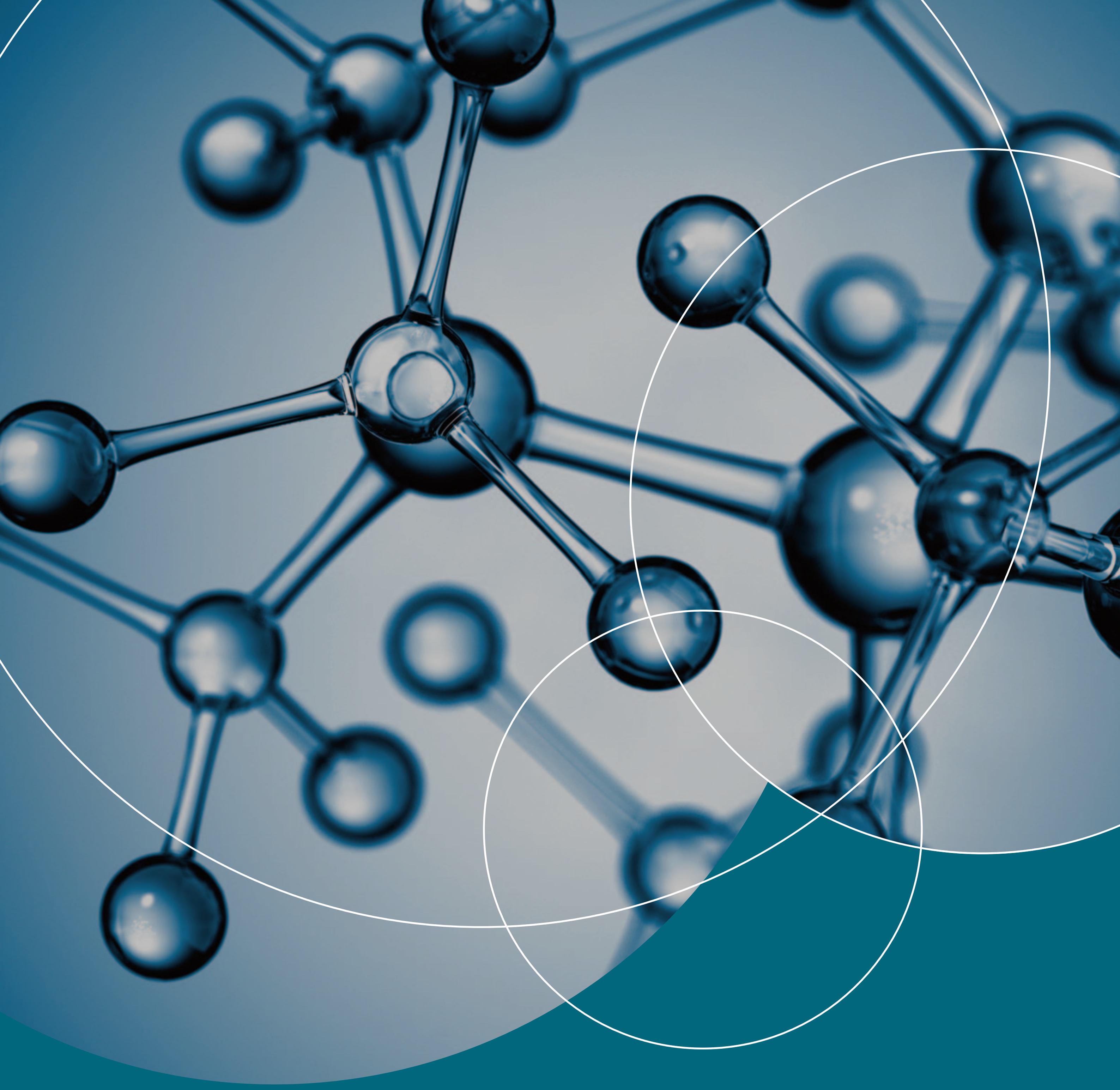


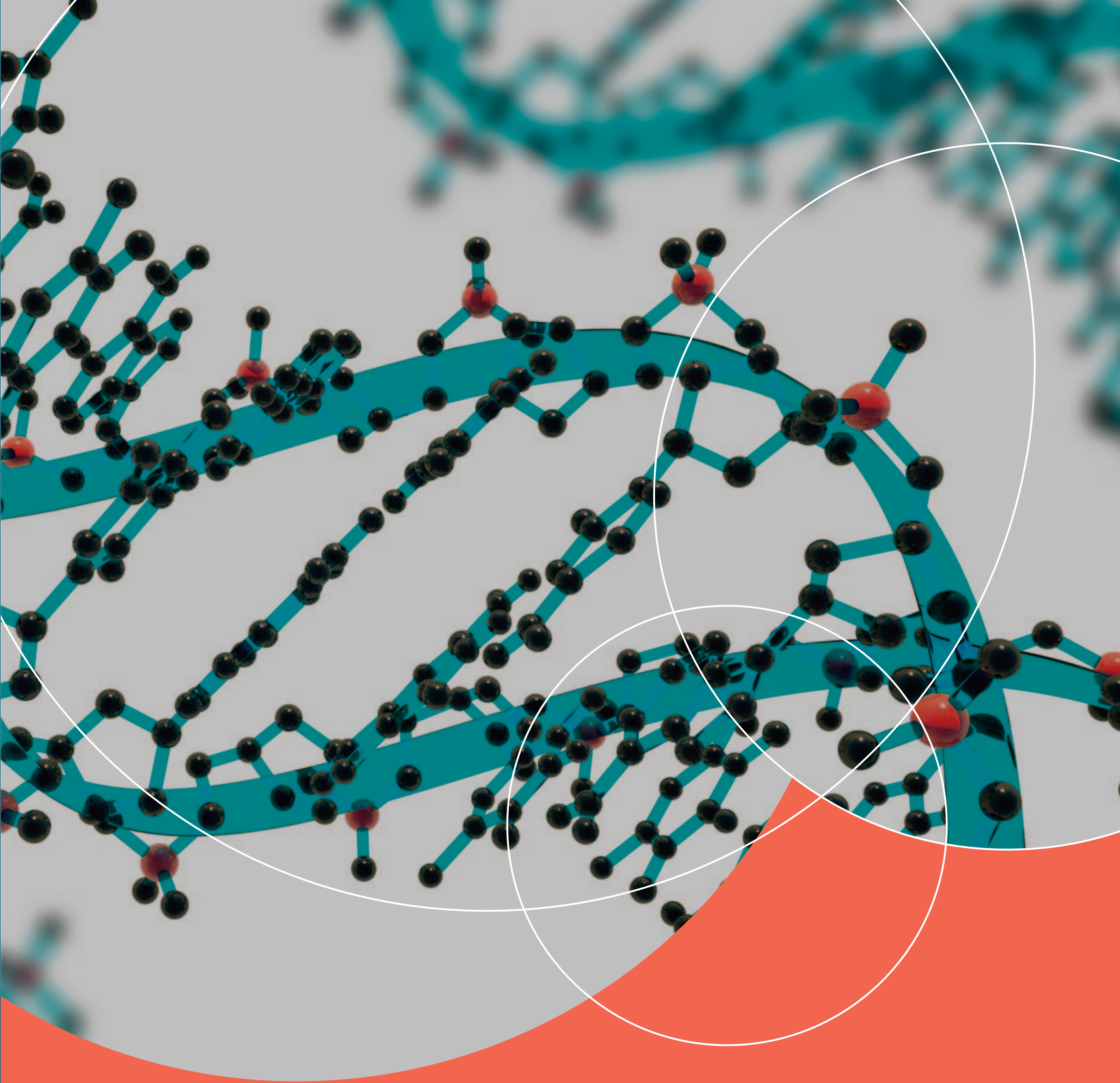
Strategy documents

Physics research communities
Round table Physics
2020

Strategy documents

Physics research communities
Round table Physics
2020

Strategy documents



Physics of Life

1. Scope or definition of the research community Physics of Life

Living systems comprise the most complex matter. Seeking a fundamental understanding of the processes that drive living systems pushes the boundaries of experimental and theoretical physics through the development of principles and concepts that balance the complexity of life with a physics-driven abstraction. The field of Physics of Life (PoL) can be broadly divided into three areas that range from fundamental research into life processes to applied research that is crucial for innovative future healthcare, energy and materials:

The physics of processes that are essential to life.

Research of PoL covers processes ranging from the level of molecules, via cells, to multiple cell type-containing tissues and organs, and ultimately to organisms, communities and ecosystems. The Dutch biophysics community has a proven strength in studies of life at the smaller scales, from molecules to cells. Currently, experimental and computational methods are broadening to include larger, more complex and multicellular systems, while maintaining the rigor of fundamental, quantitative analysis.

Key methods of PoL include statistical physics and information theory, (coarse grained) molecular dynamics, advanced microscopy and spectroscopy, single-molecule analysis, nano/microscale manipulation, structural and multiscale modelling, network theory, and quantitative cellular and molecular readout technologies. Importantly, the complex nature of living systems requires continuous and active feedback between theoretical ideas, computational modeling and experimental research. Using the increasingly large datasets that are currently generated in the life sciences, biophysicists contribute with
physics-based data processing, which is often entangled with the development of new physical models that provide insight in the sheer complexity of life processes.

Physics-based technologies that advance biological research.

The development of novel imaging modalities at all scales of life continues to play an important role. At the smaller scale, improved microscopy techniques have pushed the resolution and sensitivity limits down to single molecules. These methods are expanded, in close collaboration with biologists, to reveal more detail in biological processes, to allow longer time-lapses and larger areas, and to follow processes involving many generations of and/or populations of cells, while maintaining molecular detail. The recent instrumentational innovations in electron microscopy have opened revolutionary new applications in structural biology. Next to imaging, cutting edge tools like optical tweezers, microfluidics, self-assembled nano/micro particles and micro-fabricated devices are under continuous development together with (bio-)chemists and yield unique manipulation opportunities for single molecules and cells. Spectroscopy is another area where innovative optical methods uncover fundamental biological processes in a broad range of timescales. Automation and interfacing functional biomolecules with solid-state devices drives the development of smaller, faster, more versatile and cheaper sensing methods, high-throughput screening and other innovations.

Physics-driven research focused on health-care, diagnostics and treatments.

Work in PoL also encompasses the development of technology for clinical research and includes the discipline of medical physics. Advancing imaging technology at the (sub-)organ level, like Ultrasound, MRI, NMR, PET, CT and optical tomography is important to improve measuring organ function, characterization of diseases (such as cancer and cardiovascular disease), treatment planning, measuring treatment efficacy and monitor response to treatment. These are all important clinically driven objectives. In addition, advancing physics-based high precision intervention techniques such as (proton) radiotherapy, HIFU, laser technology may lead to more effective treatments with less side effects.

2. Vision for the next ten years

The overarching big question is: **How can we relate structures, interactions and dynamics in living systems to biological functionality across a wide range of length- and timescales?** The development of novel technologies for use at the single molecule, cell, tissue and organism levels needs to be aligned with this fundamental research program. Biophysical research is multidisciplinary by nature and often involves multidisciplinary teams, consisting of academic and non-academic partners that address major challenges in the field of life sciences. Close connections to biology, neuroscience, chemistry, computer science, mathematics, medicine, (bio-) informatics, material science and nanoscience should be maintained and enhanced.

One core fundamental research program is to elucidate the major biological processes/mechanisms at the level of the cell. Important processes that need to be dissected at a fundamental physical and biochemical level are, for example, genome organization, cell adhesion and migration, intercellular interactions and cell-cell signaling, (mechanical) signal transduction, cell metabolism, repair mechanisms, intracellular transport, nuclear transport, transmembrane transport, transcription regulation, RNA and protein metabolism. New opportunities arise when insight/results on separate mechanisms will be integrated into a complete working model of a prototype cell.

