scale design principles of life. These will have a tremendous impact on applications in sustainable food production and biotechnology. Our ability to design and control enzymatic, genetic, as well as structural molecular networks *in vitro* will shed light on the minimal requirements for life, and, ultimately, enable the creation of a synthetic cell.

The integration of nanomaterials and nanoscale devices with (modified) biological systems will extend our healthy lifespan. Technological breakthroughs in analytical sciences such as single cell analysis, sequencing, '-omics', nanotechnology, and imaging, will give unprecedented insights into the state of each cell in the whole body over time. Embedded sensors will allow real-time detection of biomarkers and appropriate feedback to correct systems at the molecular level.

Diagnostics is expected to play an increasing role and offers opportunities for physics and chemistry as well as innovation. Biocompatibility of electronic materials allows them to operate in aqueous environments including the human body. These technologies will provide crucial solutions to societal challenges such as medical diagnostics, treatment and drug delivery. Integrated multidisciplinary efforts between synthetic chemists, biochemists, and biologists will provide a new foundation for the discovery of novel pharmaceuticals. New biohybrid materials will be synthesised exploiting our ability to make molecules and materials with nanoscale structures. Such materials will control stem cell differentiation, will allow growth of 'organs-on-a-chip' and (re)generation of tissues in living persons.

3.2 Energy

Energy is the main driver for our society as it underlies all aspects: food production, housing, transportation, industry, and information technology. A transition to sustainable energy conversion and storage is required due to finite reserves of fossil fuels and the impact of climate change. This transition is of such a scale that it requires extensive short- and long-term research in physics and chemistry (combined with other sciences). In the short term, new technologies will extract and convert solar energy more directly, whereas biomass or re-use of carbon dioxide will be the key resource for many chemicals. Fusion is a promising energy source in the long run – the main challenges remain plasma instabilities and materials that can withstand the extreme conditions encountered in fusion.

In the future, scalability of energy solutions and the use of abundant elements in designing high performance materials will be key. This requires a deep understanding of the mesoscale phenomena, where classical, quantum and nanoscale meet. Examples are new steels operating at extreme conditions that increase conversion efficiency; light-weight materials that reduce energy consumption; alternatives for the magnetic materials with critical rare earth elements currently used in engines and turbines; alternatives for Lithium, a critical element in energy storage in current batteries.

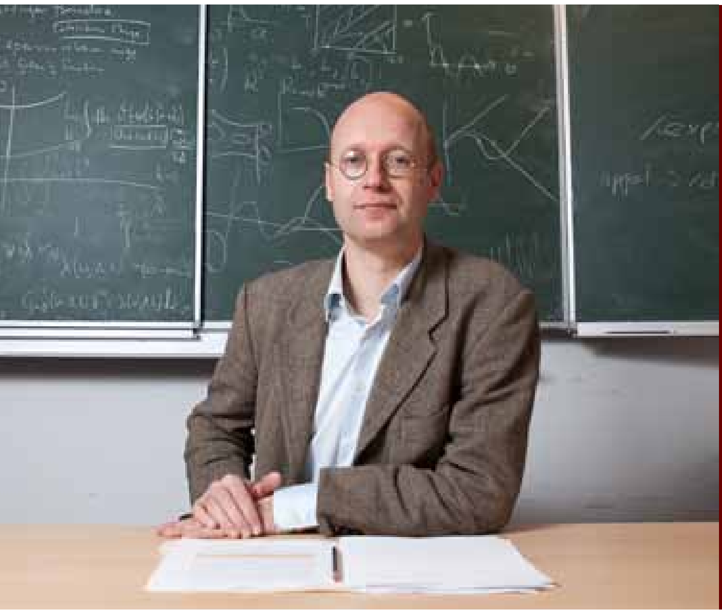
Novel technologies will make more effective use of wind, wave, fresh/salt water and solar energy. Radical improvements can be achieved in each sector with a multitude of promising avenues. Novel nanostructured material combinations and synthesis techniques will provide high-efficiency, low-cost solar energy capture, conversion and storage, e.g. in developing improved light management for photovoltaics or piezo-based MEMS. New materials such as high T_c superconductors can transport energy over long distances with little loss. Novel catalysts will yield better processes for carbon capture and synthetic photosynthesis outperforming nature (solar fuels). Nanostructured membranes are essential for fuel cells and energy generation from differences in freshwater and saltwater. New reactor technologies and more efficient catalytic pathways will enhance the molecular and energy efficiency of physical and chemical processes. Energy consumption can be radically reduced by developing materials that demand less energy for production (housing), and smart buildings that do not use energy but instead generate power and adapt to their environment. Continued miniaturisation and integration of electronic devices and sensors enables information storage/processing with substantially reduced power demands which makes their ubiquitous use possible.

3.3 Nanoscience, Nanotechnology and Advanced Materials

Totally new classes of materials are being discovered, produced, and used. Nanoscience and nanotechnology enable the design and manufacture of materials with ultimate control and precision in one, two and three dimensions. Large-scale simulation and multiscale modelling will enable us to understand the behaviour along the entire range from atoms to macroscopic scales.

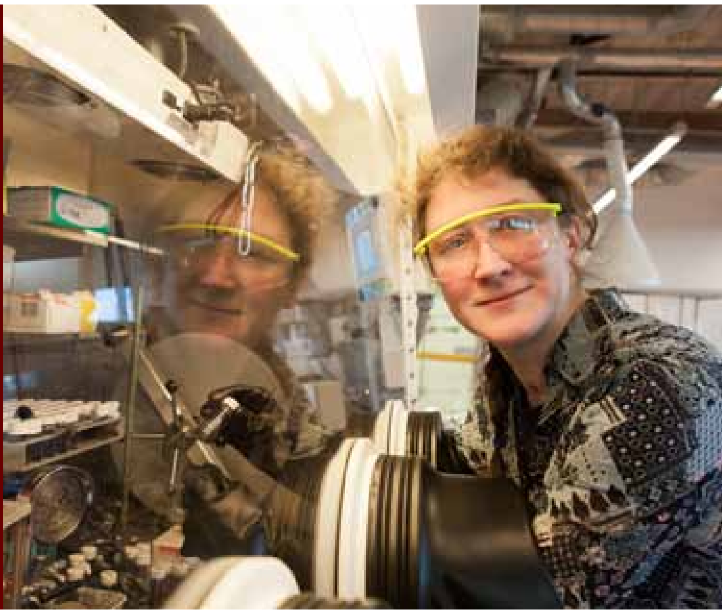
Metals and molecules can be interfaced on surfaces or in systems by (self-)assembly leading to high performance and novel materials such as metamaterials, high-strength textiles, composites/hybrids for light-weight materials, and two-dimensional flexible heterostructures with novel electronic functionalities. With large-area flexible and foldable surfaces that are light emitting, or sensitive to tactile stimuli, an entirely new range of applications comes within reach. Design of advanced biodegradable materials with targeted functionalities presents another challenge that will be addressed. Progress in materials science will also play a crucial role in reducing the need for scarce chemical elements.

Technological developments will enable the fabrication, manipulation, and study of devices down to atomic level. The continued miniaturisation and integration of electronic devices allows unprecedented functionalities for sensing and information processing as well as storage and processing with low external power demand. These devices will be fully integrated and networked in ubiquitous places like home, traffic, environment, and the body. These technologies will provide crucial solutions to societal challenges such as medical diagnostics, treatment, and drug delivery; energy conversion, transport, and storage; and the development of sustainable processes and products.



