2023

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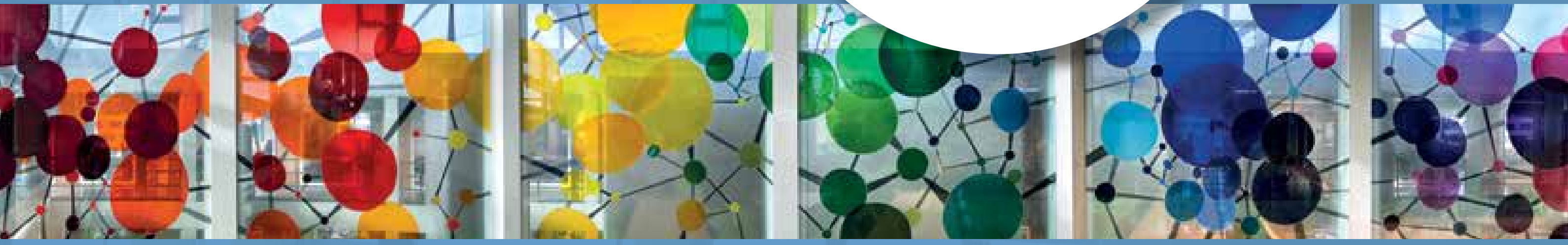
AMOLF **Strategic plan**



AMOLF

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Visiting address
Science Park 104
1098 XG Amsterdam
The Netherlands

Mail address
P.O. Box 41883
1009 DB Amsterdam
The Netherlands

Phone: +31 (0)20 7547100

E-mail: info@amolf.nl
www.amolf.nl

AMOLF is part of the Netherlands Organisation for Scientific Research

Contents

1
Mission

1. Mission

At AMOLF we wish to understand the fundamental physics and design principles of natural and human-made complex matter. We use the obtained knowledge to create novel functional materials that can provide solutions to societal challenges in renewable energy, green ICT, sustainable materials, and healthcare.

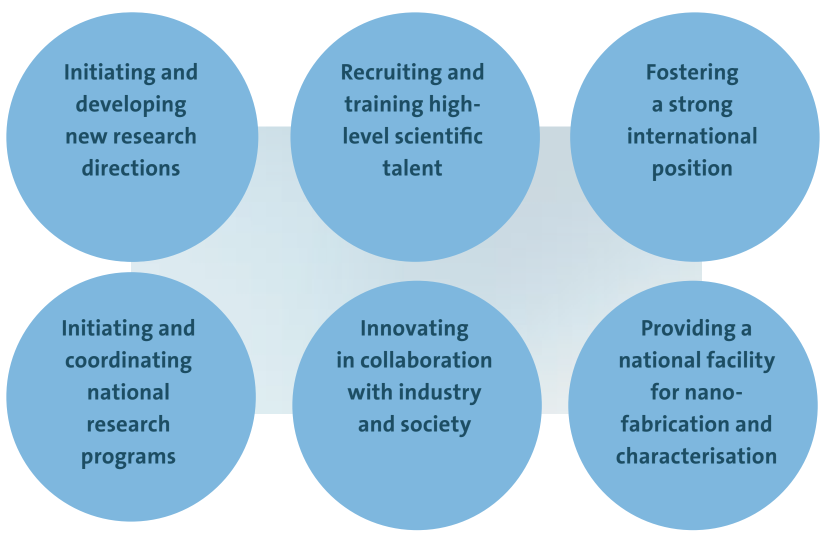
We pursue these goals by being a flexible and dynamic scientific research institute in which we work with teams of highly qualified scientists in focused research themes, and in which we constantly explore and rapidly develop new research directions. We closely collaborate with industry and university groups from different disciplines, thereby combining expertise from physics, chemistry, biology, and material sciences.

The mission of AMOLF is:
To understand the fundamental physics and design principles of natural and human-made functional complex matter, and to initiate and develop new research in is this field in the Netherlands, in partnership with academia and industry.

The present research program of AMOLF comprises three highly interdisciplinary themes:
• Sustainable Energy Materials;
• Information in Matter;
• Autonomous Matter.
Examples include metamaterials to control light, sound and motion, nanostructured solar cells, shape-morphing mechanical metamaterials, and life-like and living adaptive systems.

The themes are enabled by five disciplines, organized in expertise centers: Nanophotonics, Chemistry&Spectroscopy, Living Matter, Modern Mechanics, and Light Management in Photovoltaics. The expertise centers provide the critical mass in technical and scientific expertise required to have impact at a world-class level, and they play an important role in the training of PhD students and post-docs in their respective fields. The expertise centers also position AMOLF strategically in discipline-oriented national and international collaborations and networks.

AMOLF plays a pivotal role in national and international academic research by:



1.1 Initiating and developing new research directions

AMOLF has an important national role in initiating and incubating research directions that are new to the Netherlands, and that usually develop into larger national research programs. We started Systems Biophysics (2000) and the Center for Nanophotonics (2005), which have rapidly expanded into important and successful national research themes. In 2012, we started a FOM focus group on Light Management in Photovoltaics that we expanded with four new research groups (2012, 2014, 2016, 2021). In 2014 we initiated the research line Designer Matter with three new research groups (2014, 2015, 2016). AMOLF also played a leading role in founding the Advanced Research Center for Nanolithography (ARCNL), an exciting new form of public-private collaboration where academic partners join forces with ASML, the equipment manufacturer that is critical to the global chip industry, and key to Dutch industrial strategy. Recently, we reoriented our research portfolio into three highly interdisciplinary themes: Sustainable Energy Materials, Information in Matter, and Autonomous Matter. The development of these new themes is greatly stimulated by the hiring of three tenure-track groups leaders (Kristina Ganzinger (2018), Wiebke Albrecht (2021) and Marc Serra Garcia (2021)).

The hiring of world-class tenure-track group leaders is crucial in setting up new research themes, since they bring in expertise that shapes and strengthens

the new research themes. The new tenure group leaders also stimulate other AMOLF group leaders to shift the research program of their group to the new themes. The ability of AMOLF to initiate new research themes is enabled by its strongly collaborative culture. New research themes comprising multiple research groups can thus be established within a few years. This agility makes AMOLF also an attractive partner for companies, as illustrated by the collaborations with Shell, Philips/Signify, and Unilever, and the collaboration with ASML that led to the foundation of ARCNL.

AMOLF played a leading role in setting up MaterialenNL, a platform that coordinates materials research in the Netherlands, that stimulates cooperation across the knowledge chain and that identifies opportunities for new initiatives in material research. This has led to several national Growth Fund ('Groeifonds') applications on materials, including awarded initiatives on circular plastics, batteries, and sustainable steel. Recently, AMOLF led the formation of an 898 M€ program, *Circular integrated high-efficiency solar panels* (SolarNL), to boost the Dutch research and production of solar panels, in close collaboration with a number of industrial partners. This initiative is critical for the energy transition and technological independence of Europe in this area.

The ability of AMOLF to start new research themes is further facilitated by a dynamic turnover of its scientific staff, who are attractive candidates for senior academic positions in the Netherlands and abroad. The outflow of senior group leaders is an important aspect of the national role of AMOLF in establishing the new research themes in the Netherlands, and it creates space to hire new tenure-track group leaders.

1.2 Recruiting and training high-level scientific talent

Tenure-track group leaders are crucial in starting and developing new research themes. Therefore, AMOLF strives to be an attractive and internationally competitive institute for highly talented starting principal investigators. Our policy has a number of key components. First, tenure-track group leaders operate as fully independent scientists from the day that they start at AMOLF, allowing them to rapidly develop their research profile and to quickly obtain international visibility and recognition as an independent senior scientist. Second, we provide significant start-up funding, world-class shared facilities, and high-level technical and administrative support to facilitate a rapid start. This is particularly important for starting new research areas that require the in-house development of novel advanced scientific instrumentation. Third, while a tenure-tracker enjoys complete scientific independence, intense mentoring from the tenured scientific staff, internal reviewing mechanisms for papers and grants, and professional courses in leadership are in place. Finally, the research culture of AMOLF is strongly focused on scientific collaboration, which includes sharing lab facilities and exchanging knowledge. The competitiveness of AMOLF as a place to start a career is illustrated by our hires of tenure-track group leaders coming from international top institutes, such as the ETH Zürich and a Max Planck institute. Other indicators of our successful hiring of high-level talent are the success levels of AMOLF tenure-track group leaders in obtaining national and international funding through personal grants (NWO Talent Development, ERC grants), in leading major research consortia, and in obtaining professorship appointments at a Dutch university within 1-2 years after getting tenure.

We are also highly committed to the training of undergraduate students, PhD students and postdocs. A large proportion (66%) of our PhD students and postdocs come from outside the Netherlands. To attract international top talents, we invest in an optimal environment for research and training. This environment is created by restricting the research groups to a relatively small size, thus allowing high-quality daily supervision by the group leaders, and a highly collaborative atmosphere with joint seminars and poster sessions. We have recently renewed our PhD training program, which includes an extensive program of high-level courses for personal and scientific development, and regular mentoring moments throughout the PhD period.

The quality of the students we attract and the level of our training is illustrated by the fact that during the last strategic period (2017-2022), two AMOLF PhD students won the NWO Physics thesis prize for the best PhD thesis in physics of the year, another AMOLF PhD student won the annual NWO prize for the best scientific paper with a female researcher in the lead, and an AMOLF tenure-track group leader won the annual NWO Minerva prize for being an outstanding young female or non-binary physicist who excels in their field of research. AMOLF PhD students also regularly win prizes for the best poster or oral presentation at national and international conferences. The quality of our MSc internship program is illustrated by the fact that AMOLF students regularly win MSc thesis prizes.

1.3 Fostering a strong international position

The research groups of AMOLF have many productive collaborations with international groups. As a result, over 50% of our publications are produced in collaboration with groups outside the Netherlands. AMOLF also regularly organizes international workshops, for instance on information in matter, autonomous matter and light-driven chemistry. AMOLF also organizes a biannual summer school on nanophotonics & photovoltaics with over 100 international participants. The international standing of AMOLF is also illustrated by the large number of ERC grants (11 awarded ERC grants in 2017-2022).

AMOLF participates in several strategic international collaborations, such as MURIs (Stanford, Caltech and Austin), FET Open consortia (includes ICFO, IC2N, CSIC NanoGune, Imperial College, Cambridge University, EPFL, etc.), the Biophysics Circle Meeting (Institut Curie, EMBL and MPI Dresden), and the European Scientific Network on ‘Evolution, Regulation and Signaling’ (with groups in France, Denmark, Sweden, and Germany). AMOLF also has large collaborative programs in photovoltaics with the Fraunhofer Institute for Solar Energy in Freiburg, Germany and Cambridge University, and in protein science with Heidelberg University and the ETH Zürich. In addition, AMOLF is building up a collaboration with ESPCI from Paris, France. These collaborations lead to frequent exchanges of master students, PhD students and post-docs.

1.4 The initiation and coordination of national research programs

AMOLF plays a key role in organizing the Dutch scientific landscape into large national and international programs and in the writing of national research agendas. In 2015, AMOLF took the lead in defining the priorities for funding of materials research in the Netherlands, which led to the founding of the Dutch Materials platform in 2019 (chaired by Albert Polman). This led eventually to the Dutch Materials Agenda, and more recently to various large-scale initiatives within the national Growth Fund, a new national granting scheme launched in 2020 that finances research and innovation programs to boost the Dutch economy. AMOLF has led and has been heavily involved in the organization of four recent Growth Fund proposals: QuantumDeltaNL (615 M€), MaterialsNL (900 M€), The revolution of Smart Molecular Systems (97 M€), and Circular integrated high-efficiency solar panels (SolarNL) (898 M€), all of which have been granted. These programs involve hundreds of researchers and over 400 societal partners (companies, NGOs, local governments, research institutes, etcetera). Within the larger Materials Agenda, AMOLF also played an important role in organizing communities. For example, AMOLF took the lead in establishing SolarLab, which coordinates photovoltaics research, photovoltaics grant applications, and facilities for photovoltaics research in the Netherlands. Another example of our national coordinating role is the recently granted NL-ECO program focused on information processing with a radically lower carbon footprint, where AMOLF played a key role (10,3 M€). This grant was awarded within the National Science Agenda (NWA), which is a funding scheme started in 2015. AMOLF has led the management of the Materials Route of the NWA and is contributing to the management of the Sustainable Energy route. AMOLF also played an important role in setting up the OrganoidNL platform, in coordination with various other national partners, and in developing the Dutch ecosystem of research labs and companies in organoid research. Organoids are identified as a major new biomaterials direction, which is traditionally strong in the Netherlands.

Kick-off meeting of the national Growth Fund program SolarNL.

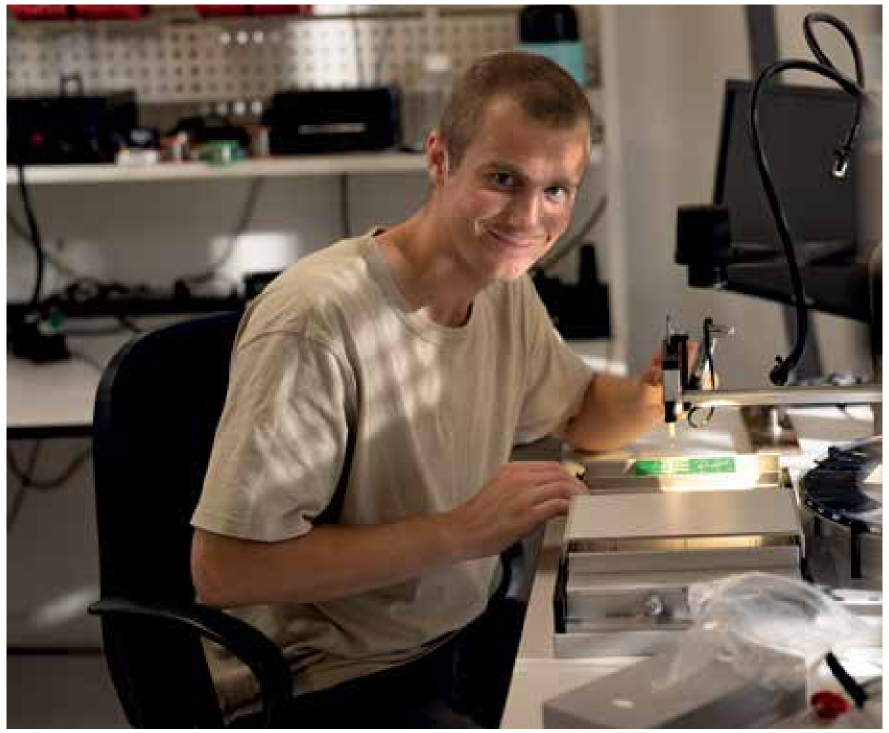
1.5 Innovating with industry and society

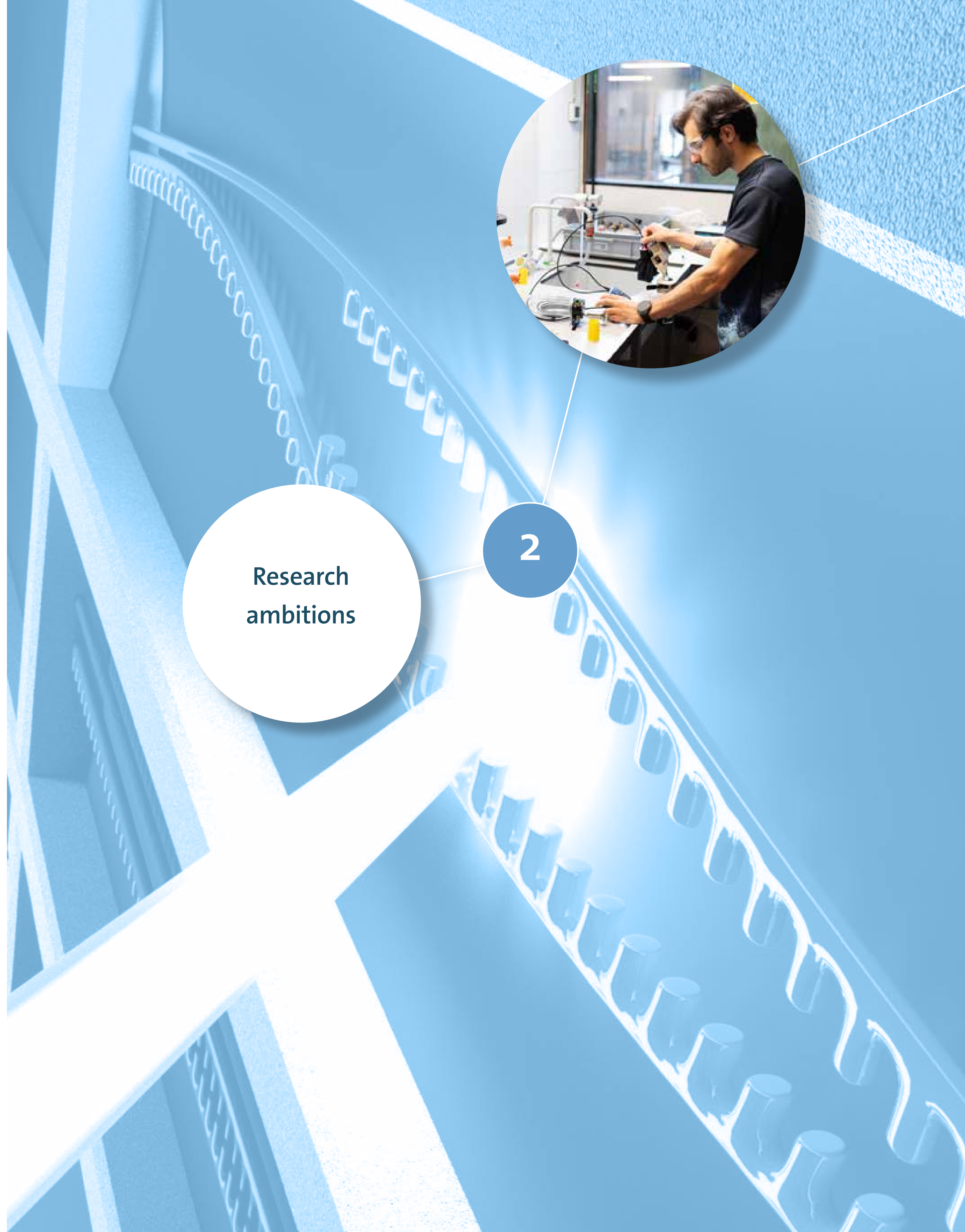
AMOLF has a strong history of collaborations and co-development with industry and society, in particular in the area of advanced instrumentation. In recent years, a main instrument innovation thrust has been in microscopy and spectroscopy, both optical and with electrons. For instance, our efforts in electron microscopy and spectroscopy have led to commercial success, with 6 instrument prototypes selling 120 units, for a total turnover of more than 50 M€ (20 M€ added value to the economy). This success arose from collaborations with large companies such as ThermoFisher Scientific (formerly FEI) and Gatan (formerly EDAX), and with SMEs such as Delmic and Amsterdam Scientific Instruments (ASI), both of which are spin-offs involving AMOLF group leaders. This leading role in the innovation of microscopy techniques will continue with the recently awarded NWO Research Infrastructure grant for a Transmission Electron Microscopy (TEM) with light in-coupling (SHINE), with which we will further strengthen the ties with ASI and enter into new collaborative scientific projects with JEOL. LumetalliX is a recent example of an AMOLF spin-off that is poised for tremendous impact. Their patented AMOLF technology for fluorescent lead detection based on an inexpensive and simple test kit, has already been used for a lead pollution detection mission in Tamil Nadu (India) led by Pure Earth (the largest NGO in lead pollution) and TAUW (a Dutch consultancy and engineering bureau). LumetalliX was a finalist for the best academic startup in the Netherlands in 2022. To stimulate the application of novel optomechanical sensing technologies, AMOLF is establishing an open-access Testbed for Mechanical Quantum Sensors (4,5 M€ project) together with Delft University of Technology, as part of the QuantumDeltaNL Growth Fund initiative. The Testbed will create a national facility for technology development and an environment to foster public-private collaborations. In the future we expect to continue having large economic and societal impact, particularly by taking a leading and coordination role in Growth Fund applications. Roland Berger’s recent analysis estimated for example that the photovoltaics manufacturing plan initiated and coordinated by AMOLF within the awarded Growth Fund initiative SolarNL, could provide an added value to the Dutch economy of 500-700 M€ per year by 2031, and a cumulative reduction in CO_2 emissions of 3-31 million tons by 2032.