Physical factors known to influence cellular (both cytoplasmic as nuclear) biochemical processes and cellular function are mechanical forces (stretch, shear stress, pressure), temperature (e.g. in directing immune cell function), phase separation, and electrical currents (important in embryo development, cell differentiation, cancer etc.). In disease pathophysiology physical forces, together with abnormal functioning of signal transduction pathways, are likely to be also dysregulated, offering novel physics-based therapeutic approaches. In addition, PoL will expand systems-scale biophysics, leveraging remarkable experimental advances from diverse, quantitative directions within the Dutch scientific community, such as RNA-sequencing, whole-brain neural imaging and multiple-cell dynamics in organoid culture.

In medical physics, novel methods to characterize and monitor organs, diseases, such as cancer and cardiovascular diseases, and vascular architecture and function remain important. Developments in high-precision treatment techniques will improve therapies for a variety of diseases and reduce side effects.

3. Scientific challenges/themes

From molecules to complex in vitro systems.

The strong single-molecule field in the Netherlands has contributed to unprecedented insights into the functioning of bio-molecules. The field has been established as an essential complement to structural biology, in-vitro biochemistry, and cell biology. A key aspect is that the biophysical and biochemical processes occur at a thermodynamic state that is far from of equilibrium. Novel techniques and principles can now be applied to study more complex in vitro assemblies involving multiple proteins, chromatin, membranes, cytoskeleton, liquid-liquid droplets, and protein aggregation. New tools are needed and require close integration with chemistry and molecular biology. Ultimately it may be possible to define, resolve and reconstitute signaling pathways, neuronal signaling, ER tubes and vesicles, cell-cell interactions, and even synthetic life/cells, and synthetic immune systems at the molecular scale. Such advances are crucial to predictive understanding of key molecular processes that research in cells cannot and traditional biochemistry cannot provide. These efforts have the potential to make substantial impact in a new type of pharmacology that acts on entire pathways and systems rather than individual proteins, and is crucial to new approaches in age-related diseases. Understanding complex in vitro systems opens up a wealth of opportunities for bio-inspired, multifunctional supramolecular materials.

From single cells to multi-cellular tissues.

Biophysical research has tremendously progressed over the past 15 years in the ability to measure the biological activity of single cells, showing a remarkable level of dynamics and intrinsic stochasticity, challenging information theory with phenomena such as stochastic gene expression, cytoskeletal organization and dynamics, population oscillations at the level of proteins, DNA, and RNA, and transport in neurons. This field has provided crucial insights into what makes cells so versatile while remaining tightly organized. The developed tools and insights provide the opportunity to make a next step in the coming 20 years: understanding how cells are organized into multicellular systems and tissues. First insights from developmental biology feature remarkable orchestration of large assemblies of cells. New developments such as organoids, gastruloids, organs on a chip and human biopsies that can be kept viable ex vivo, provide the type of experimental control that allows a quantitative physics approach. This offers a chance to understand such cellular interactions in complex tissues at a predictive level. Moreover, these developments will strengthen the bridge between physics of life and e.g. clinical challenges on development of novel precision treatments and disease models. Additional efforts include evolutionary ecology, like plant-microbe interactions. Physical theory will be crucial to for understanding and prediction of emergent systems and has enormous potential for links to other fields.

The new challenge of high dimensional data and Artificial Intelligence.

Novel techniques for measurements and characterization have been creating unprecedented amounts of data and detail from the molecular up to the patient level. For instance RNA and DNA sequencing, is driving a revolution in cellular and developmental biology, evolution, protein science, immunology, and cancer research. Less extensive, but at least as intriguing, are possibilities to measure the activities of all neurons in simple organisms. While crucial discoveries have already been driven by these data, we anticipate that far more science is hidden within it. Recent developments in artificial. While crucial discoveries have already been driven by these data, we anticipate that far more science is hidden within it. Recent developments in artificial intelligence (such a convolutional neural networks), has allowed unprecedented means of processing extremely large and high dimensional amounts of data. It is expected that AI will become more and more important for the physics of life domain to provide insights that will boost for example precision medicine.

4. Application perspective (incl. societal challenges)

Fundamental research on cellular mechanisms is exceedingly important for a better understanding of physiology and disease, which is indispensable for developing better diagnostics and therapies. A rigorous physical understanding of physiological mechanisms may lead all the way to understanding pathophysiology. Many of the great challenges, as described in the NWA themes 'Oorsprong van het leven', 'Personalized medicine', 'Energy transitie', 'Meten en detecteren', and 'Materials' have a clear PoL component.

New materials are often inspired by how novel properties emerge from the organization of molecules at lower levels in biology; some therapeutic approaches have very specific requirements, like cell and tissue culture conditions for regenerative medicine purposes and certain tissue/bone replacements. The photosynthesis research in the PoL community plays a fundamental role in the change to sustainable energy sources. Advances in imaging technology allow quantitative evaluation of anatomical, functional, metabolic and molecular changes.

These advances lead to new methods for biological research, new (multi)functional supra molecular materials, advanced instrumentation for diagnosis, new (personalized) intervention schemes and the development of innovative therapeutic approaches.

5. Strengths and infrastructure in NL & international perspective

PoL is a highly multidisciplinary community, rooted in physics with a broad unifying purpose of understanding life. Both in size and in quality, the Netherlands belongs to the international top and it has an excellent reputation. Dutch biophysicists have for example played a pioneering role in the single-molecule revolution.

The wide span of topics and approaches, theoretical, experimental and clinical, yields a comprehensive training program that educates well-trained students. This broad focus also enables the field to flexibly embark on novel research themes. With the emphasis on fundamental research, investigators in our area have been successful in connecting to different disciplines in the life sciences, often in research programs in which multiple areas of expertise are represented.

The embedding of the internationally well-known Dutch medical physics field within PoL, strengthens the possibilities for translation from fundamental findings to (sustainable) clinical applications as well as providing fundamental researchers with the relevant clinical questions.

One of the strongholds of the community is the annual DutchBiophysics meeting, where more than 500 researchers meet. Face-to-face communication is essential, especially in a multidisciplinary environment. With attractive international speakers, who generally express a great appreciation of the activity in the field, this meeting plays a key role in a vibrant PoL network.
The research in PoL is distributed over universities, medical centers and institutes around the Netherlands and infrastructure typically consists of clusters of relatively small, well-equipped laboratories that are embedded in a wider multi-disciplinary scientific environment. Such embedding is crucial, both for mutually inspiring new research lines, as well as to optimally benefit from the range of facilities, including protein purification, cell-culture, optical laboratories, state-of-the-art electron microscopes, medical imaging systems and computer networks that are prerequisite for our research.

6. Specific challenges for the community

- How do we stay well-funded, and fundamentally connected in physics, while simultaneously enga ging with more specialized topics in biology and medicine?
- How can we leverage the increased interest in health and medicine into more fundamental, phy sics-based research with partners in- and outside academia?
- How to optimally use approaches such as machine learning for processing of (extremely) large data in biophysical research?
- How can we further facilitate interactions with other fields, such as neuroscience, with which PoL can expect strong synergy?

7. Research portfolio

Based on unique registrations of staff members at DutchBiophysics in the past 4 years, our community consists of over 200 researchers. The location of these attendees is depicted in the table below:

Location of university, including their medical centers	# Staff members attending DutchBiophysics in the past 4 years
Amsterdam	39
Delft	25
Utrecht	23
Groningen	21
Leiden	20
Eindhoven	18
Nijmegen	13
Rotterdam	9
Wageningen	9
Maastricht	4
Enschede	4

Research institutes	# Staff members attending DutchBiophysics in the past 4 years
AMOLF	14
NKI	6
Hubrecht	2

Within the Dutch Society for Medical Physics there are currently 19 full professors. The location of these professors is depicted in the table below:

Location of university, including their medical centers	# professors within the Dutch Society for Medical Physics
Amsterdam	5
Maastricht	4
Rotterdam	3

Organization	# members
AMOLF	6
ASML Netherlands B.V.	1
Erasmus Universiteit Rotterdam	1
Philips Lighting BV	2
Radboud Universiteit Nijmegen	2
Rijksuniversiteit Groningen	11
Technische Universiteit Delft	11
Technische Universiteit Eindhoven	8
TNO	1
Universiteit Leiden	9
Universiteit Twente	4
Universiteit Utrecht	5
Universiteit van Amsterdam	1
Vrije Universiteit Amsterdam	4
Wageningen University & Research	5
Total	**71**

Nano, Quantum and Material Physics

1. Scope and definition of the research community

The key research areas covered by the research community (RC) Nano, Quantum and Materials Physics (NQMP) are the understanding and potential manipulation of electrons, fotons, atoms, molecules, and materials. This includes interactions between (quasi-)particles with charge and spin, their interaction with external fields, their excitations, as well as the dynamical processes that they induce. Properties that arise from confinement effects in nano-materials, as well as from collective interactions and order phenomena, are also at the center of the NQMP interest. Since the properties of materials not only depend on the constituent building blocks, i.e. the atoms or molecules, but also on the interactions between them, different properties can appear at different length scales, in different dimensions, and even in differently shaped materials. This makes the research field of nanoscale and quantum matter extremely rich in terms of fundamental physics, and provides a huge potential for current and future device applications. The NQMP RC brings together the traditional fields of atomic, molecular and optical physics, hard condensed matter, materials science, interface physics, physical chemistry, soft matter, and nanoscience.

2. Vision for the next ten years

The NQMP RC identifies three areas in which major breakthroughs, both scientific and societal, are imminent: Quantum technologies, Green ICT, and the Energy transition. These breakthroughs promise transformative solutions for an energy efficient and democratic access to both resources and knowledge, and provide natural focus points for NQMP research in the near future. The ambitions and goals of these three areas are as follows:

Quantum technologies

Quantum technology aims at controlling the quantum states of matter, and to integrate them in platforms suitable to address societal challenges. With recent advances, quantum platforms are now beginning to move beyond the realm of scientific laboratories, representing a potentially highly disruptive technology, with unprecedented opportunity for society but also with threats to existing security that need to be addressed. Quantum computers, quantum simulators, quantum networks, and quantum sensors hold promises to perform calculations fundamentally faster than a classical computer, to simulate problems in physics and chemistry that cannot be solved in a classical way, or to provide fundamentally secure communication, giving rise to exponential advances in many fields of research and technology. The increasing ability to control the quantum mechanical properties of particles or excitations of isolated systems, such as of electron spin and nuclear spins in solids, of quantum superconducting circuits, of cold atoms and molecules, ions, quantum degenerate gases, forms the basis for qubits and the corresponding quantum technology. The possibility of harnessing macroscopic degrees of freedom also offers quantum materials as platforms that can provide physical implementations of quantum systems for higher coherence.

Green ICT

Current information technology is based on electronics for computation, photonics for signal transport, and spin for memory. The current energy consumption of ICT already stands at > 7% of current world electricity use. Fundamental breakthroughs are needed to overcome the energy and bandwidth limitations of contemporary technology. A first bottleneck is the so-called von Neumann architecture of computing in a CPU separated from a memory, that requires up to 105 times more power than the human brain. The second bottleneck is the slow interconversion between light, spin, and electrons. The field foresees innovations in adaptable electronics for energy-efficient computing, materials that change their state or act as physically configurable networks, physics-based machine learning; and brain-inspired architectures such as hardware implementations of deep learning networks with particles or photons, reservoir computing, and analog signal processing based on wave physics. The energy consumption problem in computation and memory could be overcome by progress in superconducting computers. Generally, this theme pursues new concepts in processing and controlling information, to interconvert charge, excitons, photons, phonons, spins, and magnetic excitations, at ultimately low energy scales (aJ/bit) and ultrafast timescales needed for ICT.