I wish to see that the astonishing mathematical connection between strongly entangled quantum physics and the physics of string theory and black holes can both yield a first explanation of a true experiment using string theory in the next decade as well as a breakthrough understanding of the extreme physics of the Big Bang.
Koenraad Schalm, Leiden University, Lorentz Institute for Theoretical Physics

My dream is controlling and understanding size, confinement and interface effects in inorganic materials on the nanoscale, leading to the development of new and stable functional materials for renewable energy conversion and storage, and efficient catalysis. These will be essential building blocks for a truly sustainable society.
Petra de Jongh, Utrecht University, Debye Institute for Nanomaterials Science, Inorganic Chemistry and Catalysis



3.4 Complex (Molecular) Systems, Soft Materials, and Fluids

We are witnessing a revolution in our understanding and control of complex forms of matter. Complex systems (both organic, inorganic, and hybrid) are composed of individual entities (molecules, grains of sand, genes, viruses, cells, individual organisms) that interact with each other and with their environment in non-linear, dynamic ways. These interactions give rise to emergent properties at larger scales in space and/or time through self-organisation. Complex systems arise at all scales – from elementary particle properties and interactions, magnetism, genetic and metabolic networks in living systems, to oscillating chemical reactions and self-organising molecules, to intermediate scales in soft matter such as adaptive materials, colloids and granular media, turbulent multiphase and/or multicomponent flows, to macroscopic and cosmological scales such as turbulence in fluids and plasmas.

Complexity plays an ever-growing role in physics, chemistry and biology. New experimental techniques, theoretical concepts of far-from-equilibrium thermodynamics, a fundamental understanding of self-organisation, and large-scale computer algebra and computer modelling enable us to explore, understand, and control the emergence of an ever-expanding range of complex behaviour. New ideas forge connections between systems at vastly different scales, ranging from the molecular to the macroscopic regime (Nobel Prize in Chemistry 2013) as well as between living and dead matter. Applications will range from new types of smart materials with much broader abilities to adapt to their environment by 'computing' their best response, to understanding the functioning of the brain, climate change, or social phenomena. The phenomenal advances in computing power allow qualitatively novel data analysis strategies (big data), shining new light on hitherto unknowable phenomena.

3.5 Sustainable (Bio)Chemical Process Engineering

Biochemical and chemical process engineering enable the practical realisation of the fundamental scientific achievements of (bio)chemistry and physics envisioned in the previous sections. In 2025 intensified technologies in (bio)chemical process engineering, using new cascading reactor designs controlling reactions in space and time, will make a major contribution in solving the most important societal challenges related to energy, resources, health, environment and efficiency. In the area of energy, new catalysts for N_2 activation and technologies for making high-efficiency materials for energy conversion and storage will advance. Regarding resources, techniques will be developed for recovery/recycling of critical raw materials. Many critically important materials are based on scarce elements, which urgently need to be replaced and recycled. Metabolic engineering will provide new routes to fuels, fine chemicals and pharmaceuticals all based on 'green' feedstocks.

In the area of health, rapid developments in lab-on-a-chip technology will lead to (micro/nano) sensors and measuring devices as well as high-speed analysis methods for single cell genomics, transcriptomics, and proteomics. This will result in improved biomedical information (taking into account population heterogeneity), quick quality checks and on-line analysis in continuous (bio) pharmaceutical processes. New production methods for producing high-purity crystalline proteins with increased bioavailability and extended shelf life will advance, and processes in high cell-density systems (e.g. production of monoclonal antibodies for cancer therapy) will be intensified.

Regarding the environment, processes for CO_2 conversion and storage, conversion of (communal) wastes and complex biomass feedstocks into chemicals, purification and desalination technologies for drinking water supply and recyclable construction materials (building, cars, etc.) will be developed, approaching the 'zero-waste' target at minimum energy consumption. Improved methods for environmental monitoring will accompany these developments.

When it comes to improving efficiency, intensification of chemical and biochemical processes systems with ultrahigh specific surface areas for energy and mass transfer will be developed. New (catalytic) chemistries will be integrated with new concepts of 'perfect' chemical reactors, which control the chemical reaction pathways at molecular level, aiming at 100% atom efficiency and zero waste. In addition to this, novel, energy-lean, hybrid separation techniques will be developed.

3.6 The (Quantum) Universe

Fundamental discoveries in particle physics and cosmology will transform our understanding of the universe, in particular of the 95% of the cosmos composed of the still unknown dark matter and dark energy. Starting with the detection of the Higgs boson (Nobel Prize in Physics 2013), experiments at the LHC and elsewhere will explore physics of the weak scale where essential elements of our fundamental forces reside, possibly detecting supersymmetry and dark matter particles.

The mixing angles between the three known neutrino species are now all known to be sizably different from zero. New experiments make it possible to study mechanisms for matter-antimatter asymmetry in the neutrino sector that may dramatically change our picture of how antimatter has disappeared from our universe.

Astrophysics and astroparticle physics will probe the very early universe, detect gravitational waves, study black holes, possibly directly detect dark matter particles and provide a window on cosmological inflation – the rapid expansion of the very early universe. Astrochemistry will teach us about novel molecules, extreme conditions, and the birth of planets and stars. The detection and detailed study of many more exoplanets will give us a large statistical sample from which better understanding of our own planet - the earth - will be obtained. It may also lead to the discovery of extra-terrestrial life.

A theory of the fundamental physical laws unifying the quantum world of smallest particles to the largest structures of our universe is within reach. New theoretical ideas question the nature of space and time, including quantum black holes and the very early universe. An unprecedented number of connections between theoretical concepts will emerge linking areas of physics that superficially have little in common. For example, the remarkable correspondences between theories of gravitation and quantum field theories will allow us to make quantitative predictions of phenomena in solid-state physics, such as high-temperature super-conductors, which have so far been incalculable.

3.7 Quantum Technologies

Quantum science is entering a new era with a central role for extensive control over designed quantum properties. During the past five years there have been breakthroughs in such control in the fields of quantum optics, quantum materials, and quantum information. In the coming decade this new science can be expected to find its way towards entirely new applications.

In optics, the interaction between light and matter is now controlled down to fundamental quantum levels (e.g. see the Nobel Prize in Physics in 2012). The new challenge consists of making lattices with on each site a controlled interaction between a single photon and a single atom. Such optical lattices form quantum simulators for material lattices with interesting collective quantum properties, including magnetism and superconductivity.

In materials, quantum phenomena have been designed and realised for interfaces and bulk materials. An important theme is the utilisation of topology to obtain entirely new materials behaviour. Important examples include the quantum spin Hall effect in two-dimensional topological insulators and the emergence of Majorana fermions in artificial superconductors (with an engineered p-wave pairing mechanism). A major goal of quantum materials is to obtain full understanding of superconductivity and realise a material that superconducts at room temperature.

In technology, the extensive control over quantum superposition and entanglement forms an entirely new resource to be exploited as a novel conceptual basis for technology. New sensors reaching the fundamental limit of quantum sensitivity will be developed for applications such as single photon detection used in medical and space microscopes and for single nuclear spin imaging, i.e. MRI on single atoms. Using quantum teleportation in small-scale circuits and optical networks, information can be encoded in the quantum properties of light making data transfer absolutely secure. Large-scale circuits are needed for a quantum computer capable of solving yet-unsolvable problems, notably the simulation of material properties, and also for deepening our understanding of the fundamental mechanisms of quantum mechanics. It is expected this new control will allow to entirely suppress decoherence in large quantum systems, implying the ability to keep Schrödinger’s cat forever alive and thus solving what used to be a fundamental problem.