1.6 Providing a national facility for nanofabrication and characterization

AMOLF hosts and operates the NanoLab Amsterdam, which is one of the five hubs of NanoLabNL (www.nanolabnl.nl), the Dutch national facility that provides a full-service and open-access infrastructure for R&D in nanotechnology. High-quality nanofabrication and characterization are essential to a growing number of disciplines and application areas both for AMOLF and for outside users. The NanoLab Amsterdam is a cleanroom infrastructure that provides state-of-art capabilities to both academic and industrial users, and that develops world-leading specific expertise and techniques in strategic areas including metamaterials, nanophotonics, energy conversion materials and nano- and micromechanics.

In the coming years, a 12 M€ investment program in the context of the granted national Growth Fund initiative QuantumDeltaNL allows the NanoLab Amsterdam to renew and strengthen its basic infrastructure, including nanolithography, material deposition and etching, and advanced characterization techniques. Moreover, from 2024 AMOLF will host a unique facility, a TEM integrated with light injection, funded through a highly competitive NWO Research Infrastructure grant. Besides these equipment expansions and upgrades, a continued push to increase professionalization and the quality of the services offered by the NanoLab Amsterdam and its staff is planned, to meet the growing demands from the scientific and industrial communities.





2 Research ambitions

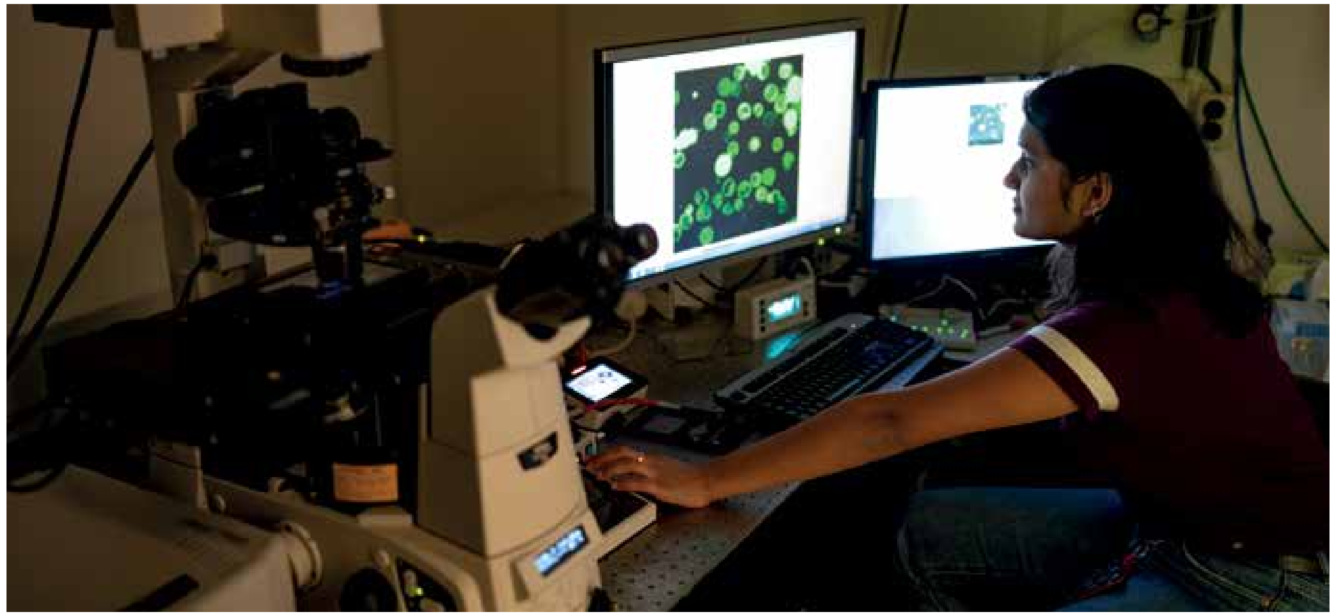
2. Research ambitions

2.1 Research vision

The past years have shown rapid progress in our understanding of complex forms of living and non-living matter. In such systems, nonlinear and dynamic interactions between its building blocks lead to extraordinary functions that surpass traditional human-made systems. AMOLF has started hiring group leaders in this field in the previous strategic period, and this strategic choice has since been validated by the strong international development of the field of functional complex matter. Key drivers are rapid innovations now emerging from new interfaces between chemistry, physics, biology, and engineering. For instance, diffusive gradients and feedbacks known in biology can yield radically new forms of chemical synthesis of nanoscale materials, coupled resonators from physics can enable new forms of optical and mechanical computing, while artificial intelligence (AI) tools from software engineering can help the design of novel functional materials and elucidate the spatial organization of cells in miniature organs. In the coming years, AMOLF will perform fundamental research exploring and developing these novel possibilities and using the obtained insights to engineer novel material systems. A large part of our research will be focused on the investigation and design of novel material systems, as these systems will play a pivotal role in addressing the huge present-day societal challenges in the energy transition, the sustainable use of raw materials, and the improvement of health and care.
AMOLF is in an excellent position to play a leading role in stimulating the international wave of research in functional complex matter. The scientific developments and converging technologies ask for a combination of disciplines that are strongly represented at AMOLF, including nanophotonics, photovoltaics, biophysics, mechanical metamaterials, spectroscopy, microscopy, and statistical physics. Moreover, our strategic decision to organize our research in three highly interdisciplinary research themes, supported by expertise research centers, fits excellently with these new international developments. We expect that the new research themes will provide exciting opportunities for new research that can tackle the key societal challenges of tomorrow.

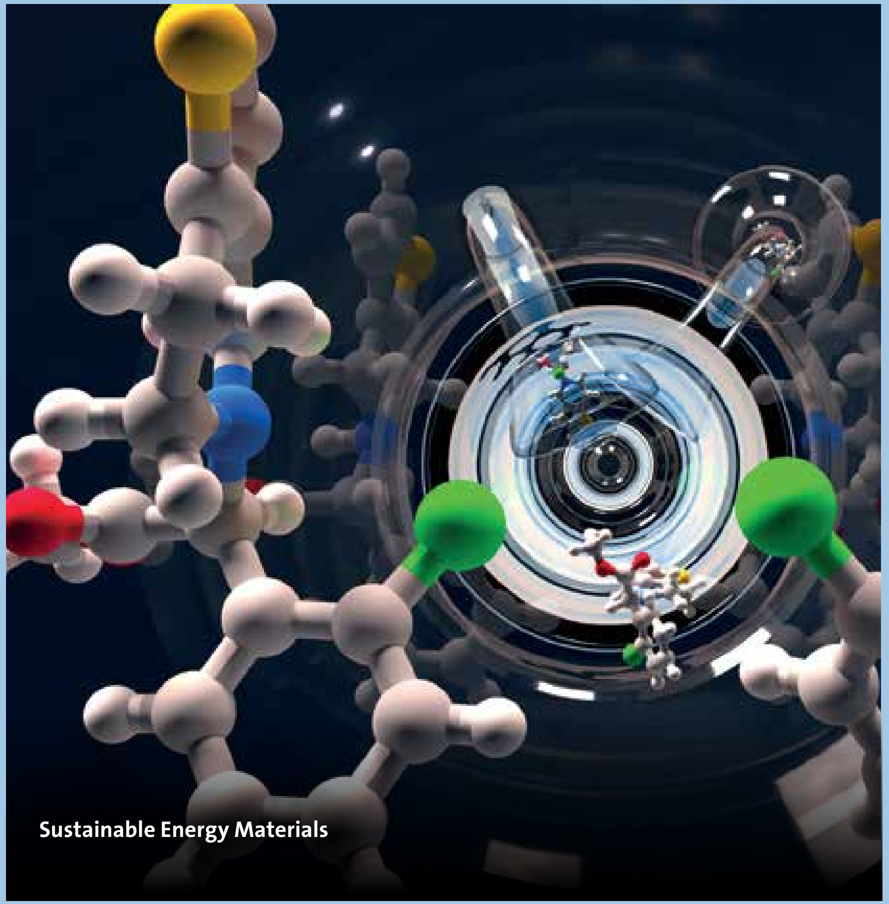
2.2 Future AMOLF research

The central aim of the research program of AMOLF is the understanding of how function emerges in complex matter systems and to leverage this understanding to create new forms of adaptive and responsive (smart) materials. We will focus our research on three types of functional complex matter systems, being systems that harvest or exploit sustainable energy, systems that can process information, and systems that function autonomously. These will be studied within three respective research themes in which 6-8 research groups of AMOLF closely work together. The three themes are introduced below; a more detailed description of the research portfolio of each of the three themes can be found in Chapters 4-6.



Sustainable Energy Materials

To achieve a sustainable society in the future, it is paramount to convert sunlight more efficiently to electricity, chemicals and heat where and when they are needed. A key unifying theme in all these solar energy conversion processes is that they require exquisite control over both light and matter at nanometer length scales and ultrafast (fs-ns) time scales.
In recent years, new highly promising materials for the conversion of sunlight to electricity have been discovered.
The challenge is to use these new materials in novel solar cell designs that can achieve an efficiency >30%, much higher than present-day silicon-based solar cells. In addition, the efficient storage of sustainable energy forms a major challenge in realizing the energy transition. Electrochemical processes for the conversion of electricity to fuels suffer from poor efficiency, selectivity, and scalability. A third recently emerging and important research topic is the use of concentrated (sun)light to control and drive chemical reactions. These three topics will be addressed in the AMOLF research theme Sustainable Energy Materials. This theme brings researchers from different disciplines together to approach the limits of conversion efficiency between different types of energy by controlling materials at the nanoscale. The overarching goal is to use fundamental insights in (nano)photonics and (nano)materials to efficiently convert sunlight to electricity, chemicals and heat. We have the ambition to design and predict where energy flows and how it is converted in artificial photosystems to different types of useful products.

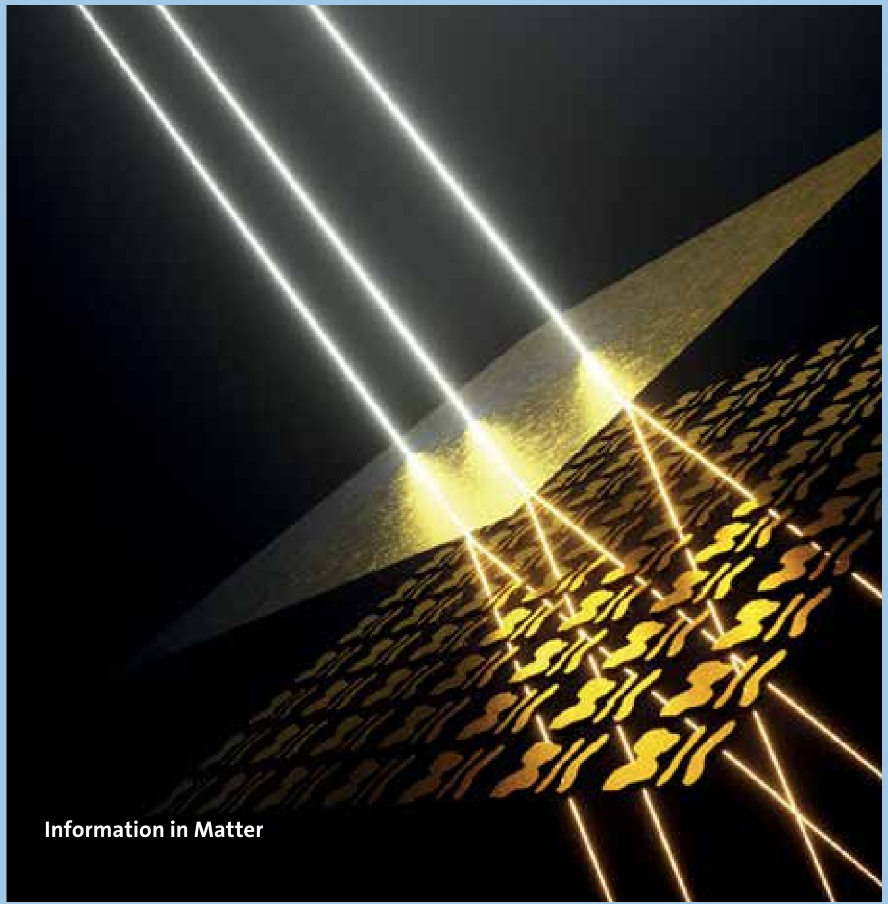

Sustainable Energy Materials

Within this theme there will thus be three main lines of research: on photovoltaics, electrochemistry, and light-driven chemistry. Within the photovoltaics research line, we will investigate novel designs for ultrahigh-efficiency solar cells and luminescent solar concentrators. We will also study solar foils made from halide perovskites, electrochemical III-V growth, radiative cooling of solar cells, and improved LEDs. Within the electrochemistry line of research, we will study the molecular-scale properties of electrodes and nearby electrolyte layers, and study how the structure of the electrode surface and the composition of the electrolyte can be optimized to improve electrochemical reactions aimed at the production of chemicals, for example using CO_2 as a feedstock. Within the light-driven chemistry line of research, we will use light to both steer and monitor chemical reactions. Replacing heat with light can enable programmable chemical transformations, change the activity and selectivity of catalysts, and lead to completely new products not seen thermally. Even in the case where light is primarily used to generate heat (photothermal), there is the potential for unprecedented thermal gradients in reaction vessels (in both space and time), which can open up completely new types of chemical behavior. For all of these research directions, a common theme is to develop new materials that are earth abundant, non-toxic, readily available, stable and recyclable in order to improve their sustainability. AI can provide new routes to materials development and play a role in the evaluation of the functioning of devices and in suggesting new experiments, especially in the light of the increasing availability of open databases for materials and energy conversion devices, thus providing a large amount of training data for AI algorithms.

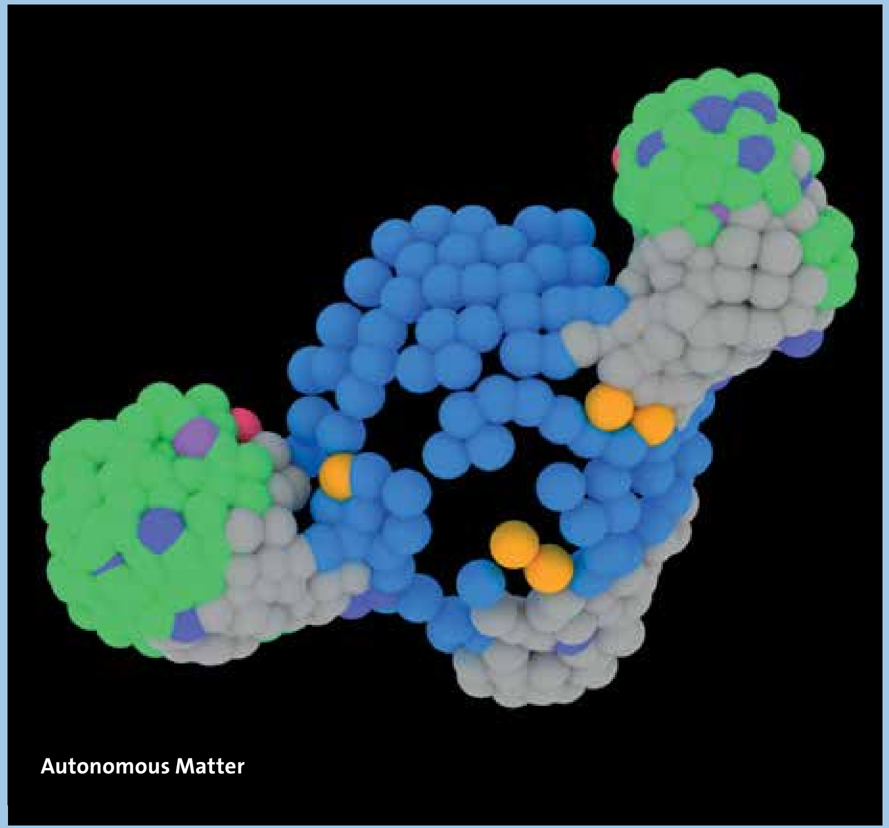
Information in Matter

Society has rapidly increasing demands on the capacity to process and store information, which presents an important challenge to science and technology. A recent scientific development is the emergence of new physical paradigms to handle information, such as DNA- and protein-based computing, analog optical computing, mechanical computing, quantum information, and physical implementations of artificial neural networks. A second important development is the strong increase of computing power which allows us to understand materials and processes of unprecedented complexity. Artificial intelligence now fuels novel forms of design and control. The AMOLF Information in Matter theme aims to advance our understanding of the fundamental physical mechanisms of the gathering, processing, and transduction of information by light, biomolecules, and mechanics. We aim to push the design and limits of future, unconventional, information technologies, and to explore new paradigms such as learning and adaptive materials.

Within the Information in Matter theme we will unite studies on emergent computing in complex matter – from crumpled sheets to the brain – with the design of systems that gather and process information by, e.g., light and acoustics. Within this theme there are two main areas of research. The first is information processing in physical systems. The second is sensing, gathering, and transducing of information. The research line on information processing revolves around logic, algorithms, learning, and computation in matter systems, ranging from inanimate mechanical metamaterials, optical resonator circuits and metasurfaces to biochemical networks and multicellular organisms. Within the research line on sensing, gathering, and transducing information, we will seek answers to crucial questions about the input, output, and conversion of information degrees of freedom. What are the fundamental limits to sensor performance, measurement accuracy and metrology? How can we evade such fundamental limits, leveraging noise, gain, nonlinearity, nonreciprocity, and entanglement? The ability to transmit and transduce information, converting information from one degree of freedom to another will be crucial for ultimate information systems. During these processes, how can information be protected from (thermal) fluctuations, scattering, dissipation, and decoherence? What is the minimum energy required to, for instance, switch an optical memory, and can we coherently transduce quantum information from photons to other quantum systems? Our research will also explore the implementation of neural networks in optical and acoustic hardware, how one should balance in silico and in hardware training, and to what extent deep learning can be employed for the design of sample structures, experiments, and data interpretation.


Information in Matter

Autonomous Matter


Autonomous Matter

Autonomy can be defined as the ability to independently perform specific functions, adapt, regenerate, and learn. Autonomous functionality is increasingly employed in man-made systems, but remains limited when compared to nature, where even the simplest cells exhibit autonomy in abundance. Biology exploits the dynamic interplay between properties that are traditionally left unharnessed in man-made systems, like diffusing building blocks, energy consumption, force generation, mechanical instabilities, feedbacks, and growth balanced by targeted destruction. The integration of these phenomena to yield self-organized systems that are robust yet dynamic, presents a range of open questions. Moreover, embedding these traits within chemical and soft-matter systems promises to form the next generation of intelligent materials.