The Energy Transition

The energy transition of the coming decade requires major fundamental breakthroughs in energy generation, conversion, and storage. The circular economy aspects of materials deserve more attention, as well as new solutions for recycling, waste management, corrosion, etc. On the interface of chemistry and physics, there are important challenges towards developing non-toxic materials and devices and for further increasing the efficiency, sustainability and durability of widely used processes. For instance, in the domains of photovoltaics, thermoelectrics or the hydrogen economy, essentially new concepts are needed to significantly overcome the currently achieved efficiencies. This will require a fundamental understanding of new materials, and hybrid or tandem device geometries. Photonic up-/down-conversion with nanomaterials may extend the applicable solar spectrum and find important applications in health care, e.g. imaging-contrast nanoagents, nano theranostic nanoplatforms, and immunoassays. Another focus is the development of new energy storage materials for batteries and supercapacitors, and the harnessing of chemistry and photochemistry in nanoscale confinement, for instance in the framework of solar fuels. Sustainable, even passive, cooling, through the clever engineering of thermal radiation management or implementation of material and energy sustainable light sources and opto-electronic/photonic devices can also lead to substantial energy savings.

The NQMP community in the Netherlands is positioned to address these societal challenges. The binding theme of the NQMP community is the understanding of the physical properties that emerge in matter and how these can be harnessed in useful applications. By its very nature, this research aligns theory, experiment, materials synthesis, nanofabrication, and novel instrumentation with extreme resolution. Open challenges increasingly deal with the understanding of emergent behavior (system properties that are different from those of the constituents) in systems of larger complexity, such as in supra-molecular systems and biomolecules, complexity in soft and hard condensed matter and strongly correlated quantum systems, and the design of emergent behavior at will, such as in quantum simulators, metamaterials and neuromorphic hardware systems.

3. Scientific challenges/themes

Technically, to achieve the visions described in 2, the following challenges need to be tackled:

Quantum control and transduction

In order to achieve the ultimate promise of quantum technologies, several challenges need to be addressed. Only by improving coherence and scaling in quantum simulators, networks, computers, or sensors, the pathway towards applications can become feasible be expected. For this, new concepts will need to be developed, and the boundaries of quantum coherence and control will need to be expanded. In order to address relevant problems, maintaining the coherence of scalable building blocks up to relevant system sizes is a crucial goal. A second key concept will be the connectivity of quantum technologies: To achieve functionality which is not possible in one system alone, it is necessary to interface for instance superconducting quantum computers, optical quantum networks, and atomic and molecular quantum gases. This concept of *quantum transduction* between different degrees of freedom, such as spins, photons, mechanical vibrations, phonons, and radio-frequency signals will play a crucial role in future interconnected quantum technologies, and it is a field currently in its infancy. New physical concepts bridging all fields of NQMP will need to be developed to address this challenge, including the control of materials at the nanometer scale using nanotechnology, and the development of new tools for advanced control of the quantum excitations in the different physical systems.

From single atoms to complex matter

Developments in atomic, molecular, optical and condensed physics can address the ambitions described in section 2 at a fundamental level, using advanced and highly precise tools. The physics questions and challenges in this area have evolved towards complexity (phenomena that arise when atoms or molecules are combined in a highly controlled way), and to understanding systems under extreme conditions, such as in high magnetic and electric fields and at high pressure, at ultrashort time scales or extreme temperatures. Monolayers of atoms, on well-chosen substrates, can become superconducting. Ultra-cold atoms, ions, and molecules can form quantum gases that exhibit exotic phase transitions. Cold atoms, as well as artificial atoms and color centers in protected solid-state environments, can be combined with macroscopic/mesoscopic structures, and have seen the realization of controllable and strong interactions at the single and few-particle level. Novel spectroscopic methods with extreme spatial, temporal and energy resolution need to be achieved to probe quantum systems with exquisite detail and to explore the boundaries of fundamental physics.

Materials design and engineering

Engineering materials at the nanometer scale, or even at the scale of a single atomic layer, allows ultimate control of devices for data storage, logic or information processing but also for energy harvesting or storage. Quantum materials and nanostructures derive unique properties from quantum confinement, many body interactions, topology, and collective excitations. Understanding the fundamental principles that underlie the emergence of materials properties from their microscopic constituents drives the development of novel nano-materials as well as their potential in technological applications. The possibility to assemble new materials a single atomic layer at a time has led to exotic physics such as relativistic Dirac spectra, topologically insulating states, light-matter interaction with confined excitons and novel spin physics on the basis of so-called `valleytronics'. Our theoretical understanding of the different transport processes in materials is fragmented and developing consistent theories for these and other exotic phases of matter (such as high Tc superconductivity or Non-Fermi liquid behavior) is expected to render substantial gains towards energy-efficient device concepts

Advanced instrumentation and research infrastructure

For all of the challenges above, the development and availability of powerful new tools that allow us to extend our knowledge to a wider range of length and time scales is essential. The possibility to overcome current technical limitations in spatial, temporal or energy resolution is often connected to developments in materials control and device engineering. New developments that allow scanning over several orders of magnitude in space, time or energy using a single setup would bring new strategies to investigate the phenomena that emerge at specific length scales (nano-, meso- or macroscale). To use this knowledge to build devices, further developments in nanoscale fabrication and analysis techniques (NanoLabNL), large magnetic fields (HFML) and intense pulsed (far) infrared free-electron lasers (FELIX) are needed as well as novel, lab-based X-ray sources, ultrafast electron techniques and deterministic single-particle delivery.

Data-driven and machine learning approaches to NQMP

As instrumentation and measurement technologies advance, the availability of huge data sets as well as the still growing availability of computational power opens the door to data-driven approaches/methods to design and tailor quantum materials, metamaterials, soft materials and complex functional materials. Moreover, new developments in quantum machine learning enable the simulation and study of much larger and more complex quantum many body systems, both in and out of equilibrium that were inaccessible before. This includes novel algorithms for simulating massively entangled states on classical computers and new (hybrid) algorithms to be exploited with quantum computers. We anticipate that both approaches can substantially speed up the development of this field.

4. Application perspective (incl. societal challenges)

Via public-private partnerships the NQMP field is traditionally strongly connected to the large Dutch companies in ICT, semiconductor technology, lighting, health and high-tech systems and materials, e.g. ASML, NXP semiconductors, Philips, Signify, Lumileds, DSM, JEOL and FEI-ThermoFisher. Further, the community is defined through an entrepreneurial spirit, where researchers apply fundamental concepts from the lab to develop products that meet a societal need. This excellent connection is evident from the large number of IPP/PPS programs (NWO-ENW), as well as TTW OTP and Perspectief projects. In these, industry co-funds academic groups in NQMP to realize breakthroughs in solid-state lighting, semiconductor manufacturing, and applications (e.g. solid state lighting and photovoltaics), materials screening and characterization of materials by spectroscopy, electron microscopy and scanning probe techniques, and so forth. Other striking examples are recent initiatives such as the ARCNL institute, which combines new impulses from fundamental academic research within industry-driven questions in the field of advanced nanolithography. It is evident that also in the coming 10 years the NQMP field will strongly contribute to applications in these domains, driven by new insights in photonics, spintronics, novel solid-state materials, and high-tech instrumentation. Also, the emerging field of quantum technologies holds significant promise for applications, as signalled by the PPS research in MESA+, QuTech. QuSoft and QT/e, with Microsoft, Intel, KPN, and significant initiatives with large application perspective emerging in the area of energy. While conventional silicon photovoltaics is a market cornered by Asia, there is significant application potential for novel materials and light management strategies for photovoltaics (AMOLF, UvA, TUD, UT), as well as their implementation into real devices (ECN, RuG, VU, TU/e), solar fuels (Differ, WUR, UU) and battery materials (UT, TUD, UU).

NQMP provides the fundamental basis for the key enabling technologies identified by the Dutch government (Kennis- en Innovatieagenda 2018-2021) i.e. photonics, advanced materials, quantum technologies, nanotechnologies, and emerging & fabrication technologies, and is also represented in several others, such as artificial intelligence (neuromorphic hardware,). A diverse range of societal challenges identified in the Kennis- en Innovatieagenda crucially rely on fundamental breakthroughs that must come from the NQMP community. In particular, we expect significant contributions to energy and sustainability, on the basis of new materials and light management for photovoltaics, battery materials, electrochemical storage and conversion, as well as new technologies for green ICT. Photonics, neuromorphic hardware that removes the energy and bandwidth bottlenecks of digital von Neumann computing architectures and enable hardware based deep learning, as well as hybrid technologies that combine photons, spins and excitons in novel materials, have the potential to significantly reduce the energy consumption of ICT. Also, NQMP will contribute to solving challenges in security (secure quantum technologies, photonics, sensing), and agro, food & water (e.g., sensing, spectroscopy, nanochemistry).

5. Strengths and infrastructure in NL & international perspective

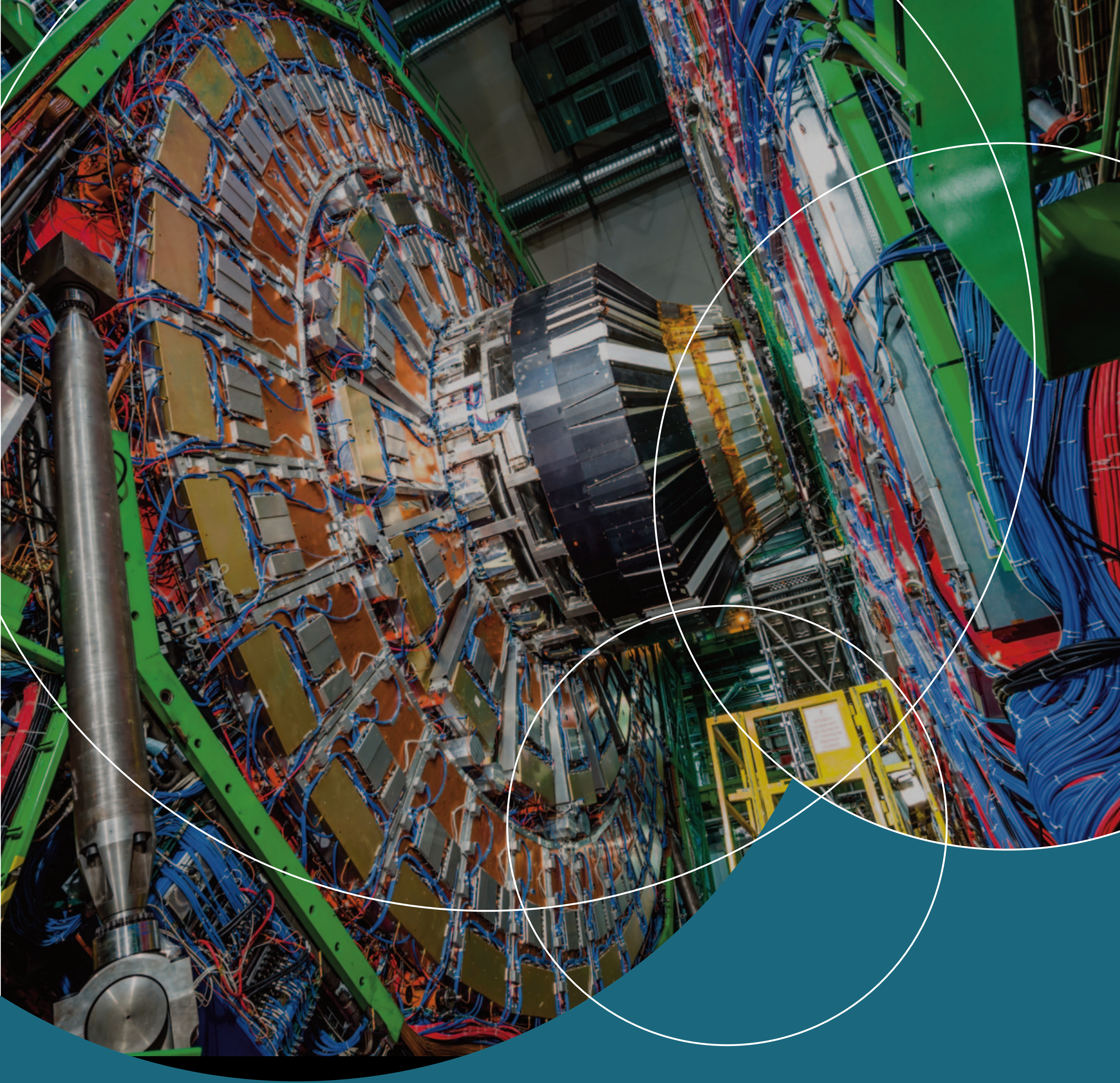
The NQMP field is strongly rooted at all Dutch universities, where condensed matter physics, quantum physics and optics have traditionally been cornerstones of research and education, and where there is a close link between research and education in chemistry and physics. There is a high degree of organization of research and infrastructure agendas through small-size programs (program portfolio below) and national initiatives. For instance, the significant national investment in nanotechnology (through NanoNed, NanoNextNL and NanoLabNL) and instrumentation (via NWO Groot's large investments) have resulted in a large and nationally coordinated basis of installed nano- and materials infrastructure (TU/e, TUD, UT, RUG, AMOLF), which are also accessible to partner universities. The NWO institute DIFFER is specifically dedicated to energy research. The efforts in quantum physics, in as far as geared at quantum information and communication are similarly strongly organized through the National Agenda for Quantum Technology (NAQT), QuTech, QuSoft, QT/e, MESA+, the Kavli Institute, the Zwaartekracht program Quantum Software Consortium, and the national alignment towards the EU quantum flagship, while national consortia and agendas have also emerged for photonics (PhotonDelta), energy (SolarLab) and materials (NWO Materials: Made in Holland). An important strength is that the NQMP field is traditionally closely linked to high-tech industry in nanotechnology, materials science, instrumentation and photonics, such as ASML, Philips, NXP, ThermoFisher-FEI. The international facilities of HFML and FELIX also play a key role in contributing, not only to the Dutch research landscape, but also to the global portfolio of large-scale research infrastructures