The cells in our body constantly change their shape in order to grow, divide, and crawl. My dream is to realise synthetic cells that can mimic this extraordinary behaviour with a minimal set of cellular components. This will reveal the basic physical principles that underlie active cell shape control.

Gijsje Koenderink, FOM Institute AMOLF, Biological Soft Matter

I envisage a world of new semiconducting materials that can efficiently convert solar light into different forms of energy. While promising new physics, the most exciting aspect will be the challenge to transform water and carbon dioxide into fuels using them.

Maria Antoinetta Loi, Professor of Photophysics and Optoelectronics, University of Groningen

4 Physics and Chemistry in The Netherlands: A SWOT Analysis

In this chapter a comprehensive analysis is presented of the strengths, weaknesses, opportunities and threats (SWOT) of chemistry and physics in the Netherlands at this moment. This analysis is grouped around five important themes: primary and secondary education, tertiary education, research, industry and innovation, and the general position in society. We also indicate how this analysis leads to the conclusions and recommendations presented in Chapter 5.

4.1 Primary and Secondary Education

Strengths • Open, free and relatively strong education system	Weaknesses • Science presence and expertise in primary education is low and incidental • Very few tracks to foster excellence • Very low number of academically skilled science teachers • Current teaching model in Dutch secondary schools is not adequate for teaching sciences
Opportunities • Growing attention for science education • Increasing number of pre-university (VWO) students choose science profiles	Threats • Most current initiatives for improvement are not structural • Insufficient numbers of students choose a science or technical education • Very little interest in becoming academic chemistry or physics teacher

Overall, the Netherlands benefits from a well-functioning education system. In primary education the teaching of physics, chemistry and the sciences in general is weak and below international standards. There is only the beginning of exposure to the basic principles of science and more abstract mathematics. Examples in other countries show that children can be fascinated by key concepts at an early age, an opportunity that is missed in the Netherlands. This has been recognised widely, and in recent years a number of initiatives have sprung up that aim at strengthening science education *(Techniekpact, Wetenschapsknooppunten, Talentenkracht, JetNet, Techniek Toernooi).*

At present, the teaching practice (rather than the capacities of the pupils) remains a bottleneck. Mastering the sciences requires intensive interactions between a pupil and a qualified teacher, and there are no structural means to recognise and foster excellence at an early age. Inquiry-based methods are an important ingredient that is introduced by the *Wetenschapsknooppunten*, but should be complemented with a firm knowledge base. In the USA science camps for children in primary and secondary school are a success and could be implemented here as a week during the curriculum in primary and secondary schools or after school time in primary schools ('naschoolse opvang'). **See Recommendation 1: START EARLY.**

The very low number of university-trained school teachers in secondary education is a major concern[3]. The number of graduating academic teachers per year is far below the required replacement level. Despite the positive trend of an increasing number of secondary school students choosing to specialise in the sciences, this growth is far from sufficient and will not yet lead to increasing numbers of teachers. Although the increase in students is to a large extent due to more girls choosing science profiles, the education field has not been able to capitalise on this improved gender balance. It is crucial that a wide-ranging perspective of science is given within the physics and chemistry secondary school courses, including the potential to contribute to the solution of the grand societal challenges (energy, health, sustainability). These inherent shortcomings of the primary and secondary educational system weaken the foundation of a stronger science culture. Despite all of the laudable efforts so far, there is every reason to take a more radical approach. Universities, and particularly physics and chemistry departments, should consider taking care of the 'supply chain' to be one of their core responsibilities. Building networks of excellent teachers closely affiliated to university physics and chemistry departments, including their research experience, has proven to be a promising direction (*Regionale Steunpunten, NWO and FOM Leraar in Onderzoek programs.*).

The successful training of science teachers requires an appropriate knowledge base in the universities. At this moment the Netherlands lacks a high-level academic research programme in chemistry and physics teaching, including PhD students and postdocs. An example of such a programme is the Science Education Initiative set up by Carl Wieman (Nobel Prize in Physics, 2001). Such an effort would require a new and dedicated funding source. **See Recommendation 2: EMPOWER THE CHEMISTRY AND PHYSICS TEACHERS.**

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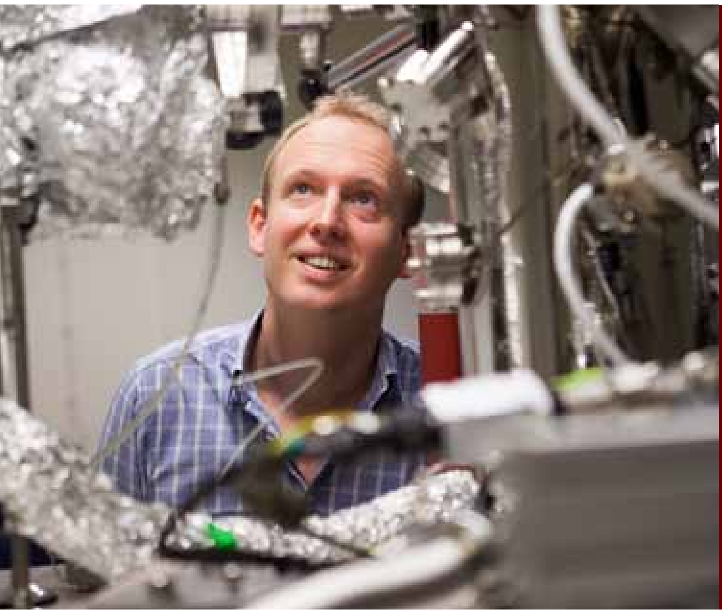
[3] *Naar een lerende economie*, WRR-rapport 90, Wetenschappelijke Raad voor het Regeringsbeleid, Amsterdam University Press, 2013

4.2 Tertiary Education

Strengths	Weaknesses
• High quality • Broad offer of disciplinary and multi-disciplinary education • Increasing overall influx • All MSc courses in English • Education qualifications systems • Focus on study efficiency	• Programmes focusing mostly on research careers • Female/minority students underrepresented, especially in physics • High tuition fees for non-EU students with limited scholarship possibilities • BSc courses in Dutch (some universities) • High dropout rates (low motivation), low mobility • In an academic career research skills valued more than educational skills
Opportunities	Threats
• Exchange academia-industry; possibility for industrial lectures • Societal challenges could motivate more (female) students • Recruiting students in neighbouring and in Central-/East-European countries • Massive online open courses (MOOCs) • Economic crisis leading to increased interest in hard sciences • Increase appreciation for applied physics and chemistry by academic staff and management	• Demography; expected decline in future student numbers • Decreasing financial support from government for education. • Decreasing quality standards

The level of the MSc and PhD graduates in the Netherlands is internationally recognised as very competitive in comparison to the best universities worldwide. The Dutch BSc physics and chemistry programmes cover the full breadth of physics and chemistry and have many elements in common between the different universities. Many universities have multi-disciplinary BSc programmes with a sizable physics/chemistry component and the option to enter into an MSc physics/chemistry programme. Within the current Sector Plan Physics and Chemistry, these multidisciplinary programmes are distinguished from the monodisciplinary programmes, albeit that they are counted in with the total number of chemistry and physics students. A number of University Colleges exist with a broad type of college education, including possibilities to do a major in science, with the option to enter an MSc physics or chemistry programme.



Solid state materials such as semiconductors and superconductors are the cornerstones of our technology. If nature can create these fascinating materials by chance, imagine the possibilities if we could design our own materials, atom by atom! In the coming decade, advanced imaging and growth techniques will bring this dream closer than ever.