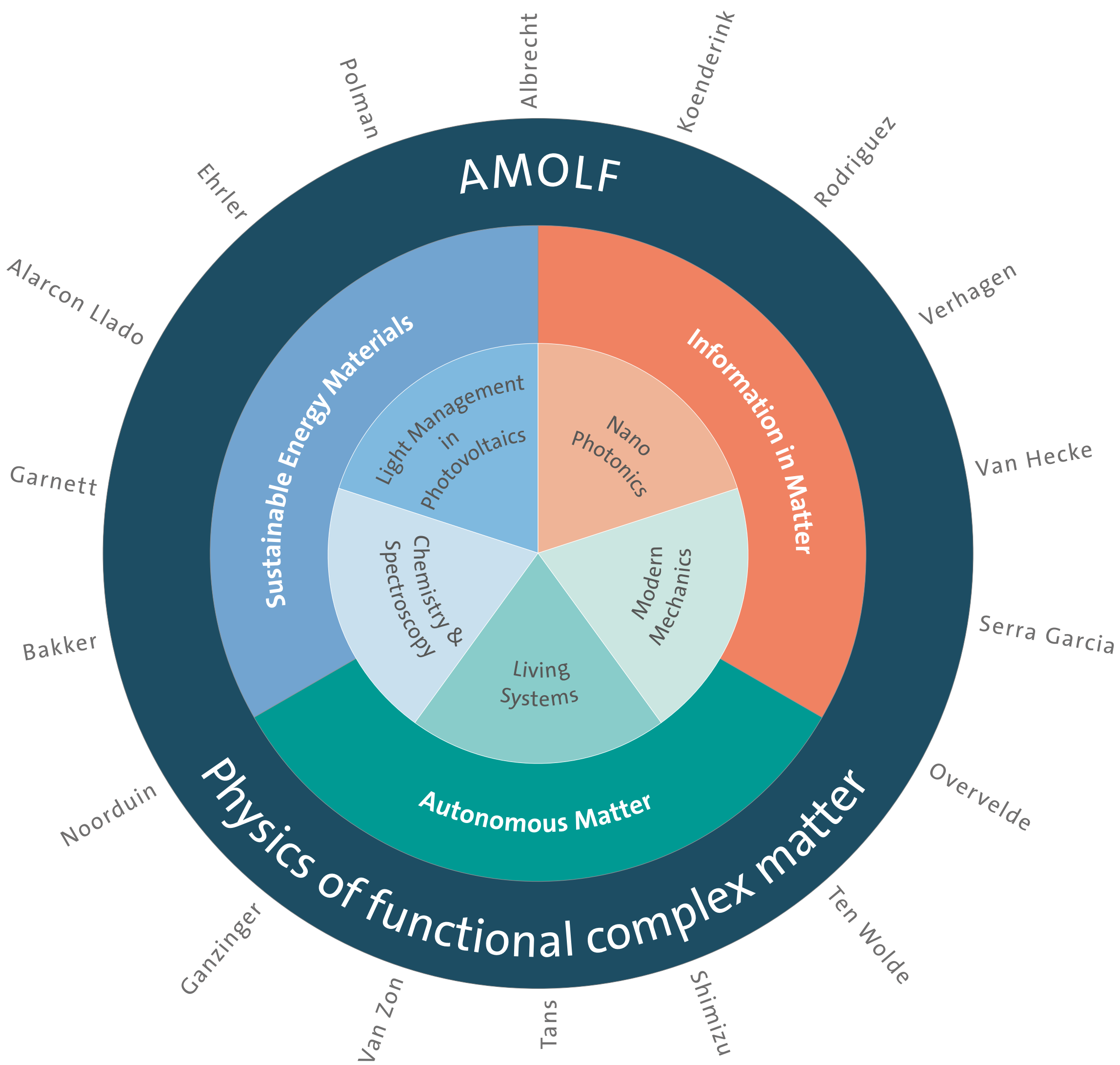
Within the AMOLF research theme Autonomous Matter we will study autonomous functionality in an emerging class of systems at the intersection of chemistry, physics, biology, and engineering. The overarching goal of this research theme will be the elucidation of the principles of autonomy, and to create a new class of autonomous matter that performs complex functions in a self-organized fashion. This initiative builds on our core strengths in molecular and cellular biophysics, bio-inspired chemistry and robotics. Topics include out-of-equilibrium chemical reaction networks that exploit diffusion and feed-backs to achieve spatial patterning, the regulation of multi-protein complex assembly by the coordination between ribosomes, self-learning in modular robotic systems that allows them to adapt to their environment, the spatio-temporal dynamics of cells that underlies organoid formation and homeostasis, and the spatio-temporal organization of receptor proteins that enables immune-cell recognition. AI plays an increasingly important role throughout these systems, for instance by enabling new forms of microscopy that follow cells and key molecular components within tissues in a label free manner, and by evolution-inspired automated experimental cycles, for instance to design materials that cannot be found by rational design.

An important feature of autonomous matter is their capacity to adaptively assemble and disassemble, and hence repeatedly form and destruct structures, enabled by the dynamic displacements of its building blocks. This process is associated with a host of questions: Can we control assembly by local cues or energy-driven processes? Can 2D confinement or signaling enable novel forms of self-organization? Can we exploit shape for novel types of catalysis? Can we evolve robotic swarming? Can we evolve reactive assembly networks? Can we define and manipulate shape landscapes? Another crucial feature of autonomous systems is the ability to self-organize in space and time, enabled by (dis)assembly in combination with other phenomena, in systems ranging from protein-membrane hybrids to soft robots. Spatial self-organization gives rise to a range of questions: What is the role of molecular gradients in spatial cellular organization, and can we exploit them in chemical reactions? How can the exchange of signals enable other forms of spatio-temporal organisation? A next level of control in autonomous systems is the ability to program self-organized behavior, which may for instance be achieved in biological systems at the DNA level and in robotic systems at the algorithmic level. Key questions are: Can we achieve programmability in actuated metamaterials? How do immune cells use spatial protein patterning to achieve specificity for many targets? Can we use DNA sequence specificity as a basis for programmable adaptive materials? Can we elucidate the role of dynamic cellular movements in developmental programs?

Expertise centers

AMOLF's three research themes span multiple complementary research disciplines. AMOLF has five expertise research centers to push the frontiers in the respective disciplines. The mission of these centers is to continuously develop new theoretical and experimental capabilities and to provide a stimulating environment for the education and training of young researchers. The expertise centers also position AMOLF strategically in discipline oriented (inter)national collaborations and networks. We have expertise centers for Chemistry & Spectroscopy, Light Management in Photovoltaics, Modern Mechanics, Living Systems and Nanophotonics. The centers are described in detail in Chapter 7.

Schematic picture of the mutual relation of the research mission, research themes, expertise centers, and research groups (indicated by the names of the group leaders) of AMOLF.



3. Strategic actions

For the coming strategic period our strategic goals are the following:

1. Further develop our three new interdisciplinary research themes

In 2021, we started three new research themes comprising different disciplines in novel combinations. For instance, in the new theme Information in Matter, we combine nanophotonics, mechanical metamaterials and biophysics. It is our strong belief that this new combination will yield many highly interesting opportunities for new science, in particular in the development of new information-processing matter and materials. In the Sustainable Energy Materials theme, we combine photovoltaics, (light-driven) chemistry, and spectroscopy. It is our expectation that this combination will lead to new materials and material systems to harvest and store sustainable energy. In the Autonomous Matter theme, we combine physics of living systems with soft-robotics, meta-materials and chemistry. Here, the expectation is that the study of living and non-living autonomous systems will lead to cross-fertilization effects, e.g. concepts that are well-known for living systems may find application in robotics and other man-made complex materials, while the engineering approach in soft-robots may lead to a better understanding of how living systems function.

In the coming strategic period, we aim to further develop the three research themes by initiating and developing cross-disciplinary collaborative projects. We will also aim to establish the new themes in a national and international context by organizing annual workshops and coordinating new national and international research programs of similarly interdisciplinary character. In these new programs we will closely collaborate with university groups and other research institutes. It should also be noted that the three new themes offer excellent and interesting opportunities for collaboration with experts in AI in the design of new material systems and in communication and information processing. With these coordination activities and collaborative projects and programs, we will introduce the three themes to other academic institutions, in accordance with our mission of initiating new research directions for the Netherlands.

2. Attract world-class scientific talent

The most important asset of AMOLF is the high quality of its scientific, technical and administrative personnel. In the coming strategic period, we will continue our efforts in attracting the best people to AMOLF. Regarding the hiring of tenure-track group leaders, we will continue to be an attractive and internationally competitive institute, by providing a generous start-up, a highly collaborative and friendly atmosphere and an intense mentoring program that we regularly evaluate and refine. Thereby we aim to hire the brightest people from all over the world and bring them to the Netherlands, which is an important aspect of our national role. To get also the best junior scientists (undergraduate students, PhD students and post-docs) to AMOLF in the coming strategic period, we will further develop our training and mentoring program aimed at junior scientists (see later points).

3. Coordination of large national research networks and research consortia.

An important task of AMOLF as a national NWO research institute is the coordination of national research networks and research consortia. Recently we had a leading role in setting up the 898 M€ national Growth Fund initiative proposal on sustainable photovoltaic materials, which was awarded in 2023. AMOLF will coordinate the fundamental research within this proposal, and will take responsibility for its central administration. In the coming strategic period, we will continue the coordination of national research networks and research consortia.
In close connection with this purpose, we intend to improve our internal organization to facilitate the writing and coordination of large collaborative research proposals. There is a tendency within Europe and particularly in the Netherlands to finance research via increasingly large collaborative programs, including involvement of academic, industrial and societal partners. The efficient writing and coordination of the corresponding proposals goes beyond the workload of an AMOLF group leader and requires dedicated support from a program officer. We intend to facilitate these tasks in the coming strategic period.

4. Expanding national collaborations with universities and other national institutes

We have many national collaborations with groups at other institutes. Examples are Gravitation consortia, like for instance the large BaSyC program with Delft University of Technology, the University of Wageningen and the University of Amsterdam. There are also many contacts with universities through the professorships by special appointment that most of the tenured group leaders of AMOLF hold, in total at seven different universities in the Netherlands.

In the coming strategic period, we aim to further develop our research and strengthen our national position. We will do this in the following ways:

- **By establishing shared PhD and postdoc positions** with university groups for which half the costs are paid by AMOLF, the other half by the partner. We believe that the best way to stimulate interaction and collaboration between senior researchers of two different institutions is by establishing a research project with a junior researcher (PhD or postdoc) who is supervised by both. In the past strategic period, we have realized several of these positions and these indeed turned out to be very effective in establishing an intense and fruitful collaboration between the PIs involved.

- **By hiring PhD students on collaborative projects** with university groups that are financed by the PhD bonuses obtained through the graduation of AMOLF PhD students.

- **By initiating and coordinating large national research consortia**, for instance within the KIC, NWA and ENW-XL funding schemes. Further stimulation of the collaborations will be achieved via shared PhD/PD positions financed by the project.

- **By participating in large national consortia** like NWO-Gravitation (Zwaartekracht) or the new NWO-SUMMIT program.

- **By being an active partner in other large-scale existing national collaborations** like the ARC-CBBC, ARCNL, and the Growth Fund initiatives The Revolution of Smart Molecular Systems and QuantumDeltaNL, in which we work closely together with research groups from the Radboud University Nijmegen, Eindhoven University of Technology, Delft University of Technology, and University of Groningen.

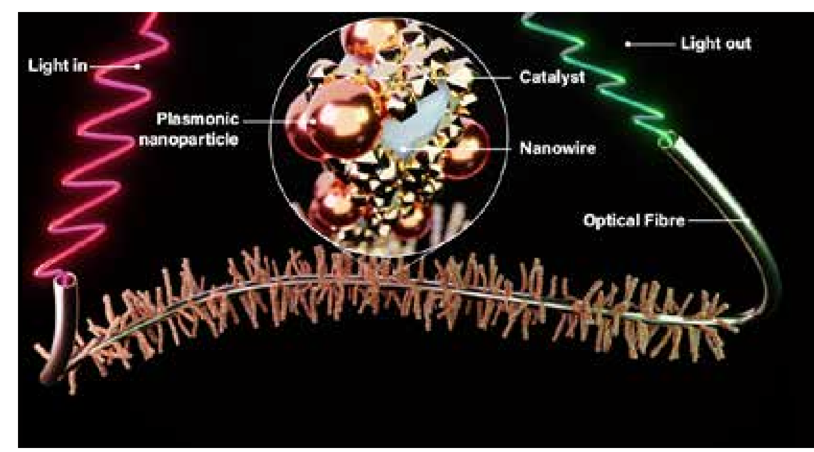
5. Further development of international collaborations

Within the last strategic period we have set up highly productive international partnerships. One example is with the Fraunhofer institute for Solar Energy Systems in Freiburg, Germany on new photovoltaic materials, another is with the University of Cambridge in a so-called Center-2-Center program. To further develop our research and to strengthen our international position in the coming strategic period, we will explore and develop additional international scientific collaborations. We are in contact with ESPCI in Paris, where we have recently established an agreement for the exchange of Masters and PhD students. We will also explore collaborations with the Fritz Haber Institute in Berlin and the Sonderforschungsbereich on Intelligent Matter in Münster.

6. Implementation of a renewed data management plan

During the last strategic period, AMOLF started a data management policy aimed at the storage and publication of data following the FAIR principle (Findable, Accessible, Interoperable and Reproducible). Important aspects of this policy concern the careful use and storage of logbooks, the formulation of a clear data management plan for every research group which lays out how data are acquired and stored, and the creation of a data replication package in connection with all publications of AMOLF for which this is reasonably possible.

To further stimulate and develop open science in the coming strategic period, we will implement our recently updated data management policy, that is available via https://amolf.nl/evaluation. Following this policy, data, metadata and logbooks that underlie 'publications', i.e., peer-reviewed articles, IP-filings,



and data sets that are made 'Open Access', are stored for at least 10 years following publication, as indicated by national VSNU guidelines. We aim to align the metadata with the standards in the different research areas. Every publication will have a Zenodo link (or similar) to its replication package. This package contains the manuscript and the raw data, metadata (the settings and parameters of the instruments used in acquiring the data), and processing codes that are used to construct the figures of the publication. The replication package also contains information on what other data exist, which will be made available upon request. For projects for which there are no IP concerns, data will be openly shared at time of publication or end of the project, whichever comes first. In instances where data is too large to cost-effectively store in a repository, its metadata record will be stored in a repository, and interested researchers will be directed to the data which will be openly available upon request.

Another aspect of our data management policy is that we provide regular training and informative workshops to AMOLF and ARCNL researchers to instruct them how to store data and how to make these data publicly accessible in replication packages. They will be combined with training on scientific integrity where we also address how data should be acquired and processed in a responsible and critical manner.

7. Improving diversity and inclusivity

We are convinced that a diverse team of people with strong mutual respect is essential to perform creative, cutting-edge research. A diverse team brings in multiple forms of expertise, different ways of working, and diverse interpersonal relationships, and thereby creates an atmosphere of innovative thinking, collaboration and trust that propels research to levels that would not be achieved by a highly homogeneous group of researchers, technicians, and other support staff. Moreover, safeguarding diversity in the hiring of personnel is important to prevent talent loss. Next to all these tangible benefits, we also experience that a diverse team makes the daily routine more colorful and joyous.

A pre-requisite of diversity is inclusivity: an inclusive environment creates a safe working culture where individuals can rise beyond themselves, promoting their talents and leveraging their self-esteem to create strong personal growth. In our view, creating an inclusive environment enables diversity at all levels in the institute, from group leader to technical support, and from MSc student to PhD student and postdoc. Our goals in creating an inclusive and diverse working environment have been recently formulated in an inclusivity and diversity plan, that is available via the website. This plan is the successor of our former gender equality plan. The scope of the new plan is broader than gender, as it also addresses other forms of diversity. Some specific targets of the new plan are:

- **Improving the on-boarding of new employees at AMOLF**. Especially when employees come from abroad (which applies to most of our PhD students and post-docs), they can be greatly helped in feeling at home and finding their way if they get assistance from other AMOLF employees who can take the role of 'buddy'.

- **Improving the gender balance among all AMOLF employees**. During the last strategic period we already aimed to improve the gender balance among the scientific personnel. For the PhD students this has been realized and we will keep a keen eye on preserving this. For the post-docs we see large fluctuations, and over the last years there appears to be a decrease of the percentage of women. This requires special attention. The gender balance among the scientific group leaders is also subject to large fluctuations. We wish to improve this balance. To this purpose, we aim to have a 50:50 balance between women and men among newly hired tenure-track group leaders, continuing our recent track record. To reach this goal we have implemented several measures, like active scouting, formulating advertisement texts and questions to candidates that are gender-neutral, and extending the deadline of advertisements in case the initial candidate shortlist does not contain at least 1/3 female candidates. In the coming strategic period, we will pay special attention to increasing the number of women in the technical support departments, and also strive for a more gender-balanced administrative support.

- **Institute-organized activities to create awareness**, like a diversity day and gender-bias awareness trainings.

- **Institute-support for community-driven activities** that stimulate diversity, like the AMOLF international lunch, language café etc. These activities are largely organized by our student population and are very effective in creating a welcoming and inclusive atmosphere.

Our efforts to stimulate a diverse and inclusive environment have been recently recognized by the Dutch Physical Society by awarding the NNV Diversity Prize 2022 to AMOLF. The jury in particular acknowledged the strong community commitment to diversity and inclusivity, as witnessed by the engagement and enthusiasm from the young staff and students of AMOLF that they interviewed.

8. Implementing our new PhD and postdoc training program

PhD students and post-docs form the scientific workforce of AMOLF. We have an extensive training and mentoring program in place for our PhD students and post-docs. In the coming strategic period we will further develop this program (new PhD policy available via https://amolf.nl/evaluation) with the following novel elements:

- A tailored portfolio with courses from a rich spectrum offered through our collaborations with Dutch universities – noting that AMOLF PhD students all receive their degree from different Dutch universities;
- An evaluation process involving also external PIs to maximize student potential and to identify issues at an early stage;
- A 'prospectus talk' after one year in which students present the plan for their PhD to the other students and PI's of their expertise center;
- Initiatives focused on mental health and work satisfaction, developed during the Covid pandemic, including a 'buddy' system for newly arrived students, workshops for boosting mental vitality, and a range of social outings and activities organized by the students themselves;
- An 'AMOLF recruitment day' to achieve a better match between students and the prospective group, with a focus on more information and choice;
- Initiatives to better orient the students toward their future career, through 'towards a new position' interviews and talks by AMOLF alumni about their diverse jobs, which we will organize within a biannual 'AMOLF career day'.

9. Further implementation and development of Amsterdam NanoLab

AMOLF has a cleanroom facility NanoLab Amsterdam with state-of-the-art equipment for the fabrication and characterization of nanostructured materials, including nanolithography techniques, scanning and transmission electron microscopy, and diverse material deposition and etching techniques. In the coming strategic period, we wish to further develop our national role in the nanofabrication and -characterization of functional complex materials within the context of NanoLabNL, the national infrastructure consortium for research cleanrooms. NanoLabNL has acquired a large investment budget within the granted Growth Fund initiative QuantumDeltaNL. As a result, AMOLF can invest ~12 M€ in cleanroom infrastructure in the coming strategic period. These investments will be used to expand our cleanroom, and to further develop our cleanroom as a national facility that welcomes and aids external users from other academic institutions and companies. To realize this, we will invest in additional dedicated personnel who will assist in the operation and maintenance of the equipment of the cleanroom. It should be noticed that the budget required for the extended operation and maintenance of our cleanroom as a national facility is not provided by the Growth Fund initiative, meaning that we have to find other resources to finance its extended operation and maintenance as a national facility.

10. Invest in and develop state-of-the-art infrastructure

We plan several actions to keep our scientific and technical support infrastructure state-of-the-art. In addition to the major cleanroom investment listed above, our investment roadmap includes multiplexed high-throughput super-resolution microscopy for live cell imaging, a transient-absorption visible and IR facility for time-resolving physical and chemical processes, and state-of-the-art 3D printing for mechanical metamaterials and soft robotics. Enabled by a recently awarded NWO Research Infrastructure grant, we will furthermore develop a facility that combines transmission electron microscopy (TEM) with light-incoupling, to study light-induced processes at the atomic scale.

Regarding the technical support infrastructure, we will invest in a state-of-the-art electrical discharge machine, a laser welding machine, in build agent software for software design, and in Fused Deposition Modeling 3D printing for mechanical design. In terms of IT infrastructure, we will replace our network switches and update our main servers. To accommodate the increasing need for data storage and to meet the standards for sound data management, we will investigate different data storage and archiving solutions. Finally, to minimize the risk of security breaches in our operating systems, we will invest in cybersecurity and other safety measures.