6. Specific challenges for the community

The structural funding from the government for large infrastructure facilities, such as NanoLabNL and HFML-FELIX, is vanishing. It is essential to keep these large infrastructure facilities up-to-date, as they are an enabling platform for a very large body of research in physics, materials science, life science and chemistry, as well as forming a necessary resource for high-tech SMEs. The community faces the challenge to find alternative funding sources to maintain the facilities at the state of the art. Funding this system from ad-hoc funding opportunities carries a great risk and strongly compromises the long term planning of ambitious research projects.

7. Research portfolio

Organization	**# NQMP members**
AMOLF	7
ARCNL	6
CWI	2
DIFFER	4
GraphenePioneer	1
NXP	1
Radboud Universiteit Nijmegen	15
Rijksuniversiteit Groningen	21
Technische Universiteit Delft	23
Technische Universiteit Eindhoven	13
Universiteit Leiden	16
Universiteit Twente	13
Universiteit Utrecht	14
Universiteit van Amsterdam	17
Vrije Universiteit Amsterdam	3
VSPARTICLE	1
Total	**157**



Particle and Astroparticle Physics

1. Scope or definition of the working group

The field of Particle and Astroparticle Physics (PAPP) comprises theoretical and experimental research on fundamental building blocks of matter and the structure of space and time itself. It aims to advance our understanding of the fundamental laws of Nature for all elementary constituents of matter, their structure and their mutual interactions. PAPP has experimental and theoretical components in particle and astroparticle physics. The experimental activities are predominantly at Nikhef, a partnership between the NWO Nikhef-institute and six Dutch universities , which allows to execute a National Strategy. The particle physics activities include collider physics, notably performed at CERN's Large Hadron Collider, where the Netherlands are involved in the ATLAS, LHCb and ALICE experiments, and the search for the Electric Dipole Moment (EDM) of the electron as an alternative technique to study particle physics. The Dutch Astroparticle Physics (APP) community is represented by the Committee for Astroparticle physics in the Netherlands (CAN) . The Dutch APP activities focus on multi-messenger observation of the Universe, through the study of gravitational waves (Virgo), the observation and understanding of high-energy cosmic neutrinos (KM3NeT), ultra-high-energy cosmic neutrinos, photons and cosmic rays (Pierre Auger Observatory); direct searches for dark matter (XENON) and searches for signatures of dark matter particles in X-ray and gamma-ray data (CTA). Some of these activities are performed in collaboration with astronomy and observational cosmology.

The Dutch PAPP theoretical research community is constituted by several university groups and Nikhef. Theoretical High-Energy Physics is a distinct discipline, which often makes major progress in unveiling surprising connections and physics principles underlying the fundamental laws of Nature. At the same time, the link with experimental research is of vital importance, challenging theorists to develop new concepts and make new theoretical predictions. The aim of the present theoretical activities is to uncover the fundamental laws governing physics at all distance and energy scales, beyond currently established theories. It revolves around a number of big, unsolved questions that are driving the PAPP field: What physics lies beyond the Standard Model of particle physics? How can we unify quantum theory and general relativity to obtain a quantum theory of gravity? What is the nature of dark matter and dark energy? How did the Universe start? Can we understand black holes? Given the unprecedented wealth of new data from colliders, astroparticle physics and cosmology, there is now added urgency to address these challenging issues. They not only overlap with the experimental research lines within PAPP, but also benefit from a multidisciplinary approach, with input from physics, astronomy, mathematics and computer science.

2. Vision for the next ten years

These are exciting times for the field covered by PAPP, with unexpected interactions between research lines and communities that were previously disjoint. With the discovery of the Higgs, the LHC has largely confirmed the Standard Model of particle physics. And yet we are certain there is new physics waiting to be discovered due to observations that cannot be explained within the Standard Model (SM), such as dark matter, neutrino oscillations and the matter-antimatter asymmetry. Other experimental anomalies may be confirmed soon. We know, for the first time since the formulation of the SM, that some new – Beyond the Standard Model (BSM) - physics must exist. Thus, there are a vast range of New Physics scenarios which will be tested with future experiments.

Major upgrades at the LHC are envisaged in the coming years to increase the event rate by an order of magnitude, further boosting the LHC discovery potential. These upgrades will permit to assess the details of the Higgs mechanism and to maximize the reach for the discovery of new particles (ATLAS); to reach the ultimate precision in specific b-quark systems (LHCb), and to expose the collective dynamics of quarks and gluons in extreme conditions (ALICE). It will allow to search for long lived particles at ATLAS and LHCb and directly probe the origin of neutrino masses and baryogenesis. The SHiP experiment at CERN aims to search for low-mass long lived particles in a new generation intensity-frontier experiment. The sensitivity-frontier is further probed through low-energy ultra-high precision measurements of the electric dipole moment of the electron. The mission of the KM3NeT experiment is to discover PeV neutrino sources in the Universe and to study the properties of neutrinos, including BSM physics. The upgraded Pierre Auger Observatory is set to find the sources of the highest energy particles and study their acceleration mechanism, whereas the GRAND experiment will detect neutrinos at the highest energy attainable in the Universe. The particle nature of dark matter, and neutrino physics, will be studied with the XENONnT and DARWIN detectors. Complementary indirect dark matter astrophysical searches will occur with KM3NeT in neutrinos, with XRISM in X-rays, LOFAR and SKA in radio, and FERMI-LAT and CTA in gamma rays.

The detection of gravitational waves from coalescing black holes and neutron stars (Virgo) and the first imaging of a black hole horizon (Event Horizon Telescope) have confirmed the existence of black holes and the validity of Einstein's gravity in a strong gravity regime not previously explored. Gravitational waves are a new window on the universe that enables us to see even further back in time. Their detections are now routinely correlated with other detectors, in what is called multi-messenger astroparticle physics. A future third-generation gravitational waves instrument, the Einstein Telescope, possibly hosted in the Netherlands, has a high scientific potential.

Much higher precision theoretical calculations are required for the LHC upgrades, and beyond, for an exploration of the intensity frontier and for the imminent upgrades in dark matter detection, both direct and indirect, from the ground and from space. In a parallel development, we now also have a "standard model of cosmology". By treating the infant quantum universe as a one-time particle accelerator, we are beginning to probe the first moments in the life of the universe, including questions about the origin of matter, spacetime and the nature of gravity. A quantum theory of gravity remains the holy grail, with tantalizing recent hints that we may finally be able to explain long-standing questions about black holes and the nature of spacetime. A key conceptual and technical challenge for quantum gravity is to bridge the enormous scale gap between Planckian spacetime dynamics and the realms of particle physics and cosmology.

Traditionally, the PAPP field both relies on - as well as moves forward - "enabling technologies" such as physics data processing, where new high-performance algorithms and programming, and flexible computing infrastructures play a major role. Detector R&D in advanced gravitational wave instrumentation and new and "smart" pixel detectors is essential for the coming experimental challenges.

3. Scientific challenges/themes

The recent discovery of the Higgs particle and the observation of gravitational waves are ground-breaking scientific achievements, recognized with a Nobel Prize in Physics in 2013 and 2017, respectively. The Netherlands played a major and visible role in both, with top-ranked scientists and NL-built instrumentation. These discoveries also demonstrate a key characteristic of the experimental efforts in PAPP: the experiments are major international collaborative efforts that take many years to prepare and execute. The Dutch PAPP community has invested heavily in these efforts in the past decades and the coming years will be the time to benefit scientifically. Most experimental efforts have a strong theoretical counterpart and theory often guides the experimental direction. Indeed, the interaction between the experimental and theoretical programs is essential.

The following are, in no particular order, scientific themes and scientific challenges studied in PAPP:

Theoretical Particle Phenomenology

Signs of physics beyond the Standard Model could explain the dominance of matter over antimatter and the nature of dark matter. Theorists aim to explore, in three mutually coherent approaches, new physics up to the zeptometer scale (1015eV), well beyond the LHC reach. By computing collider physics observables with unprecedented precision, confrontation with data will offer exquisite sensitivity to new-physics effects. Possible imprints from top-down models and bottom-up effective field theory methods are leveraged for maximum benefit. In this direction, there is much interaction with LHC, astroparticle, and low-energy precision experiments as well as with cosmology and the physics of the early Universe. Modern computational and statistical tools (high-performance computing, machine learning, symbolic algebra) are a key ingredient of this endeavor.

1 Nikhef's detailed strategic plan for 2017-2022 and beyond is at https://www.nikhef.nl/wp-content/uploads/2016/03/STRATEGISCH-PLAN_STRATEGY_lowres.pdf

2 CAN's strategic plan for 2014-2024 is at http://www.astroparticlephysics.nl/papers/astro-roadmap-2014-2024.pdf

The Higgs Particle

All properties of the Higgs particle are fixed by the SM, but at the same time the Higgs particle may be a portal to physics beyond the SM. Unique among all elementary particles known to date, the Higgs boson is believed to be a manifestation of a complex mechanism that regulates several fundamental aspects of Nature, such as the unification at high energy of the electromagnetic and weak nuclear force, the origin of mass of all elementary particles and the CP-violation underlying the particle-antiparticle asymmetry. The ATLAS experiment at CERN aims to stress-test the SM by measuring the life-time, the (self-) couplings and CP properties of the Higgs particle, study Higgs production in exotic regimes and develop a unified theoretical interpretation of Higgs measurements.