Sander Otte, Delft University of Technology, Kavli Institute of Nanoscience

The pharmaceutical industry as we know it today will not exist anymore in 2025. The development of novel therapies will also become a responsibility of the public and their governments. I aim to provide an important contribution to these developments with novel assay reagents and smart chemistry.

Huib Ovaa, Netherlands Cancer Institute, Chemical Biology

The Dutch BSc programme is primarily geared towards research. Even though the vast majority of graduates will pursue a career outside research, little emphasis is given to education in innovation and entrepreneurship on the one hand and education and communication on the other hand. This may explain why the vast majority of students enrol in the research MSc rather than choosing the business or communications/education variant of the MSc. Excellent working relations between academia and industry in the Netherlands may create opportunities for involving more industrial lecturers in the education process at universities.

Enrolment into the BSc physics has nearly doubled, from a historic low of 482 in 2002 to 707 students in 2012. The past five years have seen an increase of over 26%. In chemistry, this increase over the past five years is 13%; in 2012 672 BSc-students enrolled in chemistry. On top of that, 252 students started a BSc in a multidisciplinary area that for to a large extent teaches chemistry and/or physics, e.g. BSc Medical Natural Sciences (VU University Amsterdam), BSc Nanobiology (ErasmusMC/Delft University of Technology), or BSc Molecular Life Sciences (Wageningen University)[4]. The 2013 enrolment figures confirm this positive trend.

For the last 15 years the percentage of female students in physics has remained constant at roughly 13% without any sign of increase, whereas in chemistry a modest increase has become visible, from 29% in 2008 to 33% in 2012. As a result, women (and minorities) remain underrepresented in Dutch university physics and chemistry education, which leads to an under-utilisation of talent that is very much in demand. A similar trend is found in the multidisciplinary studies, where the share of female students is now around 39%. The number of female role models in the combined physics and chemistry university faculty has been growing from about 8-9% from 2009 to 11% in 2011. This number is expected to further increase to at least 15% in 2016 due to targeted recruitments through the Sector Plan, but further measures will be needed to reach the desired target of 20% in 2020 and to increase the too low a share of Dutch women in these new recruitments. An increasing number of role models at all career levels will positively influence the number of women opting for an education in physics or chemistry in the future. Improving the awareness that physics and chemistry contribute to solutions for grand societal challenges may provide another attraction for (female) talent. **See Recommendation 4: WOMEN AND MINORITIES.**

The first results are emerging of the increasing outreach activities to encourage more young people to study physics and chemistry. Given the lead time of many of the activities, the number of physics and chemistry students should continue to improve. To counter the expected demographic shrinkage of 18-year olds by 2025, however, these outreach efforts will need to be further enhanced, for example through initiatives such as Nationaal Techniekpact 2020 and the Masterplan Bèta en Technologie of the joint top sectors, who put forward the high ambition that that by 2025 40% of all students obtain a degree in science, technology, engineering and mathematics. Currently, this is about 25%[5]. Dutch universities can benefit from increasing international competition for the best

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[4] *Eerste tussenrapportage Commissie-Breimer inzake Implementatie Sectorplan Natuur- en Scheikunde*, commissie-Breimer, 9 juli 2012

[5] *Masterplan Bèta en Technologie: Naar 4 op de 10, meer technologietalent voor Nederland*, Nelo Emerencia et al., februari 2012

students in the world. Attracting these excellent students to the Netherlands will be of significant benefit to Dutch (innovative) economic activities provided a sufficient number of them can be convinced and allowed to stay upon graduation[6]. In a recent study on the German R&D-landscape[7], the Advisory Council for Science and Technology Policy (AWT) concluded that the Netherlands could learn from the German success in attracting foreign students, researchers and technicians, as this is mainly due to its consistent R&D-policy.

At present, the vast majority of BSc students are Dutch. The teaching of BSc courses in English should attract more international students, as has been demonstrated by the Maastricht University and the University of Groningen. The MSc programmes all are taught in English; in some universities the international MSc students are the majority, which raises the fraction of female and minority students. The new development of teaching university students via massive open online courses (MOOCs) provides excellent opportunities for Dutch scientists and universities to reach prospective Master and PhD students around the world. A unique opportunity is the recruitment of more students from neighbouring countries (Germany, Belgium, United Kingdom), where interest in sciences remains high and the Netherlands is considered an attractive option. Another interesting pool are students from the Central/East-European countries, where physics, chemistry, and mathematics are traditionally taught at a high level in secondary schools. The tuition fees for non-EU students are high, however, and may present an economic barrier. On the other hand, high cost is seen as an indication of quality. Introduction of scholarships for the very best students would raise their interest in a MSc degree from the Netherlands, also allowing future selection of better PhD candidates. **See Recommendation 3: ATTRACT THE BEST STUDENTS**

Of all students that are still enrolled in the BSc programme in the 2nd year, about 50% finish the programme in four years (up from 40% a few years ago). Attempts to further increase graduation rate within a limited time should not jeopardise the present high standard of the diplomas. The past five years have seen a strong increase in attention for quality control and the improvement of (young) lecturers: a promotion to associate professor requires successful completion of the Basic Teaching Qualification course. In many universities the importance of educational qualifications for an academic career is still lower than those of research quality. The problem is, however, receiving increasing attention and several policies are being implemented.

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[6] *Make it in the Netherlands! Advies over binding van buitenlandse studenten aan Nederland,* SER-advies 13/01, Sociaal-Economische Raad, april 2013

[7] *Vasthoudend Innoveren. Een onderzoek naar het Duitse Wetenschapslandschap en R&D-beleid,* Ton Nijhuis, Adviesraad voor het Wetenschaps- en Technologiebeleid, november 2012

4.3 Research

Strengths	Weaknesses
• Very high quality • Well organised • Broad range of expertise areas with high relevance • Strong earning power for large grants (NWO ‘Gravitation’, ERC)	• Multidisciplinary research less well facilitated • Gap between science and engineering • Ius promovendi (right to award doctorates) reserved for full professors only
Opportunities	**Threats**
• Grand societal challenges have significant chemistry and physics components • Well developed public-private-partnerships • Attract large infrastructure	• Shrinking budgets in fields already close to subcritical mass • Underfunding of strong small-scale curiosity-driven research • Too much rigidity and top-down choices, blocking new developments • Loss of competitiveness in attracting (international) research talent

Dutch physics and chemistry research is of the highest quality. According to the 2012 STI[2]-analysis Dutch physics[8] ranked number one in terms of impact, cited 1.8 times more than the world average; in the same ranking chemistry ended up third, Dutch chemistry articles being cited 1.6 times more than world average. According to a recent Canadian review[9], the Netherlands are ranked the no. 1 country for chemistry and the no. 2 country in the world for physics (behind Switzerland) based upon citation impact. Several elements contribute to this culture of excellence: deep historical roots (with a relatively high number of Nobel laureates), a strong national identity, dedicated funding agencies, national research institutes, and a remarkable open research atmosphere with a high percentage of international collaborations.

This exceptionally high scientific quality is paired with a very good national organisation and infrastructure that optimally benefits from the compact size of the Netherlands. For Dutch physics, five focus areas have been identified in the 2007 ‘Fysica voor de toekomst - Toekomst voor de fysica’ document[10]. Similarly, four such focus areas have been defined for Dutch chemistry[11].