11. Preserve and develop industrial collaborations and start-ups

We find it important that the fundamental physics and design principles of functional materials that we discover come to the benefit of society. Therefore, we seek collaboration with companies and other non-academic organization that can use the new insights in new products, production methods or therapies. AMOLF has many ongoing collaborations with companies. Prime examples from the recent past are the large Industrial Partnership Programs with Philips, Unilever and the collaboration with ASML, the latter resulting in the foundation of the Advanced Research Center of Nanolithography, an NWO institute that is 50:50 financed by academic partners and ASML. We have also been successful in developing commercial products together with industry (e.g. in electron microscopy and spectroscopy). In the coming strategic period, we wish to build up and broaden our collaboration co-development with industrial partners in the following ways:

- **Initiating collaborative joint projects with companies.** These projects are relatively small-scale, usually performed by a postdoc who is appointed for two years. These projects are financed by at least 15% (in-kind + cash) by the industrial partner. Every two years we will organize an application round in which we can grant three of these projects with AMOLF group leaders in the lead. This program is mainly targeted at engaging companies that are not yet in our industry network, with the aim that the projects act as seeds for follow up collaborative grants.

- **Setting up a valorization team** that focuses on both awareness around impact and facilitates connections with industry and society.

- **Hiring a project officer** who actively searches for industrial partners and helps us to evaluate IP opportunities.

- **Organizing Industrial contact days**. Every two years we will organize a day on which we invite companies to come to AMOLF and to get more information on our research and techniques, with the intention to start new collaborations.

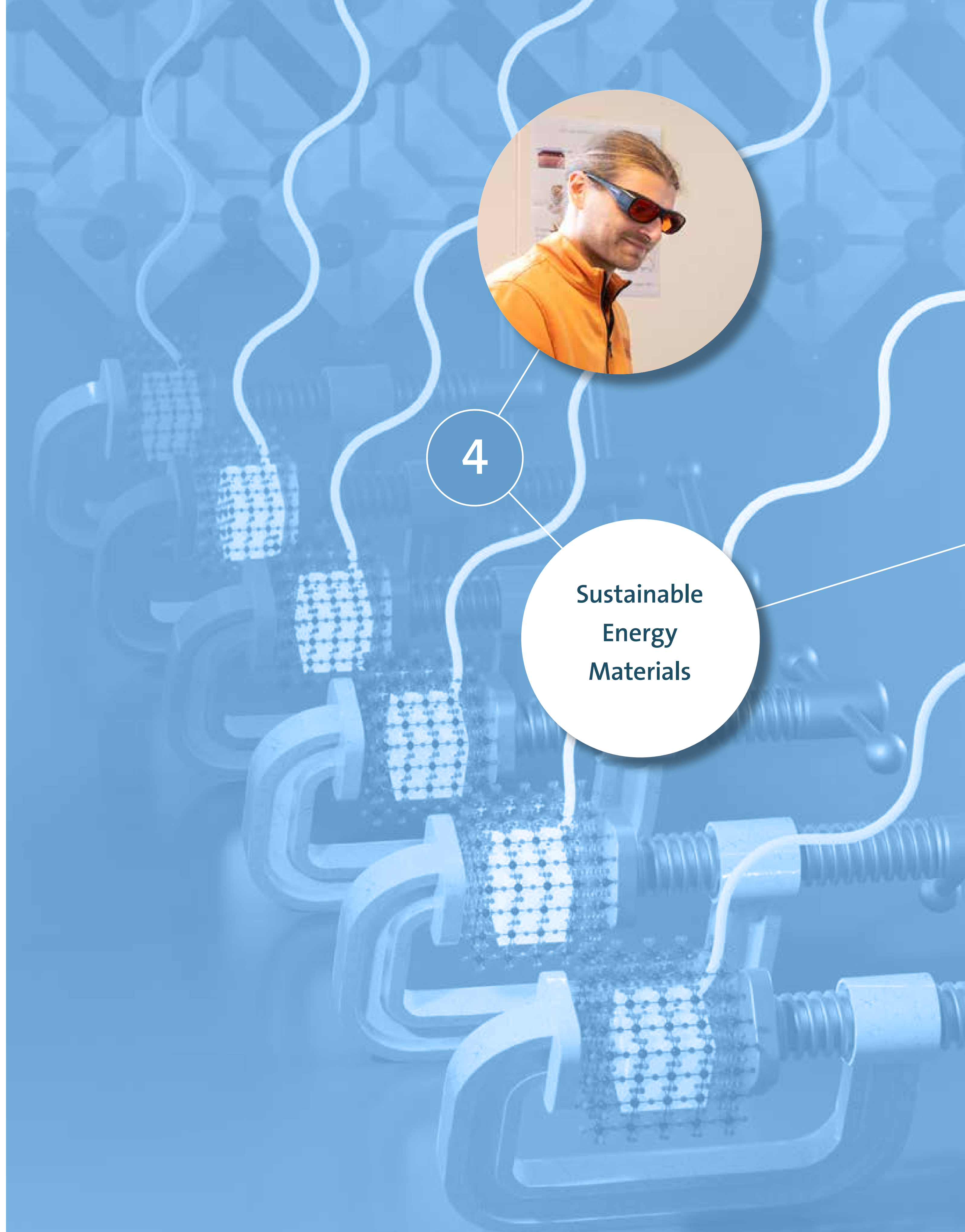
- **Stimulating start-ups** that originate from research discoveries at AMOLF. A recent exciting example of a start-up originating from AMOLF is LumetalliX. This new company is led by a former AMOLF PhD student, and sells a new, highly efficient and cheap method for detecting lead contaminations, which is increasingly being recognized as a major health concern, both in the US and in developing countries. The method is already being used in different countries.

- **Organizing so-called valorization colloquia**. We regularly organize special colloquia for all employees at AMOLF where the speaker is someone who has worked at AMOLF and is now working in a company, a start-up or as a consultant showcasing the transfer from academic research findings to industry.

- **Exploring larger-scale collaborative programs**, involving several groups and either a big industrial partner or a consortium of SMEs, for instance within the NWO national funding schemes for public-private partnerships.

12. Reducing our CO_2 footprint

The research program of AMOLF is strongly focused on fundamental research that contributes to the solution of important societal problems. The presently most pressing societal problem is global warming and climate change. In that perspective we should maximize our efforts in reducing the CO_2 footprint of our (research) activities. Therefore, in the coming strategic period we aim to strongly reduce our CO_2 footprint, by reducing and changing travel, stimulating the use of public transport, and by installing a large array of solar panels on the roof of our building. The action plan for becoming climate neutral by 2030 is drawn up in the AMOLF Sustainability Roadmap 2030, written by our internal sustainability taskforce, with input from the sustainable engineering and consulting company Arcadis (Roadmap available via https://amolf.nl/evaluation).



4. Sustainable Energy Materials

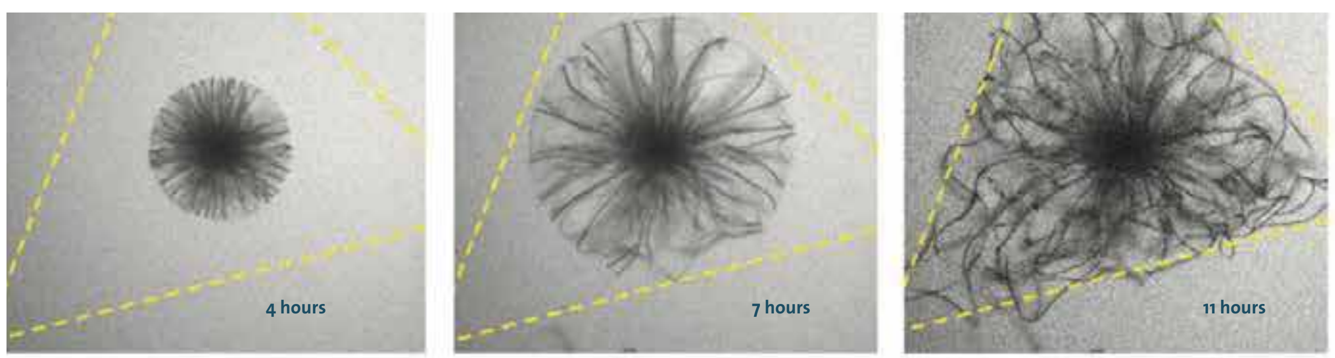
4.1 Goal and ambition

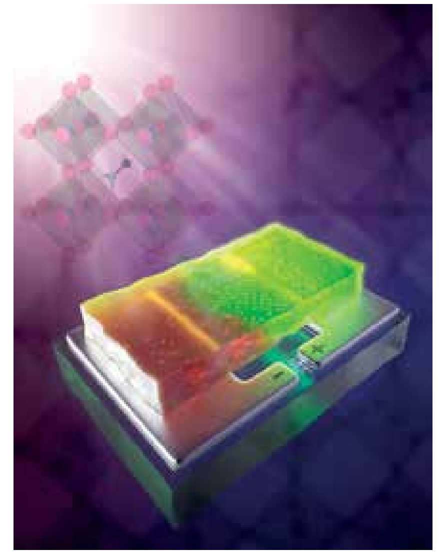
Climate change is one of the greatest challenges facing society in the coming decades. There is an urgent need to transition from a world fueled by fossil energy to one powered by sustainable energy. All future energy scenarios show that renewable electricity, primarily from photovoltaics (PV) and wind turbines will be the dominant future power source. In many markets, renewable electricity is already the cheapest form of energy and the price, particularly of PV, continues to decline. Even though we are only at the beginning of this renewable electricity revolution, it is already clear that new challenges are emerging. The required upscaling of solar electricity implies a substantial fraction of land, buildings, vehicles and infrastructure needs to be covered with PV. This integration requires entirely new types of solar cells that are lightweight, flexible, adaptable, customizable and aesthetically pleasing (e.g. colorful or 'invisible'). From a practical standpoint, the massive integration means PV energy conversion efficiency must continue to increase not only to reduce cost but also to reduce the required installed area. Finally, the switch from relying primarily on burning fossil fuels to using renewable electricity requires massive electrification of industrial processes and developing new routes to make chemicals and materials that can store energy efficiently. Using light and electricity offers the possibility to power chemical reactions in controlled ways by creating unprecedented gradients in temperature and chemical potential both spatially and temporally. The ability to inject energy into systems with nanoscale spatial resolution and picosecond time resolution can usher in a new chemistry where molecules are escorted through a pre-programmed energy landscape. The idea of moving from a static to highly dynamic free energy landscape is uncharted territory both theoretically and experimentally and will require the development of new characterization tools and theoretical models.
The overarching goal of the Sustainable Energy Materials theme is to use fundamental insights in (nano)photonics and (nano)materials to efficiently transform sunlight into electrical, chemical and thermal energy. We have the ambition to design and predict where energy flows and how it is converted in artificial photosystems to these different types of useful products. The AMOLF research program in Sustainable Energy Materials brings researchers from different disciplines together to approach the limits of conversion efficiency between different types of energy by controlling materials at the nanoscale. This can translate to completely new material properties and device functionalities, ranging from self-optimizing tandem solar cells to programmable and reconfigurable catalysts that enable totally new designs for light- and electricity-driven chemical reactors. The urgency and scale of the energy transition requires national and international coordination of research at both fundamental and applied levels. AMOLF has already played an important role in organizing the Dutch PV field, coordinating a just submitted comprehensive proposal for 898 M€ over the next 10 years (with 586 M€ coming from private partners) that outlines a research and technology development roadmap for all academic and industrial partners in the Netherlands (see https://amolf.nl/evaluation for the complete plan). This plan includes bringing PV manufacturing industry back to Europe (>7 GWp/year of PV factories). To support that industry, fundamental and applied research must continue for the coming decades. Such coordination is a key aspect of AMOLF's national role, and we have the ambition to expand our coordinating efforts beyond PV into other areas of the energy transition.

4.2 Research program

The sustainable energy materials research program explores how manipulating light, charge and heat in space, time and propagation direction can lead to new energy conversion possibilities. We aim to understand the fundamental mechanisms underlying energetic and material transformations to provide higher efficiency, better stability and new functionality in solar cells, light-emitting diodes and chemical (photo, electro) catalysts. For more mature research directions, we also connect to applied research institutes (e.g. TNO, Fraunhofer, UNSW) as well as industrial partners (e.g. BASF, Shell, ExxonMobil, Toyota) to ensure maximal impact. Our research is fundamentally rooted in our historical strength in nanophotonics. Starting in 2012, this direction was supplemented by additional tenure trackers (Garnett, Ehrler, Alarcón-Lladó) with expertise in (nano)materials and the focus was expanded to include PV. More recently, we saw the emerging opportunity for applying nanophotonics to chemical systems to drive and monitor reactions and thus further expanded to the current research portfolio of Sustainable Energy Materials with a tenure track hire (Albrecht) and two tenured group leaders (Noorduin, Bakker). Although the specific material/chemical systems are different, the expertise in light-matter interactions fundamentally link all the research directions described in further detail below.

A timelapse with optical microscopy images of the growth of a triangular $BaCO_3$-silica nanocomposite.



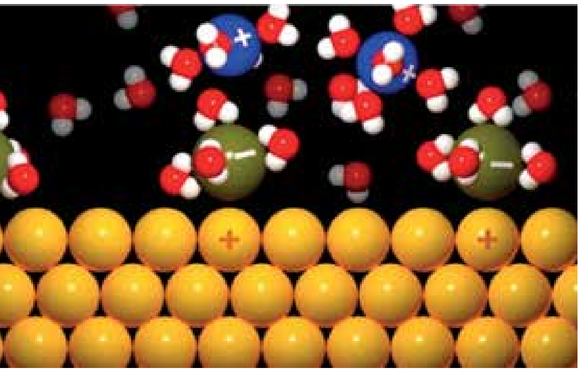


Ion migration.

• Perovskite solar cells
The Netherlands has a strong position in roll-to-roll technology for the fabrication of perovskite solar foils, with key innovations developed at TNO/Solliance, and HyET Solar, a company that is bringing solar foils to the market. Together with TNO and HyET Solar we will develop novel perovskite materials that can be applied in a roll-to-roll process to fabricate perovskite solar foils. The aim is to realize a conversion efficiency for roll-to-roll fabricated foils beyond 25%, using an innovative environmentally friendly manufacturing process. We will develop water-, alcohol- and DMSO-based synthesis procedures, in particular for low-bandgap tin-based perovskites, that will be used as the bottom cell in an all-perovskite flexible solar foil. Flash annealing using laser or LED beams will be developed to rapidly crystallize and stabilize the deposited perovskite solutions in air. To measure the (poly-) crystalline structure of the perovskite films we develop a novel in operando electron backscatter diffraction (EBSD) instrument to see how light and electrical bias lead to degradation in performance. Our structural investigations are then correlated with measurements of opto-electronic properties. We aim to find the origin of the relatively high degradation in perovskites and study the origin and effect of ion migration, also employing drift-diffusion simulations in combination with advanced impedance spectroscopy that we develop for this purpose. We also study how perovskite films can change their structure under illumination, an intriguing effect that we will exploit to achieve self-adapting geometries that can steer and concentrate uncollimated sunlight by decomposing stable intermediates and nucleating highly efficient emitters in programmable locations.

• Electrical to chemical energy conversion
The temporal variability of green power generation from solar or wind energy makes energy storage crucial. Electrochemistry is the field that studies electrically driven chemical reactions at electrocatalyst surfaces and allows the conversion of electricity to fuels through the formation of energy-rich compounds such as hydrogen, hydrocarbons or alcohols from water and CO_2. The key limiting factor in making these relevant reactions efficient with non-precious metals is the lack of detailed understanding of how these reactions proceed on the nanoscale.
Our goal is to develop new materials and methods that unravel key physico-chemical properties of the water-solid interface that rule electrocatalysis.

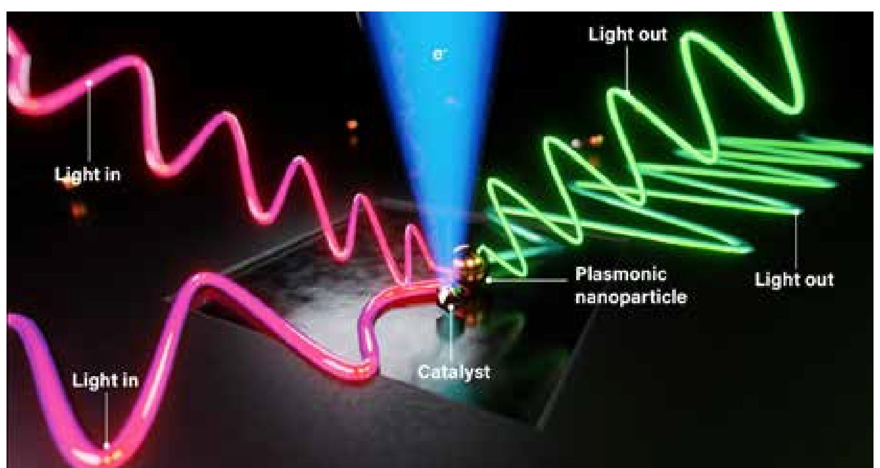
It is well known that an electrolyte solution close to a charged electrode rearranges itself into a so-called electrical double layer. All electrochemical reactions thus take place in a structured environment of ions and water near a surface, which has direct impact on the rate and efficiency of the reaction. Detailed knowledge of the hydrogen-bond structure and molecular dynamics in the interfacial region near the electrode surface is still missing far from equilibrium, which is of fundamental importance to understand electrochemical reactions on a molecular scale and will contribute to providing rational routes to highly efficient electrocatalysis. We will capitalize on our advanced in-situ femtosecond spectroscopic techniques and operando nanoscale (force) microscopy to investigate the nanoscale structure of electrochemical systems. We are now combining force microscopy and nanoscale monitoring of electrochemical reactions with ultrafast (vibrational) spectroscopy that will use phase-sensitive sum-frequency generation to study the dynamics of electrochemical interfaces. This combination of techniques will provide unprecedented insight in the structure of the water and its complex interaction with ions and surface atoms at electrocatalytic hot spots. These studies will help guide the development of new electrolyzers, thereby enabling the



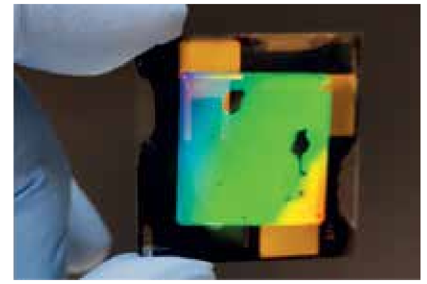
Schematic picture of the interface of a solid electrode with an electrolyte solution. The positive and negative ions in the electrolyte solution arrange in an electrical double layer. that screens the electric field exerted by the positively charged electrode.

efficient storage of sustainable energy. Leveraging on the high degree of spatio-temporal control over ions in solution combined with nanophotonics we will also explore their synergistic interplay, enabling new types of electrochemistry. We also now have a new project that aims to control and tune electrocatalytic reactions via strong coupling in plasmonic nanoantennas, enabling shifting the famous ‘volcano plot’ of competing reaction pathways and breaking scaling relations, a holy grail in catalysis.