Gravitational waves

With the first detection of gravitational waves, we have unlocked a new research field with implications for particle physics, cosmology and astroparticle physics. The LIGO/Virgo detectors aim to continue the study of gravitational waves with increasing precision and test the physics of black holes. The multi-messenger correlation of electromagnetic, neutrino and charged particle observations with the gravitational wave detection of a neutron star merger provided insight into the production of heavy elements and impacted many other areas of science. ESA's LISA mission will open the long wavelength domain of gravitational waves where supermassive black holes and potential signals from the Early Universe can be studied. Moreover, we are investigating the possibility of hosting the Einstein Telescope in the Netherlands, this would be a Game Changer in the field.

Quantum and Classical Gravity

A consistent microscopic formulation of quantum theory of spacetime and gravity is a major challenge. We study whether the collective behavior of these quantum degrees of freedom lead both to new physical and observable consequences and demonstrate the emergence of the usual, classical spacetime at macroscopic scales. Several techniques and approaches will be developed further to attack this deep problem, in both non-perturbative quantum gravity and string theory with its connection to the holographic principle and quantum information theory. On the classical side, the emphasis will be on strongly gravitating systems and gravitational waves, and the new insights they can give us into the nature of gravitational theory.

Discovery of new particles and symmetries

A discovery of new particles can directly indicate what kind of extensions to the SM we should be testing further, and what underlying symmetries these extensions should have, with immense implications on our understanding of the fundamental building blocks of the Universe. The ATLAS experiment searches for signatures of new BSM particles or interactions in LHC data. The abundant production of top quarks and vector bosons at ATLAS offers opportunities to perform high-precision measurements of the top quark mass and search for other very rare phenomena. The LHCb experiment searches for deviations from the SM in precision measurements of exceedingly rare decays, such as Bd μ+μ- and Bs μ+μ- or in studies of CP violation in B-decays to test the CKM paradigm. Separately, a measurement of a non-zero electric dipole moment of the electron would be direct proof of BSM physics. The eEDM program aims to detect the electric dipole moment of the electron using a highly sensitive experiment. All these programs aiming to uncover BSM, require tight interaction between theoretical and experimental work.

Dark Matter

Numerous astrophysical observations lead to the conclusion that a large fraction of matter is invisible. The identity of this 'dark matter' remains a mystery. Viable particle physics models for dark matter include candidate particles that differ by many orders of magnitude in, e.g. masses and interaction strengths. The dark matter search combines experiments that test particular classes of dark matter models directly or indirectly with strong synergy with cosmology and astrophysics. The XENONnT and DARWIN experiments aim to discover the dark matter particle by searching for 'direct' collisions of dark matter with ordinary matter. ATLAS studies the production of dark matter particles through searches of, e.g. "invisible" particles in pp-collisions. KM3NeT and CTA will look for telltale signs of dark matter annihilation in astrophysical bodies. Finally, LHCb and the proposed SHiP experiment search for long lived or 'hidden' particles that may lead to dark matter candidates. Theorists build dark matter models and combine experimental results with astrophysical and cosmological data, deriving constraints on particle physics models. New Machine Learning tools and statistical methods may find subtle effects due to dark matter in experimental, astrophysical and cosmological data.

Neutrinos

We now know that neutrinos have non-zero masses, in contrast to what the SM assumes. Other fundamental neutrino properties are still unknown and may hold other surprises. KM3NeT will study atmospheric neutrinos for neutrino oscillation patterns with the goal to establish the neutrino mass ordering. The XENONnT and DARWIN experiments will search for signs that neutrinos are their own anti-particles, i.e. Majorana particles. The Auger and GRAND Observatories will study neutrinos at ultra-high energies. The future DUNE experiment will use an intense beam of neutrinos to study leptonic CP violation and test the neutrino oscillation paradigm.

Cosmic messengers

Cosmic messengers may expose the origin and acceleration mechanism for ultra-high- energy cosmic rays, arriving at Earth as charged particles, neutrinos and photons. KM3NeT and GRAND aim to discover the neutrino sources in the Universe, while the Auger Observatory investigates the origin and composition of cosmic rays, their consequences for the understanding of astrophysical objects, and the interaction of these particles with the Earth's atmosphere. High-energy photons will be measured with CTA providing detailed localizations of astrophysical sources. Theorists use these observations to make models of some of the most violent phenomena in the Universe and describe cosmic messenger propagation through space. In addition, high-energy neutrinos and cosmic rays provide unique opportunities to test the Standard Model and its extensions in an energy domain well above that available from the LHC.

Nuclear Matter and Nuclear Astrophysics

Our knowledge of the collective behavior of matter rests on studies of particle ensembles with relatively weak (Abelian) interactions. The ALICE experiment studies the collective effects in QCD, a strong and non-Abelian interaction, using heavy ion collisions, recreating the high temperature state of the Universe just a few microseconds after the Big Bang. The collective behavior in this quark-gluon plasma is tightly connected to the equation of state (EoS) of hot dense QCD matter. These systems are the prime examples of the application of gauge/gravity duality (AdS/CFT correspondence), which is one of the most successful realizations of the holographic principle. The possibility of collective behavior in very small systems has sparked a deeper theoretical investigation of the foundation of fluid dynamics. Another open question is that of the existence of saturated gluon matter in the initial state of such reactions, which can be interpreted as the only classical field limit of a subatomic interaction. Separately, X-ray astronomy (e.g. with NICER) and gravitational waves provide a path towards the dense matter EoS. Studies of the EM counterpart of gravitational waves provide insights into the r-process responsible for the heavy element formation in the Universe. Complementary studies of neutron-rich nuclei in the laboratory, such as planned in the NEXT experiment, provide key data to predict the path of the r-process.

Theoretical Cosmology

The challenge is to unravel the nature of dark matter, the cause for the accelerated expansion (dark energy) and the quantum origin of the primordial perturbations. In the Netherlands, there is a particular focus on string theory/quantum gravity effects, cosmic inflation, cosmological phase transitions, and ultra-weakly-interacting particles beyond the Standard Model. There is a strong involvement in major international efforts addressing these long-standing puzzles both at CERN (e.g. SHiP) and from space (the EUCLID mission, X-ray probes XMM-Newton and Athena, and the space gravitational wave antenna LISA). The latter activities are primarily coordinated by our colleagues in astronomy.

4. Application perspective (incl. societal challenges)

The overall research theme of PAPP is to answer the question “What are the fundamental building blocks of our Universe?”. The activities of the field are therefore represented in the National Science Agenda, in the route “Building blocks of Matter and Fundamental of Space and Time”. In pushing the research frontier, the field makes key contributions to innovative technologies, such as computing and detector technology that can be used in other fields as far apart as medical imaging and seismic monitoring.

The 'Big Questions' on the origin and foundations of the universe provide a strong motivation for students to take up physics, and have a continuing appeal to society at large. Students trained in theoretical and experimental (astro)particle physics have analytical and computational skills that are in high demand in many areas of modern society. Innovative numerical methods and software tools developed in PAPP research programs find their way into other applications in astronomy, cosmology, artificial intelligence and beyond. For example, our machine learning, computer algebra and error propagation tools are relevant for many data-intensive fields outside of academia and are deployed at companies and in government.

5. Strengths and infrastructure in NL & international perspective

The experimental research of PAPP is 'Big Science', characterized by large-scale infrastructures with large collaborations. Therefore, the adoption of a national strategic agenda has proven to be very successful over the last decades. The Nikhef partnership coordinates most of the experimental activities in Particle and Astroparticle physics as agreed between NWO and the Executive Boards of the partner universities. Almost all experiments are located abroad and typically last for years or even decades; long-term commitment is essential for successful participation and requires commensurate funding instruments: small project funding will not sustain these efforts. CERN is and remains a foremost research partner for the particle physics program and increasingly also for astroparticle physics (e.g. through the recently established European Center for Astroparticle Theory). Other experimental programs are performed in international collaborations hosted in Argentina, China, France, Italy and the United States.

The Dutch theoretical community has a strong tradition and continues to have a disproportionately large impact on the field internationally. Its strength derives both from the quality of its researchers and the strong national links. In addition to the research groups and institutes at individual universities, many theoretical activities within PAPP take place at the national level: the Dutch Research School for Theoretical Physics (DRSTP) organizes annual PhD schools and the biannual Trends in Theory symposium, the Delta Institute for Theoretical Physics (D-ITP) organizes the national holography and theoretical cosmology meetings, and the theory division of Nikhef organizes monthly theoretical particle phenomenology meetings.

6. Specific challenges for the community (optional)

- The experimental PAPP research is built on 'Big Science' projects and commitments. With the new NWO funding instruments, how can we ensure long-term strategic funding?
- Specific to the new NWO structure and Astroparticle Physics: how to further facilitate interactions be tween APP themes in PAPP and the separate NWO domain Science advisory committee Astronomy?
- How can we facilitate hosting the Einstein Telescope as a global international facility in the Netherlands?
- PAPP research is fundamental in nature and can be rather technical or downright esoteric, it is therefore hard to summarize in one-liners. This may lead to challenges in communicating the relevance of the field.

7. Research portfolio

Organization	**# PAPP members**
CERN	2
NIKHEF	24
Overig	1
Radboud Universiteit Nijmegen	12
Rijksuniversiteit Groningen	14
SRON	2
Universiteit Leiden	4
Universiteit Utrecht	9
Universiteit van Amsterdam	19
Vrije Universiteit Amsterdam	4
Total	**91**

Physics for Technology and Instrumentation

1. Scope of research community advisory committee

'Physics for Technology and Instrumentation'
'Physics for Technology and Instrumentation' (PTI) covers the fundamental physical understanding and development of new technologies and engineering innovations, in e.g. acoustics, optical metrology, medical technology, microscopy, integrated photonics, nano-electronics, quantum information, magnet technology, advanced light sources and (charged) particle and X-ray beam techniques. The gained knowledge is used to advance the capabilities of new and existing technologies and instrumentation. The application of the technologies and instrumentation is primarily addressed by the other physics research community advisory committees of NWO. The PTI research community advisory committee divides her field up into four main themes: 'Physics for Fabrication', 'Sensing, Detecting and Probing', 'Sources', and 'Actuation and Manipulation' which are outlined in section 2.

2. Vision for the next ten years

New and improved materials, sources, sensors and actuators, and manufacturing methods are key ingredients for practically all 50 Key Enabling Technologies identified in the Elsevier report "Quantitative Analysis of Dutch Research and Innovation in Key Technologies" (June 2018). Therefore, PTI research is highly relevant for meeting the "Grand Societal Challenges of the 21st century".

In the coming decade, significant breakthroughs must be realized in the quest for "materials by design". To make this happen, we must develop novel methods and tools for reliable and accurate massively parallelized actuation and manipulation of particles, fields and materials, and for in situ and in operando characterization, monitoring and control of the fabrication of micro-, nano- and quantum materials, structures and devices with atomic or molecular precision on a large scale. Seamless integration and control of multiple physical processes, materials and components is essential for building high-performance devices like robust many-qubit quantum chips, ultra-sensitive hyphenated sensors, massively parallelized biosensors and biopolymer sequencers, advanced sources of both radiation and particles, and fusion reactors. Source development is a key technology driver to meet future needs in science, industry, health care and other areas such as agriculture. The Key Enabling Technologies rely for a large part on advanced source technology, either directly (e.g. photonics) or indirectly (e.g. advanced materials, nanotechnology, food and agriculture, health, etc.). Sources with improved brightness, efficiency and accuracy must be developed to enable novel applications. In addition, transitioning innovations from research laboratories to users requires increased attention to aspects such as compactness, robustness, cost and ease of use.

The advent of new capabilities in control and information technology (e.g. control of fields, dynamic models, machine learning) will change how we generate, process, and utilize scientific data, leading to new advances and greater complexity in materials design and instrumentation (e.g. stochastic and multivariate sensors). All these developments also enable high-precision intervention in complex matter and processes.