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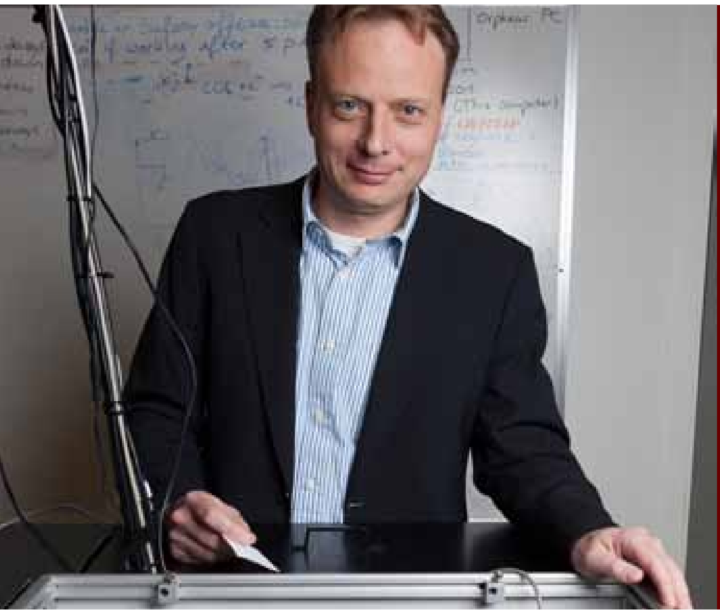
[8] *Science, Technology, & Innovation Indicators 2012,* Pim den Hertog et al, STI2, December 2012

[9] *The State of Science and Technology in Canada, 2012*, The Expert Panel on the State of Science and Technology in Canada, The Council of Canadian Academies, 2012

[10] *Fysica voor de toekomst. Toekomst voor de fysica,* Commissie *ad hoc* Sectorplan Natuurkunde, 6 juni 2007

[11] *De perfecte Chemie tussen onderwijs en onderzoek,* Regiegroep Chemie, 6 juni 2007



I believe that by fundamental interdisciplinary research on the interface of chemistry and physics we will achieve full understanding and control of charge transfer in single molecules. This will lead us to new design rules for single molecule electronics, explicitly exploiting the quantum mechanical properties at this small scale.
Ferdinand Grozema, Delft University of Technology, Chemical Engineering, Opto-Electronic Materials

I dream that in 2025 the gap between biochemistry and cell biology will be closed. (Bio)chemists provide snapshots of isolated biomolecular complexes at atomic-level detail. Cell biologists produce lower-resolution images of whole living cells. Closure of the gap between the two disciplines will reveal how life originates from basic chemical and physical principles. Such insight will have tremendous impact on medical sciences and technology, but above all it will satisfy many scientist's curiosity.
Dirk Jan Slotboom, University of Groningen, Department of Biochemistry, Membrane Enzymology

Within each focus area the deans of the faculties of science have identified ‘centres of gravity’, a number of which have been further strengthened by funds assigned through the Sector Plan in 2010 and additional profiles in the top sectors (economic priority areas). The intensified collaboration of the two Amsterdam universities culminating in the foundation of a joint ASML-FOM-UvA-VU Advanced Research Centre for NanoLithography, is a beautiful example of the Sector Plan success.

Although the Sector Plan focus areas have generally been well chosen, there are a number of strategically important areas, in chemistry in particular, which are not part of the current focus, or at risk of becoming sub-critical. These areas are mostly found in chemistry related to life sciences, including synthetic chemistry and drug innovation. If these subdisciplines are to survive then synthetic and biomedical chemistry efforts in faculties of science, university medical centres, and institutes such as the Netherlands Cancer Institute will have to be connected. The dearth of Dutch industry in these areas has led to its exclusion from thematic top sector funding as well, despite the theoretical inclusion of relevant topics on the Life Science and Health agenda. It is crucial to be alert to the emergence of promising new areas within, but especially between existing focus areas and between disciplines. Such new areas emerge very clearly on the interfaces of engineering and the fundamental areas of chemistry, physics and biology. Examples include bio-engineering, synthetic biology, systems biology, intensified reaction and separation systems using electromagnetic fields (microwaves, plasmas, lasers, etc.), super-resolution live-cell imaging technology, technologies for production of complex biomaterials (artificial tissues, organs, etc.) or advanced solid and soft products (nanomaterials, pharmaceutical crystals, thin layers, colloids, surfactants, etc.), as well as devices for information generation in chemical and biomedical applications. **See Recommendation 8: FUTURE-PROOF CHEMISTRY AND PHYSICS.**

Funding in the Netherlands in the past few years has seen dramatic changes. The total budget for the Dutch funding agency NWO has decreased from M€ 720 to about M€ 630. Additional funding up to M€ 500, available in the last years from natural gas revenues (FES), has disappeared for (basic) research and about 40% of the NWO budget is earmarked for the top sectors (a M€ 100 contribution to public-private partnerships and M€ 175 for science supporting the top sectors). FOM, the funding agency for physics, and NWO Chemical Sciences, are facing their share in these cuts. As a result, award rates for open grants (non-thematic research) have dropped dramatically, and an increasing number of excellent proposals can no longer obtain funding.

The Dutch competition (organised through NWO) for extra large multi-group grants (NWO *Gravitation*, around M€ 30) has brought additional money into the physical and chemical sciences, but at the same time these large strategic frameworks put further pressure on small-scale exploratory programmes. As a consequence, the options for non-thematic projects and programmes have decreased and will decrease further by an estimated 20% or so in the coming three years due to NWO budget cuts and the absence of an inflation correction. Scientific breakthroughs are frequently the result of bottom-up, curiosity-driven research, where good ideas often emerge when borders of traditional disciplines are crossed. Insufficient financing for exploratory programmes risks putting Dutch physics and chemistry in the position of trend-follower rather than trendsetter. **See Recommendation 7: BOTTOM-UP FUNDING.**

Attracting and retaining research talent in an international market is becoming increasingly difficult. As a result of funding assigned by the Sector Plan an important step forward has been taken in strengthening academic research and education, but the talent that has been recruited is facing a lack of funds for start-ups and a decreasing number of open programmes where they can compete for funds to support their research and establish their research independence. An additional Dutch disadvantage in the competition for junior talent, is the fact that the *ius promovendi* is reserved for full professors at nearly all universities. **See Recommendation 5: EARLY-CAREER RESEARCHERS**.

The recruitment of early career researchers, in particular women, is furthermore hampered by the so-called ‘two-body-problem’; offers become much more competitive if a position for an academic spouse can be found. Internationally universities operate very forcefully on this point. More inter-university collaboration in a relatively small country such as the Netherlands may help address this. When it comes to hiring and retaining professors at the senior level, it is becoming almost impossible to offer start-up packages and grants that can compete with offers made in neighbouring countries. **See Recommendation 6: SENIOR SCIENTISTS.**

Top quality infrastructure is a *sine qua non*. Facilities and advanced instrumentation remain of utmost importance for conducting world-class physics and chemistry research. Facilities range from regional (e.g. a clean room, next-generation sequencing, advanced microscopy) and national (e.g. a free-electron laser, National Proteomics Centre) to international infrastructure (e.g. various European XFEL’s, High Magnetic Field Lab, European NMR Large Scale Facility, CERN and ITER). The infrastructure plans *NWO Large* and *Roadmap for Large Scale Infrastructures* have enabled the creation and exploitation of medium and large scale facilities for the science community in the Netherlands. This infrastructure needs to remain attractive to researchers world-wide and Dutch researchers need continued access to relevant infrastructures abroad. **See Recommendation 9 RESEARCH INFRASTRUCTURE.**