• Light-driven chemistry and spectroscopy
Using light to drive uphill chemical and material transformations is still in its infancy with essentially no commercial market yet. However, over the last decade it has become clear that light-driven chemistry offers completely new possibilities compared to standard thermal chemistry. Using light instead of heat can change the activity and selectivity of catalysts, can lead to completely new products not seen thermally and even in the case of photothermal driving allows for much more localized heating and cooling (in both space and time). We have shown it is possible to change the product a catalyst produces by slightly altering the color of the light source and are now applying these first results in model systems to reactions more relevant for the energy transition (e.g., CO_2 reduction). Light pulses can alter the shape and defects of catalyst nanoparticles, which are known to be crucial for chemical reactivity. This opens up the prospect of programmable and reconfigurable chemical activity and selectivity. We are also using light to drive spatially resolved crystallization, for example using photoacid generators. Despite these numerous exciting possibilities, there is still relatively little mechanistic understanding of light-driven chemistry, which provides a barrier to technological exploitation. We aim to use light to provide the necessary energy input for chemical reactions, as a reagent to control the reactions and as a spectroscopic tool to follow the molecular transformations and discover the underlying reaction mechanism. In the future we dream about materials that can learn a desired function by training with an optical stimulus, light pulses that drive molecules through a free energy landscape in a programmable manner and systems that self-assemble into a desired and self-optimized energy conversion structure. On the more applied side, one of the major challenges of exploiting light-driven chemistry is the reactor design: making sure light can be distributed deep into a reactor without parasitic scattering or absorption. We have several newly granted projects that are focused specifically on this challenge, using for example networks of optical fibers covered in catalysts (or hollow for flow reactors), plasmonic heating particles and temperature sensing particles. These projects have a major component also on using the light not only for driving reactions, but also monitoring chemical reaction intermediates, products, and temperature in real time, to be used in a feedback loop to adjust synthetic conditions on the fly.



• Silicon/perovskite tandem solar cells, other PV materials and generic PV concepts
One of the appealing applications of perovskite solar cells is in a tandem geometry, with a silicon bottom cell. This enables the achievement of energy conversion efficiencies of 35% and beyond, well beyond the 27% efficiency record for Si solar cells. We will develop intermediate contact layers, spectrum splitting layers, and selective contacts for these geometries. We also develop a novel templated electrochemical growth method of nanoscale high-aspect ratio silver contact grids, that are highly electrically conductive and at the same time transparent for light. These geometries will also enable the use of alternative metals such as copper, and the fabrication of hybrid integrated nanoscale geometries that combine the selective carrier contacts and metal contacts. To optimize light coupling and trapping in solar cells we will further explore our recently developed hyperuniform light scattering coatings, that have spatial distributions tailored to couple to well-defined waveguide modes. These are particularly useful in thin-film silicon cells or foils, which we will explore in a project to investigate their potential for space applications. While silicon and perovskite cells will form the heart of our research, we will explore alternative materials that may become important in future specialized applications. We develop light-trapping geometries in ultrathin copper-zinc-tin-selenide (CZTS) solar cells (with UNSW) and will develop a heterojunction geometry of a new PV material, Zn_3P_2, that is composed completely of earth abundant materials and show very strong light absorption. We will also continue our collaboration with Fraunhofer ISE on Si/GaAsP/GaAs multijunction solar cells, further improving the light trapping back reflector aiming at a conversion efficiency beyond 37% (1 sun, AM1.5).



Si/perovskite 4T tandem solar cell with intermediate spectrum splitter (with TNO).

• Analytical microscopy and spectroscopy with light and electrons (method development)
A key aspect of our research is to pioneer new analytical electron and optical microscopy and spectroscopy techniques that create insights in the structure and dynamics of the new materials that we develop. For example, using pump-probe cathodoluminescence in the SEM, we will monitor nanoscale temperature variations in our novel fiber-optical chemical reactors. Using a new aberration-corrected TEM that we will install in the near future we will perform atomic-resolution TEM, including 3D tomography, of materials in operando – under light excitation (unique in the Netherlands) and/or gaseous and liquid environments. In addition, we will use machine learning techniques to reconstruct their (atomic) 3D structure from optical scattering measurements. Using similar machine learning concepts we will develop SEM-CL tomography as way to reconstruct the nanoscale geometry of 3D objects, which has applications in semiconductor metrology. As many of the PV excitation and de-excitation processes take place at ultrafast time scale and in a spatially selective way, we develop time-resolved pump-probe cathodoluminescence and transient absorption Fourier microscopy for materials analysis.

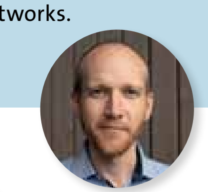
Sustainable Energy Materials Research Groups

• Garnett’s group develops nanomaterial synthesis, characterization and device integration strategies with applications in photovoltaics, LEDs and light-driven chemistry.

• Polman’s group leverages nanophotonics to improve light trapping in solar cells, perform energy efficient computing at the speed of light and develops new types of cathodoluminescence microscopy and spectroscopy methods for studying PV materials.

• Bakker’s group using surface-sensitive ultrafast vibrational and optical spectroscopy to study molecular processes at liquid-air, liquid-solid and liquid-liquid interfaces with applications in electrochemical and biological systems.

• Ehrler‘s group studies ion migration in halide perovskite materials using capacitance-based and optical measurements in order to improve the stability of solar cells and LEDs and also to use ion migration for energy-efficient future computing based on artificial neural networks.



• Alarcón Lladó’s group develops methods for the high spatio-temporal control over light and ions in solution and interfaces, using scanning electrochemical microscopy, electrochemical atomic force microscopy and nanophotonics.

• Noorduin’s group studies how the crystallization of both inorganic materials and biological compounds can be controlled and directed by confinement, local pH, light and heat.

• Albrecht’s group uses correlative electron tomography and optical spectroscopy to understand how atomic-scale morphological and structural features influence optical, electrical, and chemical processes.

4.3 Collaborations and embedding

The Sustainable Energy Materials theme is extremely well embedded in the Dutch and international landscape. We already have running grants together with several of the world leading PV research centers including Fraunhofer Institute for Solar Energy Systems, Cambridge University, UNSW, TNO, Stanford, Caltech and EPFL. AMOLF is coordinating SolarLab - the consortium of all academic PV researchers in the Netherlands and took the lead in writing the recent 8-year, 900 M€ roadmap for Dutch PV research and commercialization mentioned above. Outside of PV, we are also involved in many National consortia focused on the energy transition: the Advanced Research Center - Chemical Building Blocks Consortium (ARC-CBBC), the Amsterdam Center for Electrochemistry (AMCEL), and a Knowledge Innovation Covenant with Utrecht University and Shell, ExxonMobil, Toyota, BASF, DELMIC and DENSSolutions. At the European level, AMOLF is leading a consortium: Electron Beams Enhancing Analytical Microscopy (EBEAM) and also participating in a consortium exploring new types of fiber-optical flow chemistry reactors. AMOLF group leaders sit on or chair many important committees related to the energy transition. For example, Bruno Ehrler is the figurehead for the Dutch Science Agenda (NWA) Energy Transition route and board member of the Netherlands Energy Research Alliance (NERA), which coordinates various large initiatives in sustainable energy research including the related NWA topics. Albert Polman is on the Top Sector Energy Mission Team (coordinates industrial partnerships with academia in the Energy sector) and sits on the TNO Energy (Dutch applied energy research institute) strategy board. Albert Polman co-founded and chaired the MaterialenNL platform, which coordinates materials science research within the Netherlands (including a large effort in sustainable energy materials). Esther Alarcon-Llado is a member of the NWA Materials route theme commission, with her responsibility to link efforts in the materials field related to sustainable energy topics. Erik Garnett is on the round table chemistry (advisory committee for the Dutch National Science Foundation, NWO), where he is in charge of linking the chemistry community with the Dutch climate research initiative (KIN).

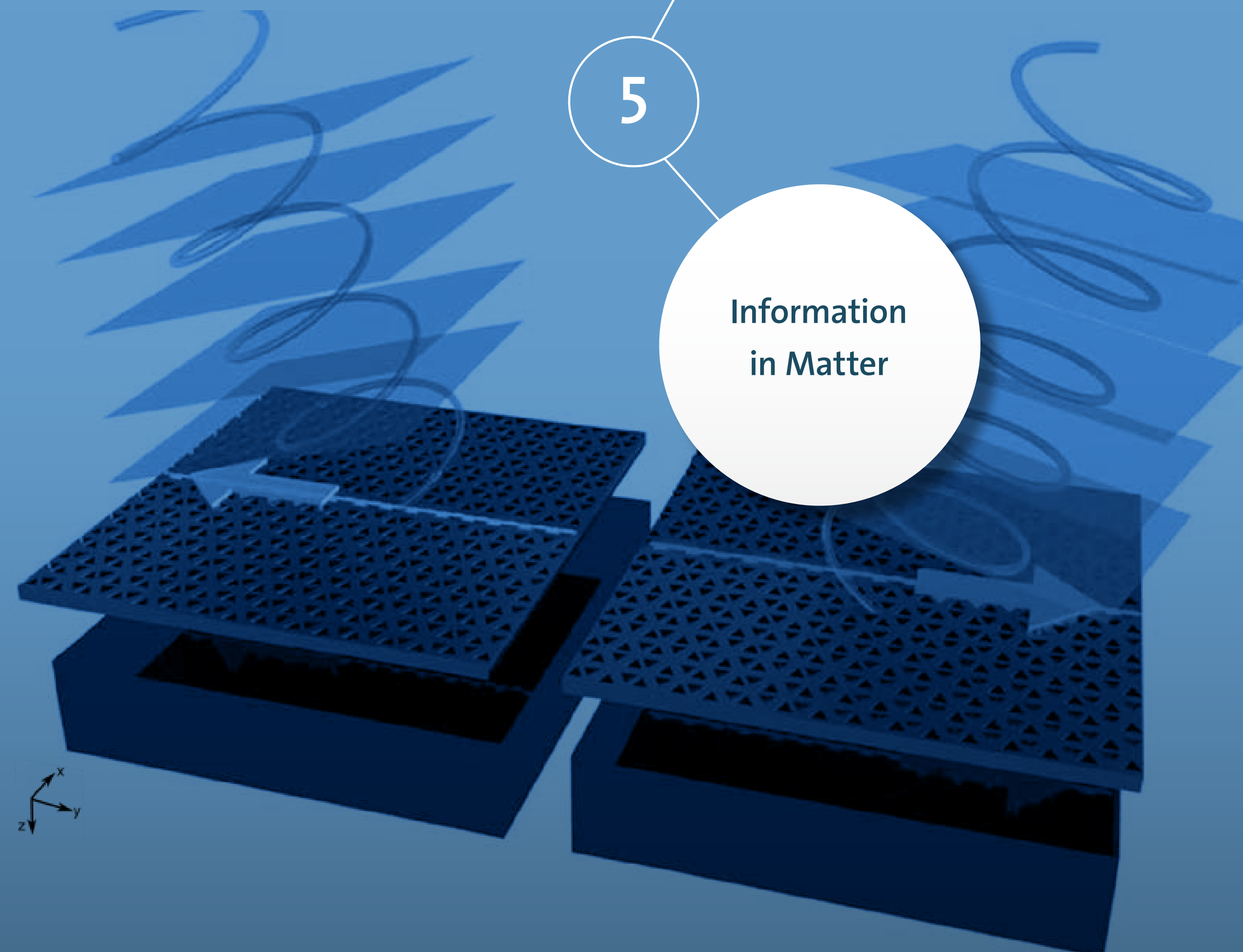
Finally, AMOLF organizes a wide range of workshops to help bring together the broader Sustainable Energy Materials community, such as an annual symposium on photovoltaics and another on light for driving and monitoring chemical reactions.

4.4 Personnel

The Sustainable Energy Materials Theme consists of 6 scientific tenured group leaders (E.C. Garnett, A. Polman, W.L. Noorduin, B. Ehrler, E. Alarcón-Lladó, H.J. Bakker) and one tenure track group leader W. Albrecht (started May 2021).

5

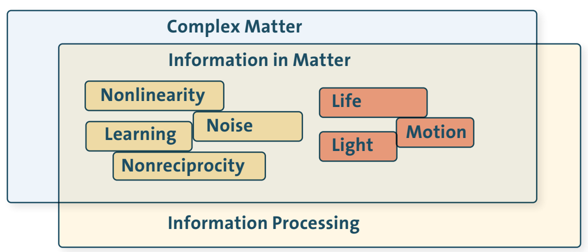
Information in Matter



5. Information in Matter

5.1 Goal and ambition

We live in the era of information. The unprecedented quantity of present-day information places increasing strains on information storage, transmission, processing and associated energy demands This drives research into new physical paradigms to handle information, such as DNA- and protein-based computing, analog optical computing, mechanical computing, and physical implementations of artificial neural networks, from electronic to optical and spintronic. At the same time, very powerful computing allows us to understand materials and processes of unprecedented complexity, and artificial intelligence fuels novel forms of design and control. With the conventional boundaries between materials, devices and software dissolving, this drives both the study and design of forms of matter that gather and process information, both living and inanimate.

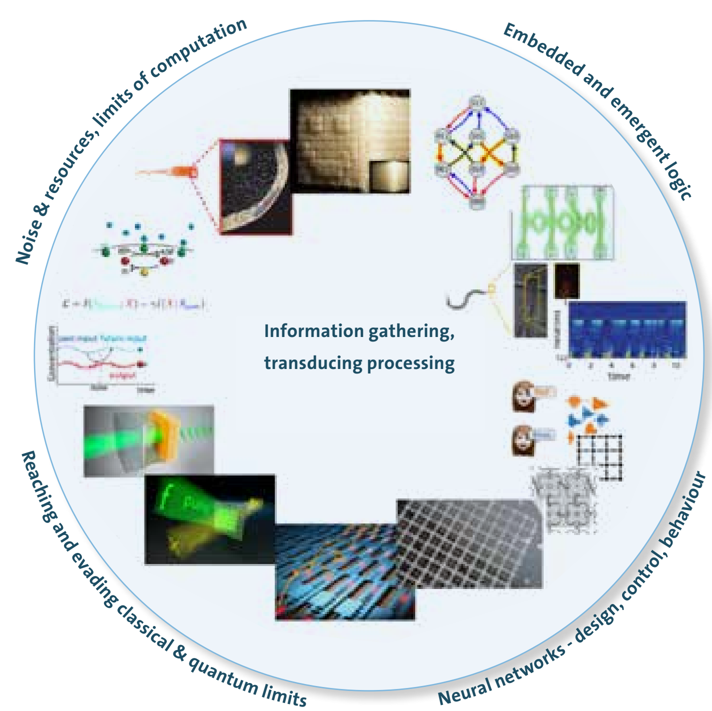


Information always resides in physical systems. Its creation, processing, preservation, and removal are therefore bounded by the laws of physics. Understanding the limits and design principles of information processing matter requires concepts from physics, such as nonlinearity, reciprocity and time-reversibility, quantum entanglement, cooperativity, and noise. This research is now possible thanks to breakthroughs in non-equilibrium stochastic thermodynamics, the massive simulation capabilities of modern computers, delicate experimental techniques to interrogate and manipulate matter, control over quantum information, and novel fabrication tools, such as nanolithography, 3D additive manufacturing, and novel materials. These furnish the experimental and theoretical foundations for developing novel computing paradigms, making use of previously untapped information-bearing degrees of freedom such as those of sound, light and biomolecules. These systems offer the potential to transcend the limits of conventional electronic computing in terms of precision, speed, and energy. The AMOLF research program in information-processing matter addresses diverse physical systems, ranging from biological, acoustic and optical systems, to mechanical metamaterials. This research program forms an excellent starting point to grow this new research direction into a field that engages a network of interdisciplinary national and international players.

The Infomatter program aims to advance our understanding of the fundamental physical mechanisms of information processing in inanimate and living matter, to push the design and limits of future information technologies, and to explore new paradigms such as learning and adaptive materials. We aim to nurture and coordinate the development of this theme in the Netherlands and internationally, by organizing meetings and exchanges, and spearheading research programs and grants, thus contributing to the core mission of AMOLF which is focused on the physics and design principles of natural and man-made functional complex matter.

5.2 Research program

The Infomatter research program explores the gathering, processing, and transduction of information by light, biomolecules, and mechanics. We unite studies on emergent computing in complex matter and material-systems – from crumpled sheets to the brain - with the design of systems that gather and process information by, e.g., light and acoustics. nonlinearities, fluctuations, and coherence are common threads among our physical platforms at different scales: strong nonlinearities in, e.g., mechanical metamaterials, neurons and light-matter interactions, govern physical bits (memory, logic, etc.); thermodynamics governs tradeoffs between energy, precision, and speed of computations;



extreme coherence offered by optical and acoustic systems down to the quantum regime allows the encoding and transport of massive amounts of information.

We address key questions about all aspects of the physics of information, which we divide in two main pillars:

- Information processing revolves around logic, algorithms, learning and computation in matter systems. For instance, we ask which analog image processing operation and reservoir computing can be performed by optical or acoustic metasurfaces that act on data encoded in complex optical wavefronts. Can we build complex nonlinear networks to solve NP-hard problems, for instance programming nonlinear microcavity arrays as hardware solvers? Do frustrated materials, such as crumpled sheets, or mechanical metamaterials composed of bistable motifs, process information? Can materials learn to process information? We will study real neural networks in living organisms, and apply the resulting insights to designing artificial neural networks for acoustic hardware that can learn to perform tasks, like recognizing acoustic stimuli. Can we build better artificial neural networks from new insights on how living systems work, and can we calculate with sound waves? Finally, an inspiring question is: can we actually use (non-equilibrium) fluctuations as a resource for information processing? Cellular systems face limited resources (energy budget, molecular copy number), and large noise. How accurately can cellular systems predict future signals, and how close can they perform to fundamental limits? Can we leverage stochasticity also as a resource in designed information matter, such as in microcavity arrays where we can inject noise at will?

- Sensing, gathering, and transducing information deals with crucial questions about the input, output, and conversion of the information degrees of freedom of information processing matter. What sets fundamental limits to sensor performance, measurement, and metrology? This question appears in all of our systems, from biochemical networks, to metasurfaces for wafer metrology, to mechanical oscillator systems in classical and quantum regimes. How can noise, gain, nonlinearity, nonreciprocity, and entanglement be used to evade limits? For instance, we will leverage nonreciprocity for both sound and light (cavity optomechanics), design nonlinearity at will for light and motion, and measure and program gain and noise in systems that range from resonant nanophotonics to biochemical networks. What is the optimal biochemical design that maximizes information transmission under resource constraints? What mechanisms enable biological sensors to achieve sensitivity in noisy environments? Can these mechanisms inspire 'sensory materials'? Crucial for ultimate information systems will also be the ability to transduce information, converting information in one degree of freedom to another. During this process, how can information be protected from (thermal) fluctuations, scattering, dissipation, and decoherence? What is the minimum energy required to, for instance, switch an optical memory, and what are the quantum limits to transducing information from photons to mechanical oscillators? We expect that while our experimental systems are diverse, unifying design principles for optimal information transmission will often emerge: e.g. use of nonlinearities to raise the gain and lift the signal above the noise, the expenditure of energy to suppress noise, breaking time-reversibility to create memory.

In keeping with the mission of AMOLF, our program focuses on the physics and design principles of information processing in matter. The research program is not focused on pushing implementation of already fully established information technology roadmaps (CMOS, integrated photonics, etc., and instead embraces unconventional matter systems, computing paradigms, and degrees of freedom. The funding backbone of our project portfolio lies in curiosity driven schemes, including ERC Advanced (Van Hecke, Pathways, Memory and Information Processing in Matter, and Ten Wolde, Optimal Cellular Prediction), ERC Consolidator (Verhagen, Challenging the limits of mechanical quantum metrology), and ERC Starting grants (Serra Garcia, Information Processing in passive elastic structures). At the same time, we also work with industrial and societal partners: sensing and metrology is central to the AMOLF/ARCNL/ASML joint program, and QuantumDeltaNL Growth Fund activities. Envisioned joint grants will tackle stochastic thermodynamics, information processing in robotic platforms, reversible computing to circumvent the Landauer limit, and metaphotonic information processing (See 5.3).

Information in Matter Research Groups

Koenderink's group develops nanoscale resonant photonics. A driving question is how to design linear, nonlinear and amplifying optical metamaterials, their illumination wavefronts, and optical readouts to optimally gather and process optical information encoded in wavefronts and near fields.

Rodriguez' group studies emergent phenomena in systems where photons interact with each other, a noisy environment, excitons, and electrons, using laser-driven microcavities with nonlinearity and controlled noise, with applications in optical sensing, energy and information transmission, and computation.