From an industrial perspective, identifying the lines of physical investigation with the highest potential for viable technologies with a broad application base remains an important challenge that requires explicit attention. For selected curiosity-driven pure scientific research, where the end justifies the means, exotic PTI concepts might be the way to go. However, in most fields, well thought out PTI concepts, consisting of a careful selection of technically and economically manufactural components are preferred, because of their higher potential to trigger new high-impact products that benefit the Dutch economy. Therefore, researchers are encouraged to explicitly apply these selection criteria when proposing new research proposals, and when making critical decisions during the execution of their research. A good connection between researchers and industry is crucial to make this a success.

3. Scientific themes

Theme 1: Physics for fabrication

Scientific challenge: Physics for fabrication is at the heart of being able to manipulate materials in two- and three-dimensions from the (sub)nano- to micro-scale regime.

Being able to precisely control materials at these length scales not only underpins many fundamental discoveries, but is also crucial to many technological advances. For example, the control and design of two-dimensional materials, correlated materials, and engineered lattices of thin films with atomic or molecular precision is still in its infancy and can lead to (r)evolutionary breakthroughs in fields such as energy, quantum information technology, data storage, national security, and health. Therefore, novel fabrication processes and techniques need to be developed to fabricate such nano-engineered materials and structures. Understanding the physics that govern the processes at play at these ultra-small dimensions is crucial to advance this field.

Current examples of such processes and techniques that are being developed in the Netherlands are plasma-enhanced atomic layer deposition of designer nanolayers to improve the lifetime of solar cells, techniques to grow 3D nanowire hashtags to prove the existence of Majorana fermions, and molecular beam deposition to realize organic/inorganic nanolayered hybrids for optoelectronics.

Theme 2: Sensing, detecting and probing

Scientific challenge: Exploring new territory in experimental physics, both fundamental and applied, depends strongly on the development of new sensors. Furthermore, there is an ongoing demand for increasingly smaller and smarter sensing devices with better performances. Their development requires a detailed understanding of matter-matter and radiation-matter interactions, synthesis of advanced materials, and novel sensing and probing techniques. For example, metamaterials can bridge the THz detection gap in the electromagnetic spectrum, complex (bio)physical systems and instrumentation need novel signal transduction techniques, and novel approaches like machine learning and Bayesian inference are needed for processing of non-trivial high-dimensional signals.

The first challenges in this field are related to the development of instruments with unprecedented performance. New research directions will focus on developing devices capable of measuring in multiple space and time dimensions, and with supreme sensitivity (down to single particles, molecules, or atoms), low noise, wide dynamic range, high specificity, high (space, time, and energy) resolution, and (ultra)fast and parallelized acquisition. Future instruments will have to take into account fabrication and operational constraints, such as the requirements of low power, low cost, high durability and a sustainable life cycle. In addition, new challenges will arise in the handling and processing of large amounts of annotated data, and in the design of the device architecture, in particular concerning miniaturisation, effective cooling, and the integration of multiple components. Finally, more and more measuring devices will be designed by taking into account their application environment and the associated safety and durability challenges, such as for biocompatible and non-invasive sensors, and instruments that operate in in situ and in operando conditions.

Theme 3: Sources

Scientific challenge: Sources of radiation and particles are at the heart of almost all areas of physics. Many advances in physics are made possible by the availability of improved sources, and therefore there is continuous drive towards better sources for better physics. A distinction can be made between sources of radiation (including but not limited to lasers, LEDs, acoustics, synchrotrons, plasma-based light sources and free-electron lasers) and sources of (charged) particles such as electron and ion beams, but also including plasmas themselves. In both cases, source development entails both the improvement of source parameters, but also improvements in the ability to accurately characterize sources.

Radiation sources are widely used for probing and manipulating matter. In such sources, wavelength and intensity are important parameters, but also the ability to control the spatial and temporal properties of radiation sources is essential. Source improvements directly impact the achievable resolution in microscopy and lithography, time-resolved measurements of ultrafast phenomena, and spectroscopy, but also opens new possibilities for e.g. element-resolved detection, studying matter in extreme fields, and quantitative 3D imaging. Major source challenges include the ability to make bright sources at extreme wavelengths (EUV, X-ray, but also infrared and THz) and increasing stability, efficiency, compactness and lifetime.

Also the ability to control the spatial and temporal profiles of radiation sources, including aspects such as polarisation and e.g. orbital angular momentum, is of crucial importance in many applications. Another particularly important property of radiation sources is their coherence: the phase of light fields is of crucial importance for focus ability and wavefront control, diffractive imaging and metrology, and access to the quantum nature of light. Single-photon sources and attosecond EUV sources based on high-harmonic generation are important examples of compact coherent sources based on quantum phenomena. Furthermore, metrology of the source itself is a challenge by its own right, as knowledge of the source parameters is often the limiting factor in the accuracy of an experiment.

Particle sources are equally important tools for probing matter, in particular high-brightness electron sources for electron microscopy and spectroscopy. For a range of other applications, the development of ion sources is crucial. One example is focused ion beams for milling and drilling at the nanoscale, where ion beam induced deposition and secondary ion mass spectroscopy are very active fields. Improved sources for focused ion beam and ion-beam-induced deposition are in fact essential for the semiconductor industry. Also for particle sources, developments towards increasing source brightness, efficiency, accuracy and lifetime are crucial for further advances and application potential.

Plasma sources are relevant for an array of applications, which roughly can be divided in (i) an array of applications in surface modification; (ii) as a source of primary particles or a mixture of particles and electromagnetic fields for triggering subsequent production of chemically active (molecular) species or other particles such as nanoparticles; (iii) a combination of both. Plasma sources operate in a wide range of pressures, gas mixtures, dissipated power, types of excitation etc. The major challenges for all of them include, but are not limited to, (i) extending the current energy range of the produced particles; (ii) precise control of the energy distribution of particles; (iii) reliable controllability and reproducibility; (iv) the ability to scale up from the laboratory size towards sources that enable beyond-state-of-the-art experiments and/or economic added value in terms of efficiency or higher throughput; (v) the ability to control the spatial distribution and uniformity; (vi) the ability to precisely tune and control the composition of the resulting chemically active (molecular) species or other particles such as nanoparticles; (vii) improving the lifetime of the sources. Diagnostics is of utmost importance in the development of the new sources. This includes the development and implementation of new diagnostics, as well as properly determining the properties of the new sources using both new and already existing diagnostics.

Theme 4: Actuation & Manipulation

Scientific challenge: The subfield of actuation and manipulation (A&M) addresses a heterogeneous set of exciting challenges, relevant for future instrumentation and associated physics. Novel A&M concepts for biomolecules, fluids, and plasmas in (micro-)reactors/detectors, e.g. based on scanning probes, ultrasound, electrowetting, micro- or nanomotors, and electric, magnetic or optical fields and waves, are required. Selective concentration of target biomolecules might speed up their reaction or detection from hours to minutes or seconds timescales, and eliminate interference from non-target molecules. Improved isolation concepts are needed, e.g. to shield micro- or nanodevices (or their content) from thermal, vibrational, and electromagnetic perturbations. Novel control concepts like model predictive control are needed to avoid limits and constraints in controlling complex dynamic system. Novel sample preparation methods, e.g. through STM or AFM, multi-beam, or guided nano-assembly are essential for many groundbreaking experiments and applications. The same holds true for A&M of fields and particle beams, optical wave fronts, and remote or non-invasive A&M under extreme conditions (e.g. in high vacuum or high pressure, or in complex biological systems like the brain). Novel massively parallelized A&M concepts must be developed for high-throughput assembly, reaction and detection (e.g. for discovering or detecting rare species in large ensembles, nano-pore based sequencing, multi-beam SEM/FIB). Calibration of such systems is a big challenge in itself.

4. Application perspective

Development of new and improved materials, detectors, sources and actuators, and manufacturing methods are expected to have an extremely wide application perspective and a large societal relevance. New developments in ‘Physics for Technology and Instrumentation’ are essential for driving advances in all Topsectors, especially in Agri & Food, Energy, Life Sciences & Health, Chemistry, HighTech Systems & Materials, as well as the Holland

High Tech innovations as described in the associated Roadmaps. Potential applications may include (non-exhaustive list):

Theme 1: Physics for Fabrication
- Better photovoltaic, optoelectronic and quantum devices
- Materials and devices to aid the transition to sustainable energy and circular economy (solar cells, batteries, fuel cells, gas storage, etc.)
- Novel and secure information processing/storage systems

Theme 2: Sources
- Better/brighter sources for improved microscopes, lithography, metrology, spectroscopy, diagnostics, lighting, process monitoring
- Plasma and particle sources for surface modification, wound healing (medicine) and disinfection (food and agriculture), fabrication, actuation and manipulation

Theme 3: Sensing, Detecting and Probing
- Autonomous monitoring for automotive, health, environment, agriculture, industrial, etc.
- Self-contained multi-modal sensors, advanced data processing and self-calibration for better, smaller, smarter and cheaper devices
- Biocompatible, non-invasive, in-situ/operando sensors/detectors for safer, faster and more comfortable monitoring
- Inspection of photonic and semiconductor materials and devices

Theme 4: Actuation and Manipulation
- Accurate manipulation and/or concentration of (bio)molecules, fluids, fields/waves, particles, etc. for improved micro-reactors/detectors
- Low-power, small form factor massively parallelized A&M for high-throughput devices/reactors/detectors

5. Strengths and infrastructure in the Netherlands & international perspective

The landscape

The research landscape related to the newly formed 'Physics for Technology and Instrumentation' is vast, and no specific (recognized) niches within the Netherlands exist (yet). The associated infrastructure is very diverse and ranges from international facilities and national initiatives, represented on the "National Roadmap for Large-scale Research Facilities (LSRI)", to the basic infrastructure at universities and institutes, which have activities on optimization of techniques and instrumentation. In addition, many companies have related research embedded in their R&D departments. Several TO2 institutes, such as TNO, regularly work on PTI projects. Below is a non-exhaustive list of examples of facilities and infrastructure that have connections with 'Physics for Technology and Instrumentation'.

Infrastructure in the Netherlands

International facilities:
Examples of large international facilities are the "High Field Magnet Laboratory" (HFML) and the "Free Electron Lasers for Infrared eXperiments" (FELIX) laboratory. NWO and Radboud University Nijmegen jointly operate HFML and FELIX, which develop and exploit the world's highest continuous magnetic fields and intense radiation with unequalled tunability in the infrared/THz range. HFML-FELIX is one of the few Dutch, open-access, international user facilities and the only facility worldwide that couples continuous high field magnets to free electron lasers.

National facilities:
A key example of a national initiative is NanoLabNL, which hosts a broad spectrum of nanotechnology tools and tailor-made infrastructure at different locations such as UTwente, Groningen, TU/Eindhoven, TU Delft and AMOLF. It is an example of creating some alignment and coordination within the PTI domain. NanolabNL has enabled new instrumentation and high-end fabrication facilities that helped define scientific roadmaps on nanotechnology, photonics, quantum technology and advanced materials. Exponents include applied research initiatives such as Photon Delta, QuTech and ARCNL,

reiterating Netherlands strategic roles in these domains. As many of the high-tech developments in physics and instrumentation take place at the nanoscale, the National Roadmap initiative NEMI (Netherlands Electron Microscopy Infrastructure), with participation of nearly all universities and many academic hospitals, is also of high importance to PTI. This national infrastructure provides access to advanced scanning and transmission electron microscopes (SEMs and TEMs) allowing nanoscale and even atomic-resolution imaging of nanostructures and devices, as well as advanced analytical spectrometric methods providing mapping of chemical and physical properties.