In addition to Big Science requiring Big infrastructure, there is an increasing requirement for diverse high-end equipment that cannot be financed by single groups anymore, let alone by starting principal investigators. Core facilities such as clean rooms, next-generation sequencing, proteomics and mass spectrometry, electron and super-resolution fluorescence microscopy, and facilities for high-throughput (genetic or compound) screening need to be available and accessible for any research group. Access to these facilities should be arranged through user groups, and quality ensured by advisory boards and revolving-type evaluation and financing. **See Recommendation 9: RESEARCH INFRASTRUCTURE.**

4.4 Industry and Innovation

Strengths

- Strong presence of international industry related to chemistry and physics
- Strong personal contacts academia-industry
- Well developed public-private-partnerships

Weaknesses

- Gap between Science and Engineering in academic research
- ‘Use-inspired’ basic research insufficiently addressed
- Difficult to tackle larger, multidisciplinary (industrial) challenges
- No tradition of collaborations between universities and SME
- Funding and human capital gap after ‘incubator stage’ of start-ups

Opportunities

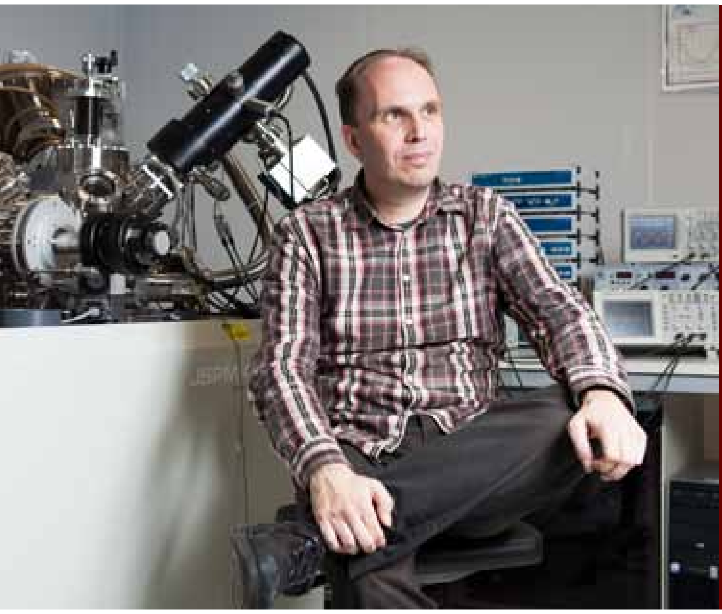
- Growing entrepreneurial spirit among academics
- Open innovation ecosystems that are developing
- International collaborations
- Regional collaborations including universities of applied sciences (HBO)

Threats

- If Dutch education and science does not maintain world-class level, industry will look abroad
- Severe decline of (innovation at) large chemical industries
- Inability of SME’s to attract larger funds necessary for growth

Physics and chemistry always have, and will continue to play an important role in innovation. The compact size of the Netherlands has led to a wealth of strong personal contacts between the academia and industry, and the top sector policy has notably brought these two closer together. Roadmaps for specific challenges are being discussed where the questions at private companies are successfully matched with possibilities at the public institutes. At the same time, many large industrial (as well as societal) challenges require a multidisciplinary approach, and at present academia finds it difficult to address these larger, multidisciplinary research topics effectively.

Given the strong connection between individual top sectors and academic disciplines, the top sector structure does not currently provide a route for radically new ideas to find their way to industrial innovation, which means Dutch industry risks missing out on the ‘top sectors of the future’. **See Recommendation 12: SCIENCE AND INNOVATION.**



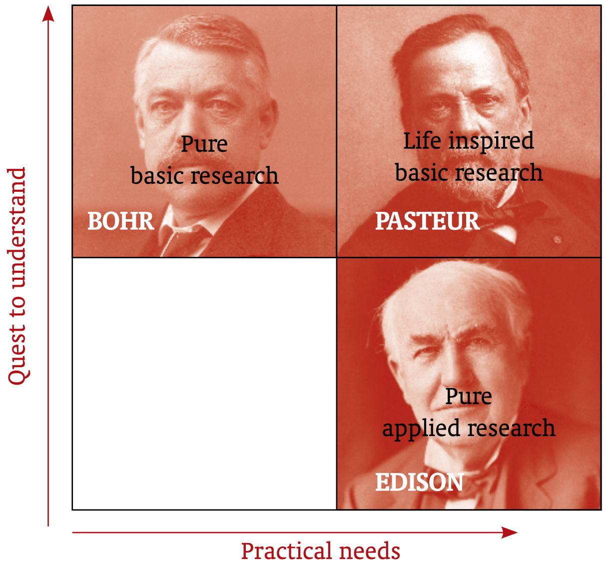
In 2025 I hope to have established a truly interdisciplinary research group at the interface between chemistry and physics, employing the unique opportunities of scanning probe microscopy to understand and control functional self-assembled systems at the highest detail possible – that of individual atoms and molecules.

Hans Elemans, Radboud University Nijmegen,
Institute for Molecules and Materials,
Scanning Probe Microscopy

Our universe is a mysterious object. We are very successful in describing matter, which is 5% of the universe. But we do not understand the remaining 95% or why there is no anti-matter. My dream is to find out why the anti-matter disappeared and what the ‘other stuff’ is.

Olga Igonkina, FOM Institute for
Subatomic Physics Nikhef, ATLAS-group

Furthermore, in practice the top sector structure risks creating unwanted barriers. For example, chemistry as a discipline is significantly larger than the Top Sector Chemistry and makes a significant contribution to the Top Sectors Life Sciences and Health, Water, and High Tech Systems and Materials. **See Recommendation 8: FUTURE-PROOF CHEMISTRY AND PHYSICS.** In this respect, the Advisory Council for Science and Technology Policy (AWT) concluded that the Netherlands can learn from Germany that an active, continuous and persistent R&D policy combined with political appreciation for science and technology is advantageous for innovation and that the switch from a line of policy focused on subsidies for large industries to policies focusing on investment in important issues of the future, has proven to be very successful[12].



Pasteur's quadrant[13]

The top sectors have encouraged academia to be more active in the purely applied research quadrant, where players like TNO operate as well. The main gap in the Netherlands, however, is in the more bottom-up, use-inspired, basic research referred to as the 'Pasteur quadrant'[13], Yet, at places like MIT, SEAS & Wyss (both Harvard), and the ESPCI this blossoms. **See Recommendation 7: BOTTOM-UP FUNDING.** Technological innovation needs a continuum between science and excellent engineering. This is insufficiently addressed in current innovation and research policies – a current weakness, but an opportunity for the future. **See Recommendation 11: SCIENCE AND ENGINEERING.**

For most sectors, Dutch academia has strong and relevant activities in fundamental research. Traditionally the large industrial labs (Philips NatLab, Shell, AKZO, DSM central research) have played an important role in connecting pure research to use-inspired, basic research and purely applied research. As pointed out in section 2.3 the role of these large labs has changed. Research that used to take place there is increasingly moving to open innovation ecosystems. Powerful examples are in the Eindhoven Brainport and the Chemelot campus. The present, fluid situation presents opportunities for creating new connections between industry, engineering, and the physical sciences community. As a result, small and medium enterprises (SME) can increasingly become an important

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[12] *Vasthoudend Innoveren. Een onderzoek naar het Duitse Wetenschapslandschap en R&D-beleid*, Ton Nijhuis, Adviesraad voor het Wetenschaps- en Technologiebeleid, november 2012