Ten Wolde's group studies design principles of cellular information transmission using statistical physics, stochastic thermodynamics, and information theory, focused on optimal designs that maximize information transmission under constrained resources such as protein copies, time, and energy.

Serra Garcia's group studies architected matter to implement complex functions such as computations, sensing and actuation. The focus is on mechanical systems, the stochastic and nonlinear nature of information processing, and developing 'programming languages' for physical systems.

Shimizu's group studies the sensing and processing of information by living matter, combining biophysical experiments with theoretical modeling and simulations, from molecular-scale biochemical computations within cells to organism-scale behavior by neural networks.

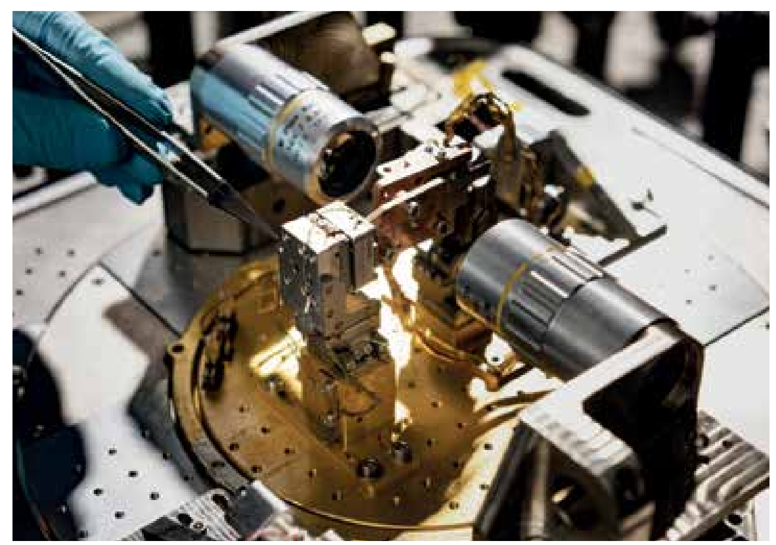
Van Hecke's group performs experiments and simulations on mechanical metamaterials and disordered matter which translate external forcing into sequences of 'mechanical bit' flips and thus process information.

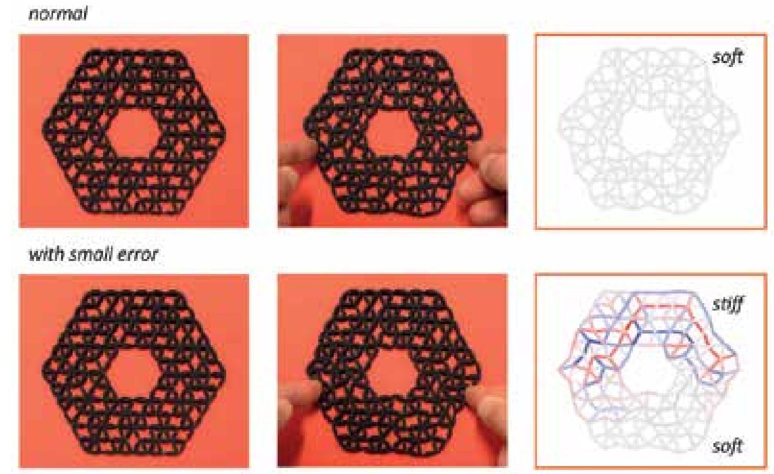
Verhagen's group explores how nanoscale system design and control over light-matter interactions can engage the conventional limits to nanophotonic and nanomechanical functionality, in application domains from sensing and metrology to communication.

5.3 Collaborations and embedding

Within AMOLF there are many underlying conceptual links with the other departments. Firstly, Information in Matter groups come from three different disciplines (Nanophotonics, Modern Mechanics, and Living Systems) that are also represented in the other themes, which organically leads through joint training events to bottom-up collaboration. Conceptually, with Autonomous Matter groups we share interest in how matter detects and responds to changes in the environment, leveraging nonlinearity as a resource to organize collective and emergent behavior, and dealing with stochasticity and thermodynamics. At the same time, 'Autonomous Matter' takes a holistic perspective and aims to include self-assembly, shape changes, force generation, while for the Information Matter theme the main currency is information, from gathering, transduction, to processing. With the Sustainable Energy Materials theme, we share techniques in inverse design, nanofabrication in materials and nanoscopy, and interest in selflearning materials: tools to design and measure the flow of light, energy and charge are similar to tools to design and measure the flow of information in matter.

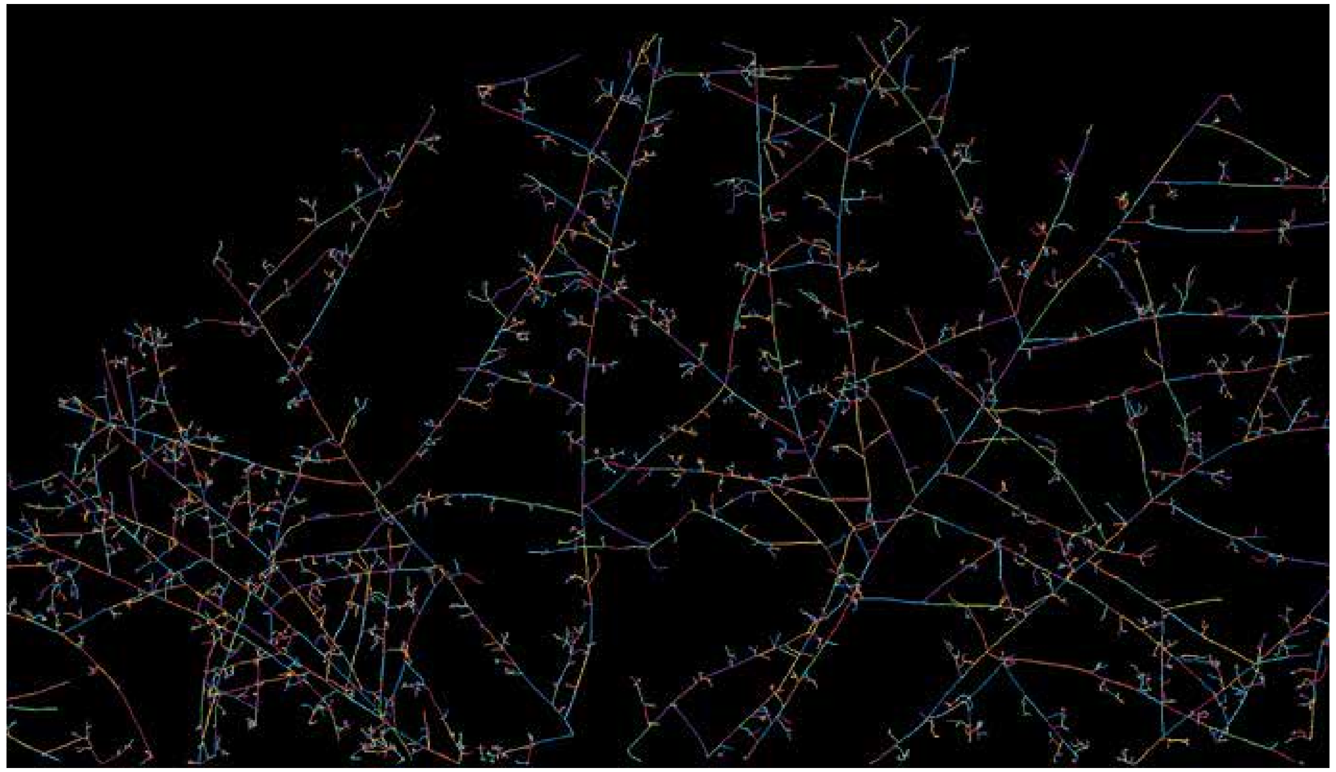
Nationally, there is a network of strong complementary partners mainly in subdisciplines, but just few with an explicit 'information materials' focus. CogniGron in Groningen has neuromorphic computing as central tenet, primarily in electronic and spintronic materials. Another strong player is the BRAINS initiative in Twente, which pursues brain-inspired energy efficient information processing nanosystems. Infomatter shares the interests of CogniGron and BRAINS in energy efficiency of computing, and in selflearning materials, while pursuing different materials systems and paradigms, and we are currently building up a joint consortium (NWA NL-ECO grant on energy efficient computing, granted spring 2023) and a Gravitation grant proposal in close collaboration with the Eindhoven University of Technology, outcome due end of 2023). From the photonic viewpoint, main other activities with an `information focus' are in the integrated photonics community (Eindhoven University of Technology, metaphotonics for sensing and reservoir computing, and in the wavefront shaping domain Utrecht University (Mosk) and ARCNL (Amitonova)). We are currently pursuing joint long-term funding for Metaphotonics with Eindhoven University of Technology, ARCNL, and Groningen through a Gravitation grant (due end of 2023). Our quantum sensing effort is part of the quantum.Amsterdam hub of QuantumDeltaNL, and we collaborate intensively on the topic with Delft University of Technology and Eindhoven University of Technology. From the perspective of the design of mechanical systems for information processing, including the use of machine learning, we are already working with Coulais (University of Amsterdam), Dijkstra (Utrecht University) and Krusyhynsky (University of Groningen), and are exploring further options within University of Amsterdam (visiting position van Hecke) and Eindhoven University of Technology (light-active polymers for use in, e.g., smart robots (Schenning, Broers)). On biochemical and cellular computing, there are strong connections with Eindhoven University of Technology (De Greef), and with Vrije Universiteit Amsterdam (Stephens) on dynamical systems analysis of the brain. Cellular information processing is central in the BaSyC Gravitation program in which AMOLF is a main hub. For this program it will be important to furthermore engage partners with a wider perspective on novel computing paradigms, and with research at higher TRL levels. To this end we will explore new connections to mathematics and information science at the University of Amsterdam and CWI (strong in computational imaging, AI, algorithms & complexity), collaborate on computational imaging and metrology with ARCNL/Vrije Universiteit Amsterdam and ASML (Witte, Kraus, Amitonova, Den Boef), and co-build the NWA NL-ECO consortium on energy-efficient computing.





The perfectly composed metamaterial is soft: it completely deforms when you squeeze it. Both experiments and simulations have shown that. However, with a topological error, the structure is different: it becomes soft on one side and hard on the other.

We are not aware of an international equivalent of Infomatter, i.e. a similarly interdisciplinary department in a physics institute with a joint strong information-focus. Key international players with whom we pursue information as a new paradigm come from diverse communities. This includes optical, RF and acoustical metamaterials (Alù and Fleury, CUNY and EPFL), optomechanics and quantum transduction (Marquardt (MPL), Nunnenkamp (Cambride), Vanner (Imperial)), emergent phenomena in photonics as basis for computation (Ciuti at Paris Diderot and Garcia-Vidal (UA Madrid)), active and topological metamaterials (Shokev (Tel Aviv), Rocklin (GA Tech)), nanomechanics (Villanueva (EPFL), Palermo (Bologna)), and cellular and biochemical computing (Ouldridge at Imperial College, and Swain (Edinburgh)).

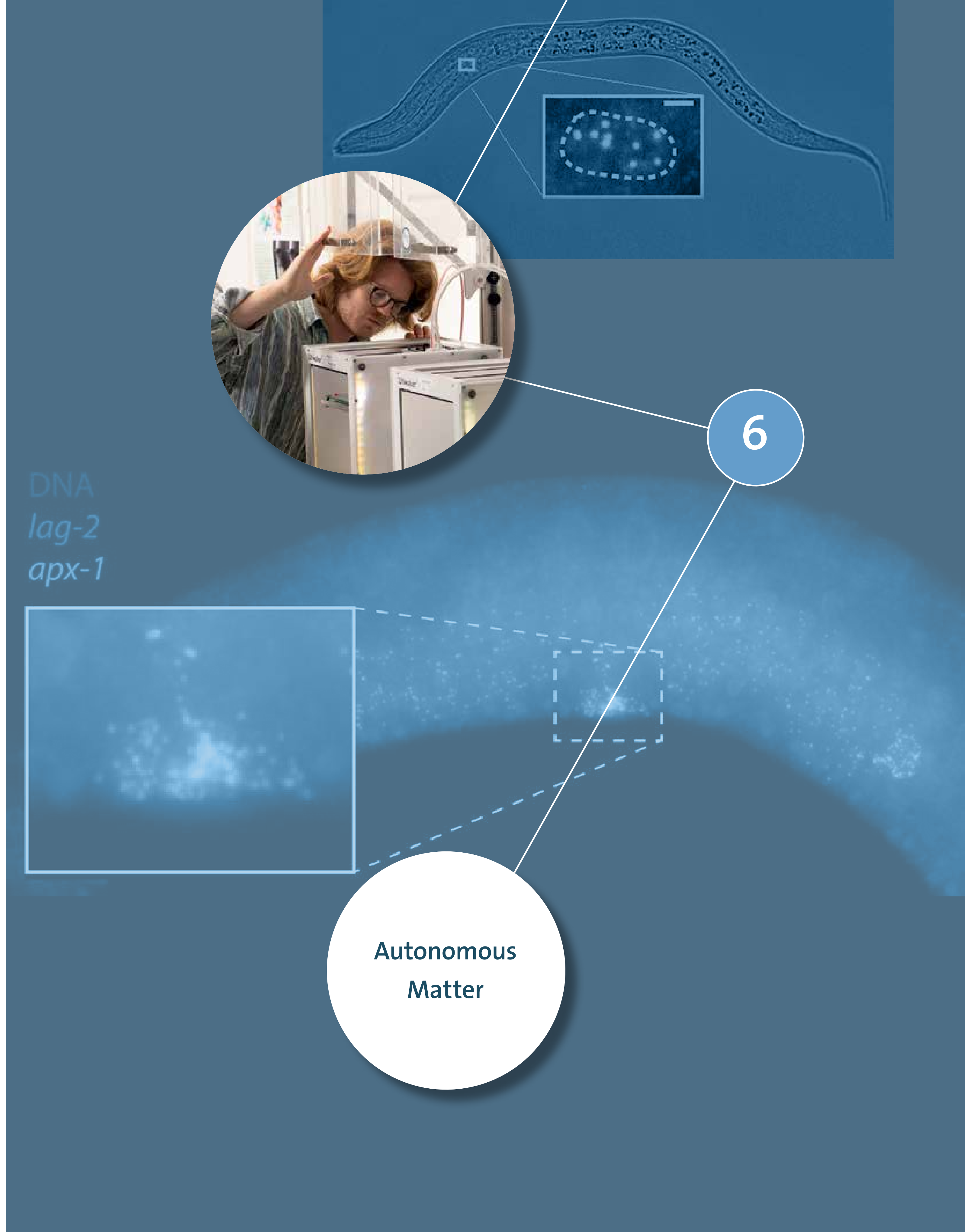


Snapshot in time of the evolving network graph of the mycorrhizal fungus R. irregularis, extracted by the mycelial imaging robot developed at AMOLF. Every node and edge of the network is assigned a unique identifier (indicated by color), and tracked over time to reveal effects of network topology on their symbiotic trade with plants.

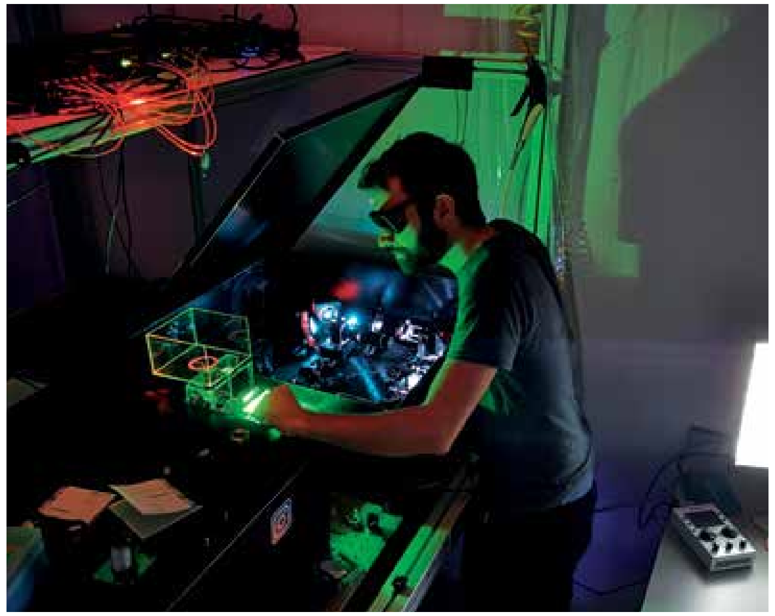
Main ongoing industrial collaboration opportunities lie in photonics for imaging and metrology in semiconductor manufacturing (ongoing with ASML and Sony, past and anticipated programs with ASML, TNO, VSL, Bruker), on-chip transduction between information-carrying degrees of freedom (ongoing participation in EIC and Dutch consortia with IBM, IMEC, Thales, Toyota, and PhotonDelta SMEs), the emerging quantum technologies ecosystem fueled by QuantumDeltaNL, and in mechanical metamaterials (planned Perspectief program, Airbus, TNO, Philips, ASML, DAF). AMOLF is one of the partners building up the 10 M€ NWA national consortium NL-ECO on energy efficient computing (funded spring 2023), which involves 30 non-academic partners (multinationals and Dutch SMEs, institutes for applied sciences (TNO)).

5.4 Personnel

The Information in Matter Theme is carried by 6 scientific tenured group leaders (A.F. Koenderink, M. van Hecke, E. Verhagen, S.R.K. Rodriguez (tenured since summer 2022), P.R. ten Wolde and T.S. Shimizu) and one tenure track group leader M. Serra Garcia (started October 2021).



6. Autonomous Matter



6.1 Goal and ambition

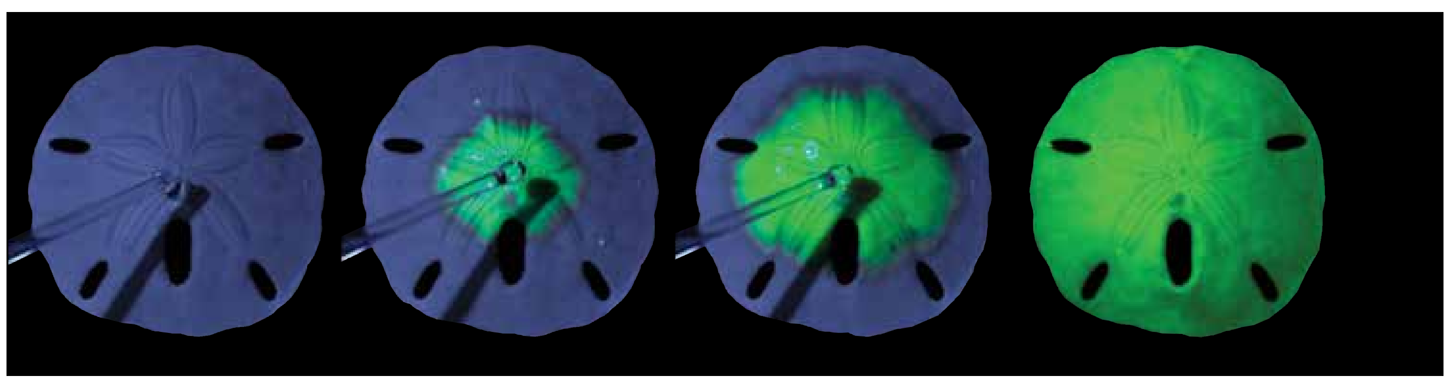
The capacity of a system to adjust to the environment, optimize its activity, regenerate its parts, and make independent decisions, is increasingly referred to by the umbrella term 'Autonomy'. Natural systems including the simplest cells show such autonomy in abundance. While an increasing set of tools is available to embed intelligent behavior in manufactured systems, their functionality remains severely limited in comparison. Currently, however, a new frontier is emerging that promises autonomous functionality in a new class of matter at the intersection of chemistry, physics, biology, and engineering.