Dutch universities:
At many Dutch universities and institutes we find groups working on subjects within the PTI scope. Some examples are listed here (non-exhaustive list): At Delft University of Technology (TU Delft) the Department of Imaging Physics focuses on developing novel instruments and imaging technologies. TU Delft also houses the Van Leeuwenhoek Laboratory for Advanced Imaging Research (VLLAIR) and the Dutch Optics Centre (a TNO and TU Delft joint innovation for next-generation optical instruments), Medical Delta (technological solutions for sustainable healthcare), and Delphi (geo-imaging) consortia. At Eindhoven University of Technology (TU/e) the department of applied physics is divided in three disciplines: 'Fluids, Bio and Soft matter', 'Plasma and Beams', and 'Nano, Quantum and Photonics' where the themes 'Smart materials and Processes', 'Renewable Energy', 'High Tech Systems' and 'Engineering Health' are tackled. They also house the following two centres: Centre for quantum materials and technology (QT/e) and Institute for photonic integration (IPI, also part of PhotonDelta). The University of Twente houses the MESA+ Institute, focusing on key enabling technologies (KETs) - photonics, fluidics, hard materials, soft materials and devices. Their main contributions are in the Health, ICT and Sustainability areas. Within the department of Applied Physics the groups 'Applied nanophotonics' and 'Imaging and diagnostics' readily fall within the scope of the advisory committee. Apart from HFML-FELIX, Radboud University also houses the Institute for Molecules and Materials (IMM). Utrecht University hosts the Debye Institute for nanomaterials. At University of Groningen, the Zernike Institute for Advanced Materials has particular expertise in technologies enabled by quantum electronic materials, spintronics, multiferroics, and optoelectronics. While Leiden has its well-known "Instrumentmakers school". VU houses the LaserLab Amsterdam, where ground-breaking scientific research based on the interaction of light with matter is performed, spanning from the research on atoms and molecules to the investigation of living cells and tissue and sustainable energy sources. Knowledge on innovative diagnostic and therapeutic techniques is effectively translated into the clinic via clinical partners such as the Amsterdam University Medical Centres. These activities have generated best practice examples of entrepreneurial physics-to-market cases, like academic start-ups Optics11, Lumicks, and OPNT. Pushed by this series of successes, the VU and the UvA have launched the Demonstrator Lab, which aims at supporting entrepreneurial academics to become academic entrepreneurs. Maastricht houses the Maastricht Multi-Modal Molecular Imaging Institute (M4i Institute). It's goal is to perform fundamental, instrumentation and applied studies in molecular imaging.

University medical centres:
Next to the universities, many university medical centres (UMC's) collaborate with physicists on optimization of techniques for medical purposes such as at the UMC Utrecht Center for Image Sciences and the Groningen Photon therapy centre at the University Medical Centre, Groningen that partners with KVI Centre for Advanced Radiation Technology, providing advanced technology for treatment of cancer. Other initiatives of collaborations are that of the Medical Delta, and the collaboration of Reaction Institute Delft with the department of Radiation Science & Technology (TU Delft).

NWO-institutes:
The NWO institutes are also home to research that falls within the scope of the research community. A clear example is the Advanced Research Centre for Nanolithography (ARCNL), a public-private partnership between the University of Amsterdam, the VU University Amsterdam, NWO, and ASML. NIKHEF has the department 'Detector R&D' where cutting-edge new instrumentation ideas are developed that can be used for research in accelerator-based particle physics and astroparticle physics. At DIFFER scientists work on new and improved energy technology for the future. AMOLF has a long history in the development of novel instrumentation, including ion accelerators, mass spectrometry, scanning probe microscopy and ultrafast cathodoluminescence microscopy. Finally also the Solliance institute (Eindhoven) has

to be mentioned, where work on new instrumentation (e.g. atomic-layer deposition) is done for the solar (instrumentation) industry.

Partnerships with industry:
Many groups have formed partnerships with industry. This is seen as an important and positive trend as this helps new ideas to achieve actually implementation in instruments. Conversely, contact with industry may also spur new activities in academia. The advisory committee aims to stimulate this contact, what she sees as cross-fertilization between academia and companies (be they small or established industrial players). Many companies fall within the scope of the research community such as (but not limited to): ASML, Philips, ThermoFisher, ASMI, NXP, Smart Photonics, Fuji, Zeiss. The research community advisory committee will consider ways to foster a creative climate in which instrumentation challenges aimed at pushing new limits and/or new directions coming from industry, might be subject to proposals/funding. Also supported projects may lead to spin offs from academia, where students will continue with the ideas they have worked on. Examples are Delmic, Leiden Probe Microscopy, Lumicks and Optics11.

International perspective

The PTI community in the Netherlands competes at a global scale in, for example but not limited to, the following fields:

- Lithography, (ASML, ARCNL)
- Electron microscopy (NEMI)
- Health Tech Systems (diagnostic imaging, intervention medical systems)
- Light and scanning probe microscopy and spectroscopy
- Plasma sources, plasma-matter interactions, plasma control, plasma science
- Research in high magnetic fields and intense infrared/THz radiation (HFML-FELIX)
- NanolabNL
- Quantum information technology
- In situ/in operando cryogenics
- Photonics
- Microfluidics
- Nano-electronics
- Scanning Probe Techniques

In all the areas mentioned above the PTI community in the Netherlands collaborates as well as competes with the corresponding communities abroad, within Europe and beyond. The Dutch PTI community participates in a number of international partnerships. HFML is part of the European Magnetic Field Laboratory (EMFL), which has obtained Landmark Status of the European Strategy Forum on Research Infrastructures (ESFRI). FELIX is part of FELs of Europe and is strongly involved in the League of European Accelerator–based Photon Sources (LEAPS) whose primary goal is to promote and ensure the quality and impact of fundamental, applied and industrial research carried out at the European synchrotron and free electron laser user facilities. LaserLaB Amsterdam is part of LASERLAB-Europe, an Integrated Infrastructure Initiative of the European Union, forming a consortium of the 33 major laser centers in Europe.

6. Specific challenges for the community

PTI is a newly introduced research community advisory committee for physics. Its members stem from the former advisory committees ‘Phenomenological physics’, ‘Nanophysics and –technology’ and ’Condensed matter and optical physics’. Building and connecting this new community is therefore a specific challenge for the coming few to represent the community properly. A first effort to stimulate community building is to attain high visibility at Physics@Veldhoven through parallel session(s) covering topics that are specific to PTI, such as ‘Sources’ and ’Physics for fabrication’.

Another challenge is funding for globally competitive facilities. It is essential that the research infrastructure in the Netherlands remains up-to-date to be able to offer the Dutch research facilities, such as HFML-FELIX, NanolabNL and NEMI. Investment programmes for new equipment exist, such as NWO Groot and the National Roadmap for LSRI. However, it is difficult to structurally finance operational, maintenance and upgrade costs once a facility has been realized. The PTI community thus faces the challenge how to finance the Dutch research facilities in a sustainable and structural way to ensure that the Dutch research community maximally benefits from the investments made and that infrastructures remain state-of-the-art. PTI advices NWO to take strategic actions on this issue by consulting the Round Table Physics and the corresponding research communities. Another challenge is to connect the community with potential industrial partners. Many subjects within PTI have potential for industrial use. To leverage this, strong connections with industry need to be built. To stimulate this process, a PTI Industry day will be organised where researchers and representatives from industry can meet. The annual Physics with Industry event provides another route to strengthen connections.

7. Research portfolio

Organization	# PTI members
AMOLF	6
ARCNL	5
Cosine Research BV	1
DIFFER	8
Nikhef	9
NXP	1
Overig	1
Philips Lighting BV	1
Radboud Universiteit Nijmegen	10
Rijksuniversiteit Groningen	10
SRON	2
Technische Universiteit Delft	18
Technische Universiteit Eindhoven	16
TNO	1
Universiteit Leiden	9
Universiteit Twente	10
Universiteit Utrecht	5
Universiteit van Amsterdam	5
Vrije Universiteit Amsterdam	5
Total	**123**

Physics of Fluids and Soft Matter

1. Scope of 'Physics of Fluids & Soft Matter'

Research in the Physics of Fluids and Soft Matter (FSM) community is centered on the understanding, manipulation, and creation of soft materials and complex flow phenomena. A crucial aspect is the interplay of the spatial structure of (complex and reactive) fluids and soft matter with their emergent properties. Often, the collective properties of these materials emerge from the organization of simple building blocks into complex structures and phases. Hence, understanding and controlling the rich equilibrium and non-equilibrium phases of fluids and soft matter, as well as structure-property relations, play a key role.

The FSM community includes well-established sub-fields such as the dynamics of "simple" atomic or low-molecular weight fluids (e.g., turbulence, micro-fluidics, electrolytes, acoustics, phase change, and multiphase flows), the dynamics of fluid-solid systems (e.g., porous materials, granular flows, elastocapillarity), physics of plasmas (e.g., magnetohydrodynamics, gyrokinetic turbulence, non-equilibrium plasmas at atmospheric pressure, dusty plasmas), the dynamics and rheology of colloids, polymers, liquid crystals, and gels including phase behavior and self-assembly, and the dynamics and properties of bio(inspired) soft matter. These highly active fields within FSM have also seen many novel recent developments including, for instance but not limited to active fluids, (soft) robotic matter, 3D printing, nanofluidics, nanobubbles, plasma jets, and mechanical metamaterials, with many more new topics expected to emerge in the near future.

2. Vision for the next ten years

The Dutch scientific community has made significant contributions to the fundamental understanding of dynamics and multiscale processes in complex fluids, flows, plasmas, and (soft) condensed matter, including the understanding of structure-property relations, fluid-solid rheology and phase transitions. These contributions are aided substantially by close collaborations between experimental investigations, theoretical approaches and numerical (multiscale) modelling studies. Additionally, FSM is naturally cross-disciplinary, with strong connections to materials science, computational science, atmospheric and ocean science, chemistry and biology, as well as a variety of technology fields, such as (ubiquitous, low cost) sensing. This provides an excellent position for the FSM community to address new 'big questions' in the coming decade. Examples are (but not limited to):

- What are the fundamental physical principles underlying flow, deformation and transport in viscous, elastic and visco-elastic materials?
- How do ionization reactions, electromagnetism, plasma-chemistry, heating and flow interact to create a huge variety of plasmas in nature and technology?
- How can we understand complex interfaces (biological membranes, bilayers, engineering micro-fabricated membranes) based on soft matter and fluid mechanics principles?
- What is the relation between molecular structure, interactions and dynamics and rheological properties?
- How to bridge the gap between microscopic (atomistic, colloidal, particulate) and the macroscopic world of continuum mechanics?
- How can the behavior and performance of fluids and soft materials in applied settings be broadened, improved, controlled or enhanced to make breakthrough steps in clean energy, food, environment and health?
- What disruptive fundamental concepts and techniques will revolutionize turbulence research, materials science and soft robotics in the future?

3. Scientific challenges / themes

Multiphase and multicomponent fluid flows

Turbulence is one of the outstanding problems in the physics of fluids community. Even though major steps forward have been made with regard to turbulent single-phase flows, additional key challenges include the extension of our knowledge in the direction of multiphase and multicomponent turbulent flows, including particle- and droplet-laden turbulent flows, bubbly turbulent flows, active turbulence. Additional challenges arise when droplets or particles in a gas become electrically charged and respond to electric fields or even change them, as in thunderclouds, many granular media, and cleaning of exhaust gases. Another challenge is to apply smart and/or active particles to affect turbulence dynamics at its core. Understanding of such systems is crucial for progress in several application areas like marine applications, chemical process technology, food processing and catalysis. Another exciting challenge is the understanding of multiphase flow systems subject to mass/heat transfer, chemical conversions, and soft matter related multiphase flows such as found in polymer processing and emulsions. This is of particular interest for applications in chemical process engineering, food processing and development of new energy solutions, and significant for, e.g., biofuel reactors, synthetic biology, and tissue engineering. A related challenge concerns dry and wet granular matter, including their fluid- and solid-like behavior and phase transitions, with industrially relevant problems like segregation and mixing.