[13] *Pasteur's Quadrant: Basic Science and Technological Innovation*, Donald E. Stokes, Brookings Institution Press, 1997

player in innovation. In part, the practical innovation issues SMEs deal with are best addressed by universities of applied sciences (HBO); these teams could profit from university expertise and academic research infrastructure. On the other hand, there are numerous, somewhat localised and non-coordinated, initiatives to encourage innovative university spin-out companies. However, these companies struggle to gain sufficient funding and management experience to grow beyond the 5-10 employee level due to a lack of access to venture capital funding. **See Recommendation 12: SCIENCE AND INNOVATION.**

4.5 Society

Strengths • Highly educated society • General fascination for (certain branches of) science • The general public trusts (hard) scientists	Weaknesses • No sense of urgency to support contribution of science to societal challenges • Physical sciences underrepresented among policy makers • Insufficient communication about science benefits to the public
Opportunities • Chemistry and physics offer many business opportunities • Fascination for discoveries in (young) children • Awareness of need for solutions to societal challenges is increasing	Threats • Limited political willingness to make long-term investments in science • Lack of political influence from scientists and scientific organisations • Poor image of some industrial sectors (e.g. chemical)

A recent report by the Rathenau Institute[14] shows that the general public trusts science more than the judicial system, and significantly more than parliament and government. This picture is different however for the chemical *industry*, which suffers from a distinct image problem. At the same time, the appreciation of the general public (including politicians) for the central role that science plays in our society, and of the direct link between science research and solutions for the grand societal challenges can be qualified as neutral at best, without any sense of urgency. Nobody is against science or against some public investments in science, but when push comes to shove, support for the sciences is lukewarm and the willingness to invest in long-term scientific research is weak.

The scientific community does not have many representatives at the highest levels of policy makers in the Netherlands (government and parliament), and this results in a situation where it is difficult

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[12] *Hoeveel vertrouwen hebben Nederlanders in de wetenschap,* Will Tiemeijer en Jos de Jonge, Rathenau Instituut. Den Haag, 2013

to convince policy makers to take unconventional measures to specifically stimulate education in sciences such as physics, chemistry, and engineering, and to invest preferentially in fundamental research and technological innovation.

The solutions to global challenges that society faces will have substantial physics and chemistry aspects. These solutions will drive new business opportunities, and will therefore positively influence Dutch economic competitiveness in the future. The link with global societal challenges offers a new chance to convince the general public of the essential role of science. Individual scientists, but also universities, schools, funding agencies, and professional organisations all have excellent opportunities to emphasise these societal challenges in the hope of attracting a wider variety of students and researchers to all levels of science education, from vocational (MBO) to university level.

All universities and many researchers have made increasing efforts to communicate their achievements to the public, and create public awareness of the long-term goals and benefits of fundamental scientific research. So far, however, the scientific community in the Netherlands has not been very effective in gaining societal support or extra structural funding. **See Recommendation 10: AWARENESS.**

5 Conclusions and Recommendations

Much has been achieved since the writing of the Sector Plan visions for chemistry and physics in 2007 and the installation of the Breimer Committee in 2009. The focus areas identified by the deans of the Faculties of Science have been strengthened with excellent researchers and the international influx of students has increased.

Now is the moment to ensure that the excellent position of Dutch physics and chemistry is maintained. This should not be taken for granted, as the world has changed considerably since 2007 and there is fierce international competition for talent. Germany for instance is increasing significantly its investments in top research (at an annual level of 5% for key institutions and funding agencies), aggressively recruiting leading researchers and enabling innovation.

In Chapters 2 and 3 we have outlined important societal and scientific challenges that need to be addressed. They require interdisciplinary approaches based on robust and vigorous chemistry and physics disciplines. We strongly recommend an extension of the current Sector Plan, taking into account the observations and recommendations listed below and translating them into a concrete action plan for which adequate funding should be made available.

Whereas many recommendations can be seen as a continuation of the current Sector Plan, we have added essential new elements for a follow-up:

- education needs to be strengthened at the pre-university level (1 and 2);
- attraction of top researchers calls for additional measures (5 and 6);
- multi- and interdisciplinary research needs more attention, including engineering (7, 8, 11);
- and actions are needed to bridge science to innovation (12).

The recommendations of this report have been grouped into three clusters: education, research, and society and innovation. Taken together they should enhance the quality of Dutch science education, boost the international influx of talent at all levels, and increase the volume of support for research and innovation, nourished by bottom-up initiatives.

Education

1. START EARLY

Observation: Young children are very interested in the grand questions of life and the universe, yet there is little in the curriculum of primary schools to feed this natural curiosity. When this curiosity is not nurtured, it tends to disappear quickly. As a result, many adults are not aware of the prominent role of science in the welfare of our everyday lives.
Recommendation: *Educate and appoint dedicated science teachers at each primary school to educate children for a few hours per week on the grand questions and to encourage the fun and fascination for science and technology. Provide good teaching programmes and materials.*

2. EMPOWER THE CHEMISTRY AND PHYSICS TEACHERS

Observation: Academically trained teachers in secondary school are crucial to provide the scientific literacy, flexible curriculum, and career awareness required for students to choose a future in chemistry and physics. The number of teachers with an academic degree in physics or chemistry however is gravely insufficient and further declining.

Recommendation: *The number of academically trained teachers has to increase. Physicists and chemists who opt for a career change towards teaching should get maximum financial and educational support. Universities should foster a strong coupling between teacher education centres and physics and chemistry departments. Teacher education must be of an excellent academic standard, reflecting modern developments in chemistry and physics as well as methods to transfer this knowledge to the future. Establishing a national centre of expertise in science teaching should be explored.*

3. ATTRACT THE BEST STUDENTS IN THE WORLD

Observation: University education will soon be a global enterprise with a majority of international students at major institutions. There will be an increased international competition to attract the best students.

Recommendation: *Dutch physics and chemistry departments should unite and jointly recruit the best international students under the name 'University of the Netherlands' with branches at the various locations. Physics and chemistry can act as a pilot in establishing attractive scholarships for the best students, e.g. through a public-private partnership as in the Chemiebeurzen-initiative in the Top Sector Chemistry. [We propose 40 fellowships for physics and chemistry, each k€ 12 per year plus waiver of tuition fees.]*

4. ATTRACT MORE FEMALE AND MINORITY STUDENTS AND FACULTY

Observation: Chemistry and in particular physics attract constant low percentages of female students or students from minority groups, thereby missing out on a considerable talent pool. Recommendations 1 and 2 should improve this in the future. International recruitment, where chemistry and physics are well positioned, provides another opportunity to increase the number of female and minority students. The efforts to recruit more female faculty members show encouraging results, although the growth rate is too low to meet the target of 20% female staff in 2020.

Recommendation: *Recruitment of women and minorities needs continuous emphasis, e.g. by establishing a larger number of role models at all career levels. Create incentives to reward the selection of women and minorities in funding schemes (see Recommendations 5 and 6 below).*

Research

5. ATTRACT THE BEST EARLY-CAREER RESEARCHERS

Observation: Recruitment of early-career researchers has become an international competition with start-up packages being vitally important. Recently, the Netherlands has been increasingly losing this competition for talent, for two important reasons: (1) the start-up packages fall short compared to international offers, and (2) assistant and associate professors in the Netherlands do not have the 'ius promovendi' which is taken as a lack of trust.