Key to this nascent field is a shift in thinking. Whereas we traditionally strive to maximize control in engineered systems, through centralized architectures and functional separation, cellular systems maximize robustness by integrating functions locally. The latter relies on properties that are traditionally left unharnessed, such as mechanical instabilities, diffusing building blocks, energy consumption, force generation, feedbacks, and exponential growth balanced by targeted destruction. How they integrate into robust, yet dynamic systems raise a range of open questions on the mechanistic basis of autonomy. The targeted functions are illustrated by biological systems, which display an extraordinary ability to grow and self-replicate, reorganize upon demand, harness the environment, regenerate upon injury, and cooperate by allocating specialized tasks. Embedding these traits in manufactured materials offers a wealth of inspiration for next-generation autonomous matter with an unprecedented range of functionalities.

Key enabling technologies and concepts were spearheaded at AMOLF in recent years. These include biology-inspired chemistry that exploits out-of-equilibrium reaction networks and spatial patterning, self-learning robotic systems that can adapt to the environment, and physics-inspired organoid analysis approaches that reveal the dynamic basis of their cellular organization. Our initiative aims to form new connections between macromolecular chemistry, biophysics, soft matter, soft robotics, and organoid biology.

The overarching aims of this theme are to elucidate the organizational principles of autonomy in material systems at all scales, and to create a new class of autonomous matter that exhibits embodied intelligence. This encompasses the ability to self-generate, sense, and exploit the environment, re-organize upon internal and external cues, and learn from historic conditions, while being low-maintenance, sustainable and biodegradable. By further expanding and cross-fertilizing our specific strengths in bio-inspired chemistry and robotics, and physics inspired molecular and cellular biology, this effort will spawn unique new directions, which could range from evolutionary robotics to next-generation adaptive (immuno)therapeutics, and unsupervised biochemical processing and manufacturing.

A sand dollar skeleton gradually converting into a light emitting perovskite.

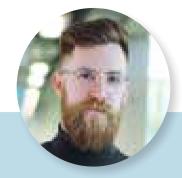


Autonomous Matter Research Groups

Tans' group studies the spatio-temporal regulation of protein assembly, through the coordination of ribosomes, proteins, and chaperones, using single-molecule methods and the cellular dynamics underlying organoid self-organization using 3D microscopy.

Mulder's group uses the tools of statistical physics to study the spatial organisation of bimolecular systems both in vivo and in a synthetic biology setting, with a current focus on designing systems that leverage the unique equilibrium- and non-equilibrium properties of biomolecules to create robust and controllable functionalities.

Noorduin's group focuses on the dynamic interplay between chemical reactions and assembly/disassembly phenomena to control the emergence of complexity in the solid state. In particular, the group aims to design physical-chemical schemes to self-organize microscale devices and functional molecules.



Overvelde's group focuses on research at the intersection between soft robotics and mechanical metamaterials, applying numerical and experimental techniques to explore how shape, nonlinearities and feedback can be harnessed to embody intelligent behavior in autonomous mechanical systems.

Ganzinger's group develops novel biophysics approaches to study immune cell recognition. Unique technologies include the ability to reconstitute immune recognition, in a combination of artificial lipid-protein hybrids and single-molecule imaging.

Van Zon's group studies developmental biology, to understand how animals execute cell fate decisions, establish spatial patterns and control developmental timing despite intrinsic molecular variability. In addition, his group develops quantitative microscopy and image analysis approaches to measure cellular dynamics in multicellular systems.

6.2 Research program

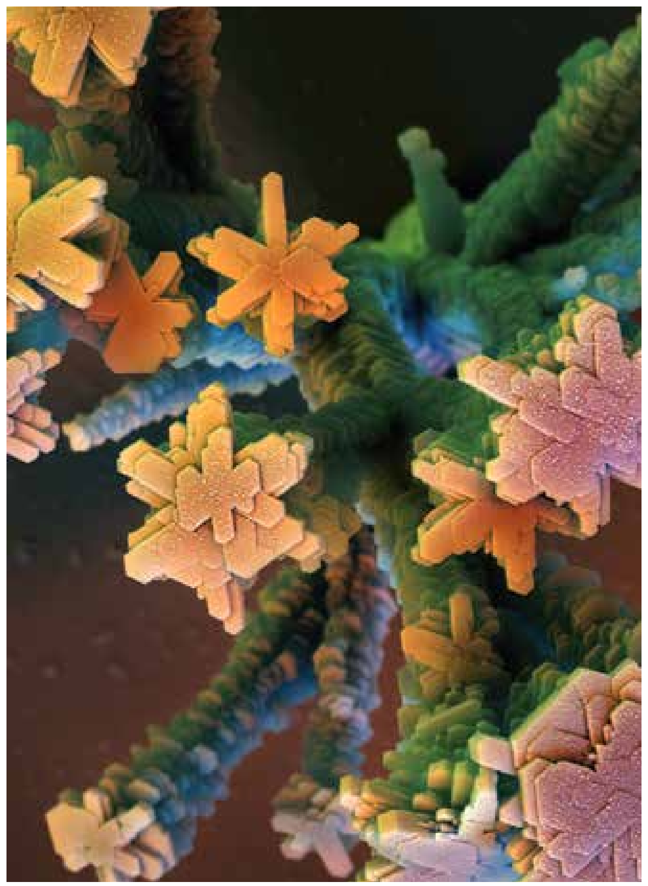
This research program studies autonomous functionality in material systems. It focuses on the ability to perform complex chemical, biological, and mechanical functions in a self-organized manner. A key enabling general principle is the local coupling between random movements, feedbacks, actuation, energy input, signal propagation, growth, and targeted destruction. We focus on systems at the frontier of current scientific advances with key application potential, including spatial (bio)chemistry, miniature organs and soft robotics.

The program is centered around the following questions:

Dynamic assembly and disassembly. An important feature of autonomous matter is their capacity to adaptively assemble and disassemble, and hence repeatedly form and destruct structures, enabled by the dynamic displacements of its building blocks. This process is associated with a host of questions: Can we control assembly, by local cues or energy-driven processes? Can 2D confinement or signaling enable novel forms of self-organization? Can we exploit shape for novel types of catalysis? Can we evolve robotic swarming? Can we evolve reactive assembly networks? Can we define and manipulate shape landscapes?

Spatio-temporal organisation. The ability to self-organize in space and time is a crucial feature of autonomous systems, enabled by (dis)assembly in combination with other phenomena, in systems ranging from protein-membrane hybrids to soft robots. Spatial self-organisation gives rise to a range of questions: What is the role of molecular gradients in spatial cellular organisation, and can we exploit them in chemical reactions? How can the exchange of signals enable other forms of spatio-temporal organisation?

Autonomous self-assembly of crystals across scales.



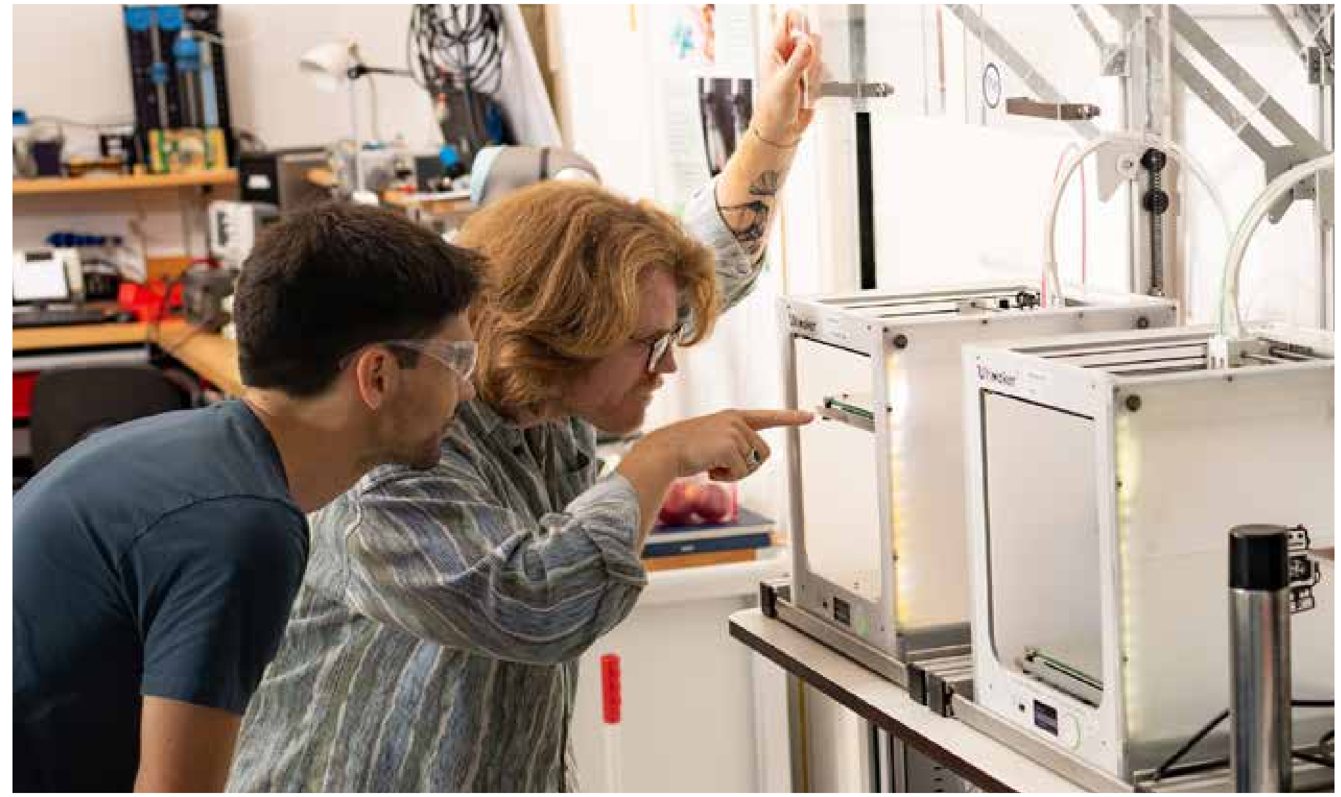
Which possibilities are opened up by energy-powered movement? What can be achieved by entropic and other passive effects?

Programmability. A next level of control in autonomous systems is the ability to program self-organized behavior, which may for instance be achieved in biological systems at the DNA level and in robotic systems at the algorithmic level. Key questions are: Can we achieve programmability in actuated metamaterials? How do immune cells use spatial protein patterning to achieve specificity for many targets? Can we use DNA sequence specificity as a basis for programmable adaptive materials? Can we elucidate the role of dynamic movements in developmental programs?

6.3 Collaborations and embedding

The Autonomous Matter theme has several key common interests with the other two departments at AMOLF. With the Infomatter theme, there are intriguing synergistic links on mechanical dynamics and information processing. For instance, protein systems display hysteresis and conformational pathways that may also enable computing in mechanical metamaterials yet involve vastly different length scales and introduce new concepts like external guidance. Thermodynamics and information processing are relevant also to autonomous matter systems but are exploited by the system rather than theoretically modelled or purposely controlled. The energy matter theme also presents interesting new connections. Specifically, functions central to autonomous matter, like self-organization, adaptability, evolvability and biodegradability, can inspire novel forms of energy conversion materials and devices. Regarding infrastructure, novel analysis techniques are critical to this theme - and distinguish it from pure chemistry or biology efforts. This includes 3D microscopy, integrated with sample control, machine-learning enabled image analysis, and complementary theoretical modelling. Hence, technical support to design and construct mechanical, optical, and electronic instruments, as well as their software control, is crucial to this direction. Key construction and synthesis infrastructure also include flow-cell technology, (bio) chemistry, nanolithography, chemistry, cell-culture, and 3D printing facilities.

We have formed a strong network of partners in the Netherlands. On the biophysics side, we interact strongly with biology groups through various research grants. For instance, with the Hubrecht Institute, the UMCU and the NKI we formed a consortium on cellular dynamics within organoids through NWO 'Building Blocks of Life' and NWO ENW-XL grants. To further boost the already strong organoid community in the Netherlands, both academic and industrial, we have taken the initiative to launch OrganoidNL. Within this platform, we have

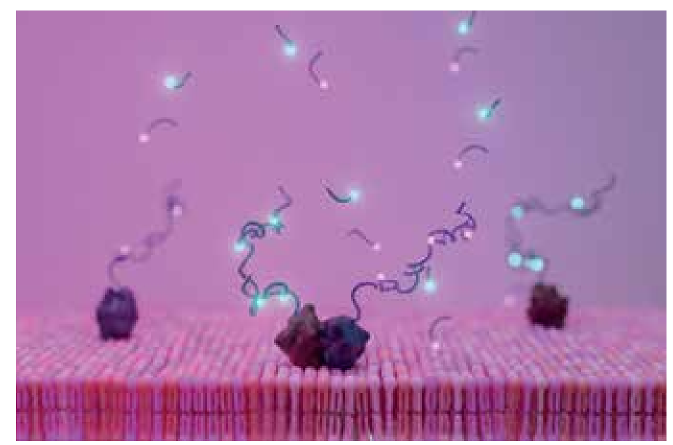


organized the first nation-wide conference on organoid science in the Netherlands at AMOLF. With the University Medical Center Utrecht (UMCU) we have several joint projects on immune cell interaction dynamics, and with Erasmus MC on developmental biology. At the biomolecular level, we work intensively with Delft University of Technology, through the two multi-million Euro Gravitation grants NanoFront and Basyc, the latter being focused on the ambitious goal of reconstituting a minimal cell, and are currently exploring follow up European funding, and a national SUMMIT grant exceeding 30 M€. We also have strong links to the chemistry community in the Netherlands, including the Radboud University Nijmegen, Eindhoven University of Technology, and University of Groningen, including with the Nobel Laureate Ben Feringa, via national Growth Fund program that exceeds 90 M€, and more locally with the HIMS institute at the University of Amsterdam. While soft robotics is a comparatively new topic at AMOLF, we have fostered close ties with major Dutch centers, including at Eindhoven and Delft University of Technology, the Amsterdam Medical Center (AMC) on hybrid hearts, and taken initiative to form a national Dutch network for soft robotics.

Our efforts also have a crucial international component. We have a longstanding research program with Heidelberg University and strengthened with the ETH in Zurich, for instance through an ERC Synergy grant, on polysome biology and biophysics. We also interact intensively with Oxford, Karolinska, and Bonn University on Immunology and CAR T-cell recognition, UC Berkeley and TAMU on protein processing, the ESPCI in Paris on organoid-on-chip systems, the Max Planck Institute for Biochemistry on reconstituted systems, the SSSA Sant'Anna, Georgia Tech, MIT, NUS in Singapore and the Center for Soft Nanoscience in Muenster on soft robotics.

Our diverse research portfolio also has strong links to startups and industrial partners. For instance, we work together with LUMICKS on protocols for immune cell interactions in CAR T-cell therapies, the HUB on Organoid imaging analysis and protocols,

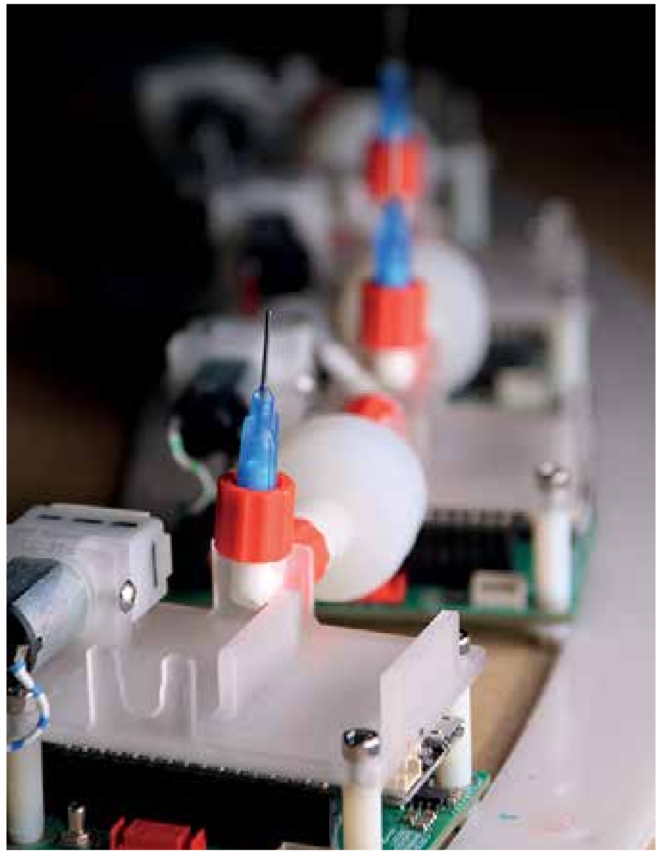
DNA-paint technology allows long-term tracking of membrane proteins.



Symeres and InnoSyn on the chirality and assembly, BASF on functional materials, ReinVad on left-ventricle assist devices, Polymer Systems Technology Ltd on medical grade silicone elastomers, medical device design agency on 3D printing silicone elastomers, and Vycellix on cell-based immunotherapies.

6.4 Personnel

The Autonomous Matter Theme is carried by 6 scientific group leaders (S.J. Tans, J.S. van Zon, K.A. Ganzinger, J.T.B. Overvelde, W.L. Noorduin, and B.M. Mulder (retirement 2023)).



Self learning robotic modules.

Research expertise centers

7

7. Research expertise centers

7.1 Introduction

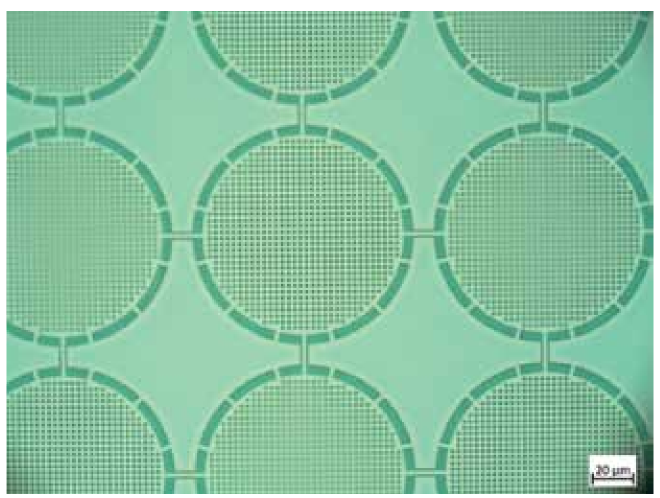
AMOLF's three research themes span multiple research disciplines that are organized in five research expertise centers:
• Modern Mechanics
• Nanophotonics
• Light Management in Photovoltaics (LMPV)
• Living Systems
• Chemistry & Spectroscopy

The expertise centers support and enable the multi-disciplinary research projects of the research themes. To do so, they continuously develop new theoretical and experimental capabilities, thereby pushing the frontiers of these disciplines. The centers provide a stimulating environment for the education and training of young researchers. The expertise centers also position AMOLF strategically in discipline oriented national and international collaborations and networks.

7.2 Modern Mechanics

The Modern Mechanics center leverages geometry, vibrations and nonlinearities to probe and design (meta)material and mechanical systems that reconfigure, sense, process information, and respond and interact with their surroundings. We develop and apply design techniques for mechanical structures and devices that straddle the boundary between material and machine. For example, we explore how complex materials ranging from specifically designed metamaterials to crumpled sheets store and process information, and where elastic stresses and strains act as information carriers. We integrate our work with soft robotics and explore how mechanical nonlinearities and instabilities can be used to incorporate sensing, actuation, and feedback can be used to build soft systems that can operate autonomously in their environment. Moreover, at smaller scales we develop micro- and nanomechanical resonators with ultralow dissipation, and explore new ways to control both thermal and quantum fluctuations in mechanical metamaterials.