Fluid mechanics for planet, climate and sustainability

Understanding the multiscale Earth System requires a multidisciplinary effort where fluid and plasma mechanics and transport processes are an essential component. For example, fluid mechanics is key for improving our understanding of the global climate, atmosphere and ocean dynamics, estuarine flows, environmental disasters like land-slides/avalanches, and transport in the atmospheric boundary layer. It is also important for technological applications like renewable energy (hydro and wind power, energy conversion and storage), maritime hydrodynamics, etc. Understanding plasma stability and turbulence impacts the feasibility of fusion as a sustainable baseload energy source. The plasma physics of thunderstorms plays a particular role in generating substantial amounts of green-house gases (nitrous oxides, ozone) in the atmosphere. In these fields several of the current-day challenges come together such as flows with (charged) particles, droplets and bubbles, effects of buoyancy and rotation on (large-scale) flows, free surface flows, multiscale phenomena and computational modeling tools, and the role of big data and machine learning in solving such large scale problems.

Complexity in Plasmas

In most plasmas – ranging from low temperature non-equilibrium plasmas (in gases at low and atmospheric pressure) to high-temperature plasmas (in fusion) - there is a multitude of physical and chemical effects at play, combining to form inherently multiscale systems. These include ionization and recombination, interaction of the plasma with external and self-generated electromagnetic fields, turbulent flows,
collisional and radiative transport, interaction with neutral gas and surfaces, Ohmic heating, and plasma-chemical reactions. This variety of processes evolve on largely different spatiotemporal scales, are typically in non-equilibrium, and create complex structures in space and time. Advances in scientific computing, model reduction, data analysis, machine learning and plasma diagnostics will boost our understanding and control of a variety of plasmas.

Designer Soft Matter & Fluids

The unprecedented toolbox available to structure and create soft matter from scratch – colloidal synthesis, self-assembly, lithography, 3D printing – paired with an explosive growth in our understanding of how complex properties emerge, is increasingly allowing us to dream of, investigate, and create entirely novel types of fluids and soft matter with exciting new properties that cannot be found in nature. The next scientific revolution will be to attack the inverse problem and create on-demand designer materials and complex fluids. Striking examples include metamaterials with properties set by their spatial architecture and surpassing those of their constituent materials, complex fluids with designed rheology, programmable and controllable smart materials, foods designed with desirable structure, and artificial life.

Self-Assembly

The autonomous assembly of building blocks into complex phases and materials is a key (bio-inspired) principle of soft matter. It offers the unique opportunity to create highly ordered and well-controlled structures on length scales where direct manipulation is impossible. The Netherlands has a strong track record in the phase behaviour and structure in bulk and confinement (e.g., colloidal crystals, liquid crystals, micelles,
wetting, capillarity, flocculation, nucleation), with self-assembly often assisted by external fields or flow. The fluidic, photonic and catalytic properties of the resulting nanostructured materials couple this research field directly with a variety of topics within the wider FSM community.

Active Matter

Strong developments are taking place in active matter, which are composed of interacting self-propelled entities (e.g. colloidal particles half-coated with a catalyst, bacteria) that move autonomously while consuming fuel/food. In addition, active (soft) solids such as photosensitive polymers, hydrogels, chiral or magnetic particles, partly inspired on the physics of biological tissues or particles, are appearing. Understanding the physical mechanisms that govern the propulsion, self-organisation and collective behaviour in these systems is the key to the design and control of these new functional and self-driven fluids. Infusing soft matter and complex flows with (externally controllable) activity allows to probe novel questions in non-equilibrium physics, opens up new avenues for advanced functionality, and has a clear link to biology, granular matter and processing.

Advanced Functional Soft Matter

The low binding energies that make soft matter 'soft', allows to create highly sophisticated, dynamic materials, which bring responsive, switchable, adaptive, self-healing, extremely deformable, programmable, and highly recyclable materials within reach. These materials of the future are able to selectively and autonomously respond to external triggers, dynamically adapt their function, and seamlessly interface with biological systems. Functional surfaces and interfaces are, next to bulk materials, key in wetting, friction and coatings, and of decisive importance for advanced materials where physical and chemical cues are communicated through the interface, and where living/non-living interfaces play a role. These materials may find their way into nanomedicine devices, self-healing prosthetics, medical adhesives, flexible electronics, and soft robotics with deep links to engineering and applied sciences.

Fluid Mechanics for Biology and Health

A surge of activities in fluid mechanics and plasma physics with a strong focus on biological systems and health applications occurred during the last few decades. These activities will expand and become increasingly important as its societal impact is large, in particular for health and security applications. It covers topics like active biological fluids (bacteria, schools of fish, flocks of birds, human crowds), flows in biological systems as plants, animals, cells and tissue, but also relates to spread of infectious diseases and ecological systems. Non-equilibrium pulsed plasmas in atmospheric pressure gases are already used for disinfection and for air and water cleaning, and they are currently being developed as plasma-medical tools. As another example, cardiovascular fluid mechanics and mechanotransduction are relevant for diseases like atherosclerosis and aneurysms. Biomechanics (tissues, fluid-structure interaction) clearly connects this field with soft matter. An important field is also the area of (model-aided) medical diagnostics and predictive medicine.

Nanoscale transport and fluidics

The fluidic transport of mass, (nano)bubbles, charge, and solutes through micro- and nanofluidic devices, membranes, porous solid-state electrodes, or at solid-liquid interfaces involves many concepts of complex flows, fluid-substrate interactions, soft-matter and liquid-state physics. It may even imply in some cases the continuum breakdown, thus going beyond Navier-Stokes. The huge surface-to-volume ratio of the nanoscale allows for qualitatively new transport mechanisms and new fluidic circuitry elements (diodes, mechanical transistors), with impact on areas as diverse as electrochemistry, heat storage, osmotic energy production, catalysis, battery development, organ-on-chip, and water treatment, and control of slip in nano/microfluidic devices.

Emergence and complexity

Uncovering how complex properties, such as self-organization, complex rheology, structure formation, and memory emerge from the multiscale interactions of simple constituents remains a key challenge. An increasingly important theme is the non-equilibrium physics of soft matter, complex flows and plasmas. This includes externally driven systems (e.g., rheology of complex fluids, pulsed electric discharges in gases), internally driven systems (active matter – see above) as well as out of equilibrium glasses, complex ionized media, complex active flows, and jammed systems. An important perspective is to look at biology as a template for new manufacturing processes of engineering living materials (biofilms for coatings, textiles, living materials, etc.). Future progress on the principles of non-equilibrium systems will have wide impact.

Big data & Machine learning

Experiments and simulations in soft matter, turbulence and plasma research have a long history of dealing with extremely large data sets (e.g., confocal microscopy, video and magnetic resonance imaging, optical measurements, and computational fluid and plasma dynamics data) to understand complex (dynamical) behavior characterizing these fields. Machine learning is presenting new opportunities to interpret, classify, and process big data. Moreover, machine learning opens up new pathways for the design of advanced soft materials, understanding complex flows and plasma processes, and the novel strategies where machine learning controls and interacts with experimental protocols. In parallel, data science techniques offer new breakthroughs in the acceleration of powerful multiscale and multiphysics simulations across FSM, by circumventing computational bottlenecks through the development of accurate surrogate models using physics-informed machine learning algorithms.

4. Application perspective (including societal challenges)

The large variety of topics in FSM is of relevance for many application areas, e.g. chemical process engineering (reactors, catalysis, electrolysis, fluid transport), agro & food technology (crop spraying, plasma-agriculture), renewable energy solutions (solar fuels, blue energy, energy conversion and storage, fuel transport, hydro and wind power, fusion), biological and medical applications (synthetic biology, tissue engineering, nanomedicine devices, self-healing prosthetics, medical adhesives, plasma treatments), maritime and groundwater hydrodynamics, waste water management, and for several innovations in the high-tech sector (plasma deposition, lithography, printing, purification, desalination, anti-fouling, soft robotics, flexible electronics).

The astonishing variety of unusual and complex behavior of complex flows, plasmas and soft matter allows to impact key societal challenges in, for example, health (medical applications), agrofood, materials (designer/meta, soft and biomaterials, processing), smart industry (HTSM), the energy transition and the green and circular economy.

5 Strengths and infrastructure in NL & international perspective

The Netherlands has a vibrant community and strong international standing in fluid mechanics, plasma physics and soft matter research, which also includes a strong experimental and computational infrastructure (provided by SURFsara), at most Dutch universities (LU, RUG, TUD, TU/e, UvA, UT, UU, VU, WUR) and several NWO Institutes AMOLF, ARCNL, CWI, and DIFFER. On the national level knowledge exchange is fostered by, for example, the JM Burgers Center, the NNV section for Plasma and Gas Discharge Physics, Softmatter.nl with annual or biannual meetings. Strong relations between the FSM community and industry exists such as in HTSM (ABB, ASML, Océ/Canon, Signify, VDL), agrofood (Unilever, Friesland-Campina), medical (Philips), chemistry (AkzoNobel, DSM, Dow, Shell, Nouryon, Sabic, Tatasteel), and also with TO2s like Deltares, Marin, NLR, TNO and Wetsus.

6. Research portfolio

Organization	# PTI members
AMOLF	6
ARCNL	1
ASML Netherlands B.V.	1
CWI	4
DIFFER	8
NIOZ	1
Océ Technologies BV	1
Philips Lighting BV	1
Rijksuniversiteit Groningen	5
Technische Universiteit Delft	23
Technische Universiteit Eindhoven	40
Unilever R&D	1
Universiteit Leiden	3
Universiteit Twente	28
Universiteit Utrecht	13
Universiteit van Amsterdam	5
Wageningen University & Research	7
Young Wadden Academy	1
Total	**149**

Composition advisory committees Physics

Physics of life

John van Noort	UL
Claire Wyman	EMC
Erwin Peterman	VU
Mireille Claessens	UT
Sander Tans	AMOLF
Stephen Petit	EMC
Marie-Eve Aubin-Tan	TUD
Greg Stephens	VU
Peter Peters	MU
Anja van de Stolpe	Philips
Patrick Onck	RUG

Nano, Quantum and Material Physics

Beatriz Noheda	RUG
Femius Koenderink	AMOLF
Irene Groot	LEI
Jasper van Wezel	UvA
Nigel Hussey	RU/UT
Harold Zandvliet	UT
Bas van de Meerakker	RU
Gary Steele	TUD
Servaas Kokkelmans	TU/e
Sanli Faez	UU
Elisabeth von Hauff	VU
Emily Kernen	Photonis

Particle and Astroparticle Physics

Patrick Decowski	UvA
Ana Achúcarro	LEI
Stan Bentvelsen	Nikhef
Eric Bergshoeff	RUG
Sarah Caudill	Nikhef
Steven Hoekstra	RUG
Eric Laenen	UvA
Thomas Peitzmann	UU
Gerhard Raven	VU
Hella Snoek	UvA

Physics for Technology and Instrumentation

Ageeth Bol	TU/e
Serge Lemay	UT
Frans Widdershoven	NXP
Marloes Groot	VU
Stefan Witte	ARCNL
Tamalika Banerjee	RUG
Jacob Hoogenboom	TUD
Pieter Jan van der Zaag	Philips
Peter Christianen	RU
Andrea Baldi	DIFFER
Anna Sobota	TU/e
Niels van Bakel	NIKHEF

Physics of Fluids and Soft Matter

Herman Clercx	TU/e
Martin van Hecke	UL
Michel Versluis	UT
Herman Wijshoff	OCE
René van Roij	UU
Jo Jansen	Unilever
Ute Ebert	CWI
Liesbeth Janssen	TU/e
Marleen Kamperman	RUG
Laura Rossi	TUD