Recommendation: *Establish a scheme for start-up grants with a short evaluation time to create a significant advantage for institutions during competitive negotiations. [~M€ 1 per start-up package.] Give qualified junior professors the 'ius promovendi'.*

6. ATTRACT AND RETAIN THE BEST SENIOR SCIENTISTS

Observation: Inspiring senior scientists have a special role in attracting and developing new talent, i.e. 'making school'. To attract and retain these role models financial support is needed beyond the NWO Vici grant that can match offers made by other countries.

Recommendation: *Establish a national fund to attract world-leading senior professors, such as the M€ 5-Alexander von Humboldt Professorships in Germany. To retain top senior scientists personal grants should exist beyond the level of Vici for the full length of an academic's career.*

7. BOTTOM-UP FUNDING

Observation: Despite the fact that scientific breakthroughs are often the result of bottom-up, curiosity-driven research, there is a growing trend to define research programmes within strategic frameworks. Consequently, the options for non-thematic projects and programmes have decreased and will decrease further. Good ideas usually cross borders of disciplines and create innovators rather than followers.

Recommendation: *Good ideas need funding, irrespective of strategic choices. The level of funding for undirected small-scale grants urgently needs to be restored to the level in the year 2000.*

8. FUTURE-PROOF CHEMISTRY AND PHYSICS

Observation: The natural multidisciplinary of both disciplines does not easily obey organisational boundaries. An undesirable side effect of strategic research funding is the formation of a fragile cluster of a small number of excellent groups in narrow focus areas. The grand scientific and societal challenges call for a broader range of expertise than covered by current funding models, which are leading to non-funded 'blank spots' of excellent and relevant research, such as the molecular life sciences that are mostly outside chemistry departments.

Recommendation: *Include the full research agenda of chemistry and physics outlined in Chapter 3 into a future Sector Plan, to maintain the inherently multidisciplinary nature, sustain critical mass and avoid blank spots.*

9. RESEARCH INFRASTRUCTURE

Observation: Equipment infrastructure is a sine qua non. The increasing complexity of research requires more advanced equipment, no longer affordable to individual research groups.

Recommendation: *Infrastructure programmes and funding for national or regional facilities should ensure national/regional access. These programs should be adapted such that they include support for infrastructure and research facilities over periods of time that extend beyond the 2-4 year funding cycles. Participation in and access to research infrastructure facilities at the European and global scale should be a high priority and coordinated nationally. The Netherlands should be a strong advocate for a more coherent European large-infrastructure policy.*

Society and Innovation

10. PUBLIC AWARENESS

Observation: Physics and chemistry lie at the basis for many of the solutions for grand societal challenges. The general public is not aware of this importance, and political appreciation is poor and needs to be improved. Exemplary cases of effective public outreach by scientists exist, but they are too few in number and remain unstructured.

Recommendation: *Continue the growing number of successful outreach activities such as Lowlands University. Science should strive for a sustainable presence in the popular media. Universities, schools, funding agencies and professional societies should highlight more effectively the important role that physics and chemistry play in addressing societal challenges motivating potential new groups of students and researchers.*

11. BRIDGE SCIENCE TO ENGINEERING

Observation: Major scientific questions, major societal challenges, and industrial problems often call for researchers in engineering disciplines to work alongside researchers in basic science. This requires a change of mentality and understanding in both teaching and research. Scientists and engineers together need to generate breakthrough solutions that go beyond incremental progress, also outside the technical universities.

Recommendation: *Establish new funding for 'breakthrough engineering' research with an associated honours-level curriculum.*

12. BRIDGE SCIENCE TO INNOVATION: THINK GLOBAL – ACT LOCAL

Observation: Big challenges require coordinated interdisciplinary approaches that go beyond the scale of individual research groups. The Netherlands has a good tradition in building and maintaining contacts and dynamics between academia and existing industry. The Netherlands, however, lacks high-risk funding systems such as venture capital, hampering start-ups and their growth to a hundred employees and on to new industries and ecosystems. To compete worldwide, the Netherlands should strengthen research and technology hotspots containing small and large companies around universities.

Recommendation: *A part of the innovation (e.g. top sector) policy should focus on future industries based on current scientific strengths in the Netherlands. The equipment infrastructure at universities should be easily available to SMEs. National and local governments should stimulate regional ecosystems around universities, where start-ups are supported by experienced management. Such ecosystems will multiply human capital and infrastructural investments. In these ecosystems mission-oriented research centres should be supported that address big challenges requiring a multi- and inter-disciplinary approach, such as the Dutch Institute For Fundamental Energy Research (DIFFER) and the ASML-FOM-UvA-VU Advanced Research Centre for NanoLithography.*

Samenvatting Vision Paper 2025

De wereld en de wetenschap staan voor grote uitdagingen: oplossingen vinden voor maatschappelijke problemen (duurzaamheid, energie, gezondheidszorg, materiaalschaarste, klimaatverandering), globalisering van wetenschap en onderwijs, en de opkomst van regionale innovatiegebieden. In de wetenschap zelf spelen ook nog drie grote wereldwijde trends: steeds meer informatie en big data, leren van en ontwerpen voorbij de natuur, en het slechten van grenzen tussen disciplines en samenwerken met de technische wetenschappen. Chemie en fysica zijn bij uitstek vakgebieden om al deze uitdagingen aan te gaan. De Nederlandse chemie en fysica zijn toonaangevend in de wereld en verkeren in een uitstekende positie om bij te dragen aan een gezonde toekomst van Nederland. Om zowel die toppositie te behouden als de mogelijkheden voor Nederland zijn nieuwe initiatieven, inspanningen en investeringen in wetenschap, onderwijs en samenleving nodig. In dit document beschrijven de Nederlandse chemische en fysische gemeenschap hun wetenschappelijke ambities voor 2025. De gekozen onderwerpen van onderzoek sluiten goed aan bij eerdere keuzes in het Sectorplan Natuurkunde en Scheikunde en de Research Agenda van de KNAW en dichten gaten die in het topsectorbeleid zijn gevallen. Het document sluit af met een aantal aanbevelingen om de excellente en cruciale positie van de Nederlandse chemie en fysica te versterken en te benutten. Dit visiedocument kan dienen als uitgangspunt voor een toekomstige actualisering en uitbreiding van het succesvolle Sectorplan.

Ambitie

De opstellers van dit document hebben een groot aantal gesprekspartners in Nederland gevraagd wat naar hun idee in 2025 aan nieuwe wetenschappelijke ontwikkelingen gerealiseerd zou kunnen zijn, en op welke terreinen je dan het komende decennium onderzoek moet doen. Dat heeft geleid tot het identificeren van onderzoekslijnen die alle aansluiten op onderzoek waar de Nederlandse chemici en fysici wereldwijd gezien in uitblinken, gegroepeerd in 7 terreinen.

1. *De chemie en fysica van leven en gezondheid*
2. *Energie*
3. *Nanowetenschap, nanotechnologie en geavanceerde materialen*
4. *Complexe (moleculaire) systemen, zachte materialen en vloeistoffen*
5. *Duurzame (bio)chemische proceskunde*
6. *Het (quantum) heelal*
7. *Quantumtechnologieën*

Het visiedocument beschrijft per onderzoeksterrein lijnen van onderzoek waarin Nederland kan excelleren.

Aanbevelingen

De aanbevelingen richten zich op vier aspecten.

1. Het pre-universitaire onderwijs versterken.
2 Aanvullende maatregelen om een carrière in de wetenschap aantrekkelijker te maken en toponderzoekers naar Nederland te halen en ze hier te houden.
3. Meer aandacht voor multi- en interdisciplinair onderzoek, inclusief samenwerking met de technische wetenschappen.
4. Acties om de kloof tussen wetenschap en innovatie te dichten.

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