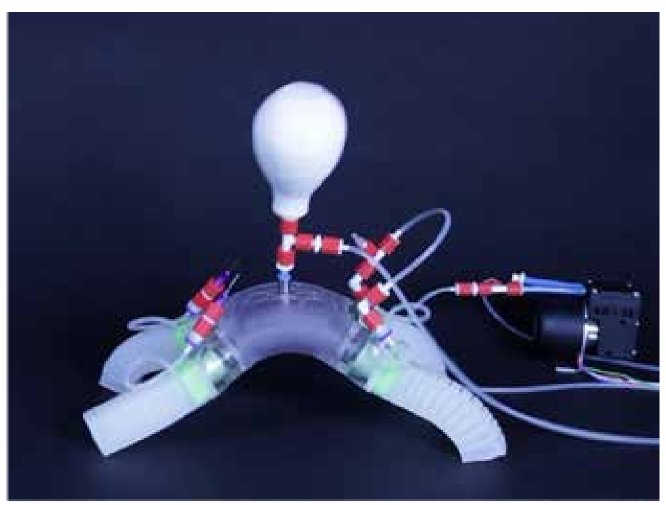
Mechanical neural networks can process information with near-zero energy dissipation, opening the door to battery-less smart devices.



Specific activities of the center

Our activities are centered around mechanics, essential in the research performed by the groups of Serra-Garcia, Overvelde and van Hecke, with occasional input from the group of Verhagen that works on opto-mechanics. During our biweekly meeting, group members share the latest unpublished research to provide feedback. In particular, we share analytical, computational, and experimental method developments that happen in our group, as many of these tools catalyze new collaborations within AMOLF. Part of this effort are the occasional tutorials and lab tours. Other type of meetings include a very successful 'Everything you always wanted to ask about mechanics' session and an annual session where the group leaders present their perspective and plans. Moreover, to keep everyone within the Modern Mechanics center up to date of the latest developments, we will add one-minute presentations for papers that got submitted, and will allow some time for 'latest news' items, such as upcoming workshops and conferences, striking papers, new equipment, software and of course new people.

Soft robot with embodied fluidic circuit that exhibits a complex walking gate based on continuous input.



Besides these internal meetings, we also occasionally invite external speakers that work on topics closely related to mechanics. For example, in September 2022 we organized a 2-day modern mechanics meeting with the groups of Benoit Romain, José Bico (ESPCI) and Corentin Coulais (University of Amsterdam); >50 people attended.

Infrastructure

Table- top fabrication: 3D printing (from ultimakers and modified 3D printers to Stratysis), casting, lasercutting, water jetting.
Microfabrication: NanoLab Amsterdam cleanroom facility, specifically two-photon 3D lithography and direct laser writing lithography.

Mechanical testing: Unixial and torsional Instrons, custom flow measurement, durability and efficiency setups.
Optical measurements: 2D imaging (various digital camera setups), high speed camera, 3D scanning, microscope-equipped direct laser vibrometer.

Connections

With the three research themes at AMOLF: Modern mechanics has a strong presence within Infomatter (van Hecke, Serra-Garcia, Verhagen) and in Autonomous Matter (Overvelde).

With the other expertise centers at AMOLF: The group of Verhagen is also part of the Nanophotonics center. Within the group of van Hecke there is also a collaboration with the group of Noorduin that is part of the Chemistry & Spectroscopy center.

National: Modern Mechanics is strongly connected through shared projects with the University of Amsterdam (Coulais, Bonn), Leiden University (Soft Matter), Eindhoven University of Technology (Dynamics and Control group, ICMS, Van de Burght, Liu, Dankers, Bouten), Utrecht University (Dijkstra) and the Amsterdam Medical Center (Kluin). We are also part of the Dutch Soft Matter Consortium, and the Dutch Soft Robotics Consortium.

International: We have strong connections with mechanical metamaterial and soft robotic groups, located at institutes such as ESPCI ENS-Paris, Chicago, Harvard, Caltech, Princeton, EPFL, ETH, IST Austria, SSSA, Politecnico di Torino.

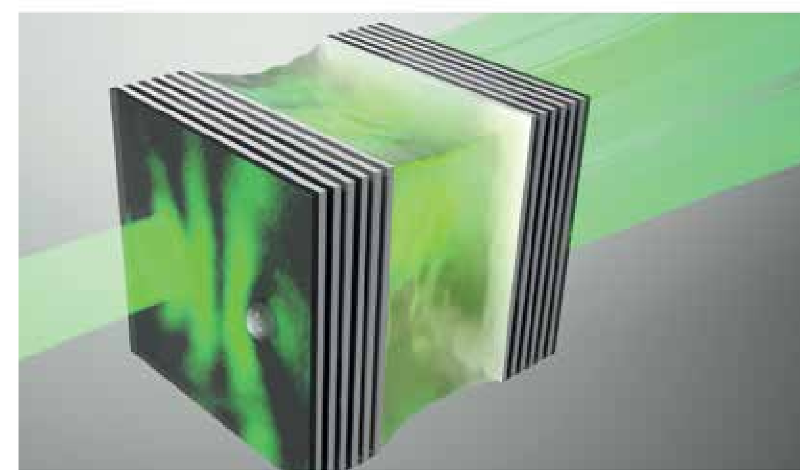
7.3 Nanophotonics

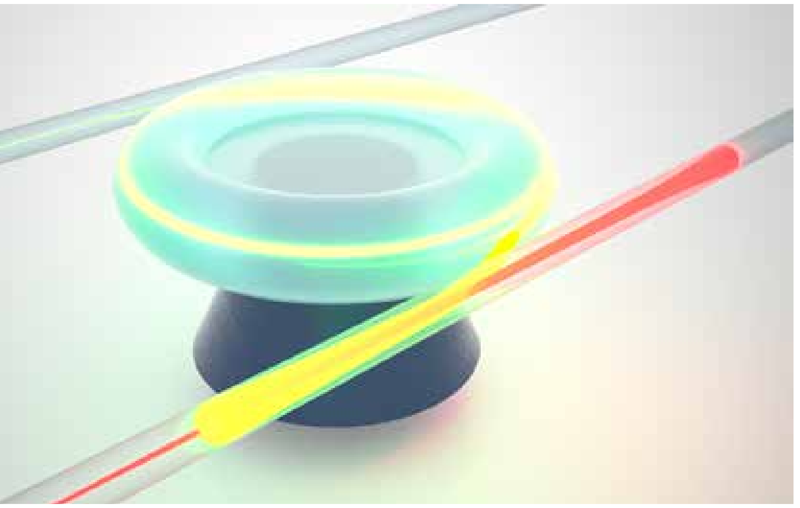
The Nanophotonics expertise center investigates new physical phenomena and functionalities emerging from the interaction of light and nanoscale matter. We strive for spatial and temporal control of various degrees of freedom of light and matter, often down to the atomic scale and the quantum regime. We do so through combining nanoscale design and materials in novel optical systems. We exploit nonlinearity, non-Hermiticity, fluctuations, quantum correlations, nonreciprocity, and memory effects, as resources enabling unique functionalities. Moreover, we develop advanced measurement techniques to gain deep insight into light-matter interactions. With these, we aim to address important problems relevant to the acquisition, transport, conversion, and processing of energy and information in optical systems.

The implications of nanophotonics range from fundamental science to applications. In our research, we span that spectrum, together with partners. For instance, we seek to develop metamaterials that can perform energy-efficient analog calculations on complex datasets, to assist energy bottlenecks in information processing ('green ICT'). This topic is pursued within a new 10 M€ national program on energy-efficient computing (NL-ECO) in which multiple AMOLF groups participate. Together with national partners with complementary strengths such as Eindhoven University of Technology (integrated photonics) and Groningen (optoelectronic materials), we initiate new research direction that push the boundaries of photonic science and technology. For example, we investigate how the physical concepts of topological protection and the breaking of reciprocity can benefit the routing of on-chip light.

Within the areas of sensing and metrology, we study the fundamental limits to optical sensing, and how these could be evaded to enhance both classical and quantum sensing. In

Light in an oil-filled cavity can behave like a superfluid.





Artist impression of the light circulator. The yellow beam enters at the upper left port and is forced to leave the resonator at the lower left port. The red beam enters at that port (lower left) but cannot follow the reverse path of the yellow beam as it is forced to propagate to the lower right exit.

collaboration with industrial partners such as ASML, we develop new metrology methods based on those insights. Moreover, AMOLF co-leads the Testbed for mechanical quantum sensing together with Delft University of Technology, a 4,5 M€ project within the QuantumDeltaNL program that establishes a new lab to stimulate the application of high-precision optomechanical sensors in collaboration with industry.

Specific activities of the center

Joint training is organized in the weekly Nanophotonics colloquium where junior and senior group members share with each other the basics of the expertise and their ongoing work. Sharing of knowledge is enhanced through the common use of facilities as well as group technicians.

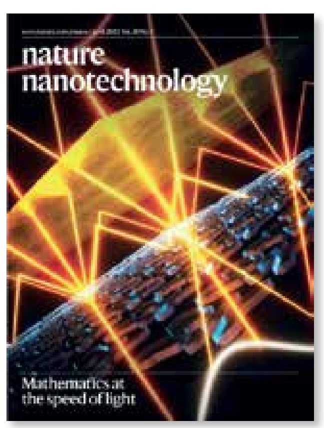
Infrastructure

Nanophotonics strongly relies on the ability to engineer materials at the nanoscale to create functional devices. Examples of such nanostructured materials include plasmonic nano-antennas concentrating light at the atomic scale, optomechanical resonators with ultralow dissipation, and advanced metamaterials. The cleanroom facilities offered by the AMOLF NanoLab Amsterdam are therefore of high importance. Conversely, the development of new experimental characterization techniques is also an important focus. Distributed over several optical labs, the groups develop forefront techniques, from superresolution microscopy and Fourier-polarimetry to quantum-limited interferometry in a wide range of environments. Unique capabilities are also offered by the merger of optical with electron-beam interrogation that AMOLF pioneered and continues to develop, including cathodoluminescence spectroscopy and correlative electron microscopy. Combining the extreme resolution of scanning and transmission electron microscopes with the spectral and temporal control of optical excitation and measurement allows unique insight into the working of new materials at the atomic scale as well as the fundamentals of light-matter interactions down to the single-photon, single-electron level. Finally, theory and design of nanophotonic systems and light-matter interactions is a strength of all groups, and the analytical and numerical methods they develop a source of inspiration and collaboration among the involved groups.

Connections

With the three research themes at AMOLF: The expertise in nanophotonics that continues to be developed at AMOLF is crucially enabling for both the Information in Matter and Sustainable Energy Materials themes. This is reflected in the scientific questions that drive the research, which include for example: How can photonic metamaterials process information in a massively parallel and programmable fashion? How can photons be transduced to material degrees of freedom and vice versa, with ultimate efficiency and quantum coherence? Can strong light-matter coupling enable frictionless energy flow, like superfluid light or superconducting materials?

With the other expertise centers at AMOLF: Many natural interactions exist between the Nanophotonics and Nanophotovoltaics expertise centers, whose participating groups partially overlap. A bi-weekly joint poster session between these two expertise centers facilitate these interactions and broaden the students' education and presentation skills. Another natural link is nurtured with the Modern Mechanics expertise center, as it concerns optomechanics research and optical interrogation of mechanical metamaterials.



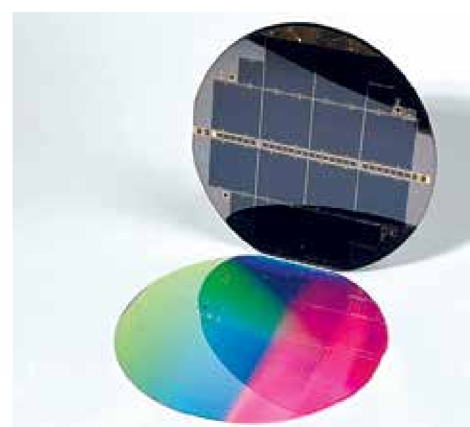
National: AMOLF group leaders take important roles in the MaterialsNL, NanoLabNL and QuantumDeltaNL platforms, in all of which nanophotonics is an enabling factor. We maintain close links to PhotonDelta, Optics Netherlands, and many national academic partners through joint projects and links. Our expertise in the area is also shared with student populations, with MSc level courses on Nanophotonics given by AMOLF group leaders at both the University of Amsterdam/Free University and Eindhoven University of Technology.

International: international collaborations with both European and North American partners are carried out, e.g. within EU Pathfinder programs.

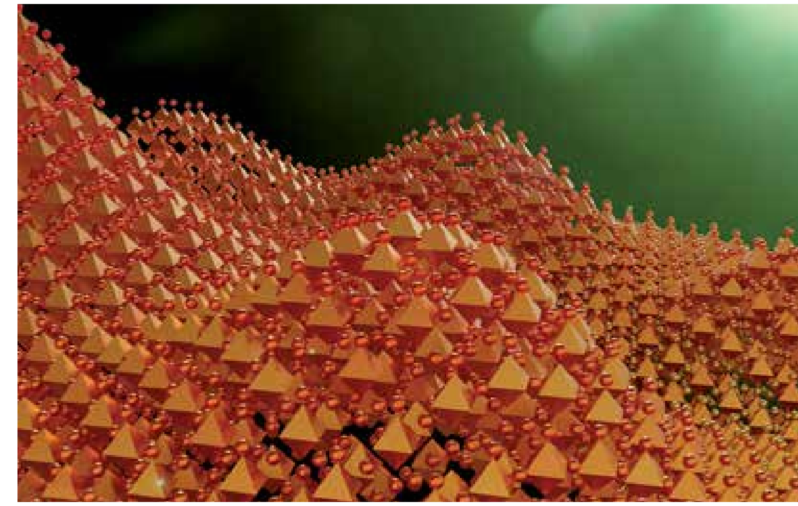
7.4 Light Management in Photovoltaics

The LMPV program is an Energy Research Focus group on photovoltaics (PV) established at AMOLF by FOM/NWO in 2012. LMPV develops fundamental understanding of (nano)materials that enable new or improved photovoltaic and related energy conversion concepts to accelerate the energy transition. The LMPV program is carried out by five group leaders: Prof. Dr. Albert Polman (program leader), Prof. Dr. Erik Garnett, Prof. Dr. Bruno Ehrler, Dr. Esther Alarcón Lladó, and Dr. Wiebke Albrecht.

The LMPV research program aims to obtain fundamental understanding of light absorption and carrier generation, recombination and collection in novel PV materials and solar cell architectures. We develop novel absorber materials such as perovskites, novel contact layers and light management geometries with the aim to optimize the capture and conversion of sunlight to electrical power. Our research focuses on obtaining fundamental insight in the complex interplay between the dynamics of light, electrical carriers and (mobile) ions at the atomic and nanometer scale. Our work can find applications in lightweight flexible perovskite solar cells, silicon/perovskite tandem solar cells with efficiency potential above 35-40%, and several other solar cell materials. Solving our research questions often requires novel analytical spectroscopy tools and materials synthesis techniques, which we also develop. Related to our PV research, we also started research programs on plasmonic catalysis and nano(electro-)chemistry (see section 2.2 Sustainable Energy Materials and section 4.2).



World-record 36.1% efficiency for silicon-based multijunction solar cells. A GaInP/GaInAsP/Si multi-junction solar cell was made in collaboration between LMPV and Fraunhofer ISE. LMPV designed and fabricated the nanopatterned backreflector.



Segregation of bromide and iodide in perovskites results in an inhomogeneous energy landscape, depicted as hills and valleys. At high pressure, the iodide and bromide remain homogeneously distributed, so that the perovskites maintain their favorable properties for solar cells.

Specific activities of the center

The LMPV center's activities are clustered in three categories:

1. **Knowledge development**: LMPV has grown from a single group (Polman in 2011) to a strong team with 5 group leaders and 45 PhD students and postdocs at the end of 2023, with a 50/50 gender balance. We perform a coordinated collaborative research program with the five groups, and organize weekly colloquia and poster sessions, as well as workshops, symposia, and schools. LMPV has a strong dedication to all aspects of sustainability in the training of a new generation of sustainability experts that are highly needed for the energy transition. More than half of the LMPV staff find a job in sustainability after their tenure at LMPV. The citation impact of LMPVs publications on solar cells is 3,24 times the world average. The LMPV team is very active in publishing (highly cited) perspective, review and opinion articles.
   As a dedicated NWO Energy Focus Group/research center, LMPV strongly coordinates the management of research planning by the five group leaders, through the joint development of research plans and targeted collaborations with industrial and academic partners. The group leaders hold regular management meetings to coordinate collaboration and undertake activities to optimize impact. In this way LMPV also

provides an effective breeding ground for the group leaders to develop and further grow a high-level research group, a strong strategic vision, and a strong (inter-)national network.

2. **Securing funding**: The joint efforts due to collaborating in the LMPV program result in a high success rate for grant applications (48%). Operating as a strongly visible team with focus and critical mass also attracts industrial partners. LMPV's research for the coming years is secured by 27 research grants, of which 11 are with industrial partners: Delmic, ThermoFisher, EDAX, Toyota, Nanonics, Seaborough, HyET Solar, SALDtech, VDL-ETG, BASF, DENSSolutions, Exxon Mobil, Shell, ASI, Witec and SCIL Imprint Solutions. In the coming years, LMPV will collaborate with many institutions within funded research projects, including key international PV research labs such as Fraunhofer ISE, UNSW (Sydney), and universities such as Cambridge, Stanford, Caltech, EPFL, and others.

3. **Ecosystem creation**: LMPV has grown to become an internationally visible and effective PV research program with a leading role in the Dutch PV community, focusing on maximizing the impact of the research for our economy and society. LMPV is firmly embedded in the NWO research structure, as an FOM/NWO Energy Focus Group. LMPV led the establishment of the national research, innovation and industrial development program called 'SolarNL: Circular integrated high-efficiency solar panels' that was funded by the National Growth Fund in 2023 (312 M€ subsidy). In this program industrial partners, TNO and academic PV groups collaborate to create a PV industry in the Netherlands for Si solar cells, flexible solar foils, and building-integrated PV (www.solarnl.eu). LMPV also founded the SolarLab national network for PV research that brings together all academic PIs active in PV research (www.solarlab-nl.org). This network creates joint roadmaps and research applications and acts as a strong voice for PV research in the Netherlands; it received a 41 M€ research grant from the SolarNL program.

Impact strategy 2023-2027

LMPV organizes the management of its activities according to an Impact Plan by creating Output (results that flow directly from the activities), Outcome (follow-up activities taking place outside of LMPV based on output of LMPV), eventually creating Impact on the energy transition, the economy, sustainability and the scientific position of the Netherlands.

In 2023 an economic and societal impact analysis of the LMPV program was performed by Roland Berger consulting (see www.lmpv.nl/impact). The analysis shows that LMPV's research and ecosystem formation strategy creates significant impact in CO_2 reduction, materials circularity and reduced use of scarce materials. It helps create strategic autonomy for the European energy technology and supply. LMPV's PV research insights and technologies also help the seamless integration of PV in our densely populated country. The added value to the economy of the national SolarNL plan that is led by LMPV is estimated to be over 400 M€ annually after 2032. LMPV's coordination activities helped raise a total amount of 950 M€ from the National Growth Fund for innovation programs for the materials ecosystem in the Netherlands for the coming years, among which 160 M€ for academic research. Roland Berger concluded: "LMPV plays into a huge societal need and therewith future-proof market potential."

Based on the analysis, the LMPV group leaders defined six key strategic actions to further improve the impact of LMPV in 2023-2027:

1. **Research**: Maintain strong focus on fundamental research in selected PV topics.

2. **Technology transfer**: Improve the transfer of low-TRL (1-3) PV concepts to PV technology institutes and PV companies to create PV applications that help speed up the energy transition.

3. **Economic gain**: Further develop imaging technologies and bring them on the market through new startups or license agreements with companies, strengthening the economy and boosting PV research and applications.

4. **Funding**: Write fewer grant applications while applying for bigger grants; connect to the EU Green Deal and major US programs. Acquire a new base-funding grant for the NWO LMPV Energy Focus group and continue to acquire grants for the broader PV and materials ecosystems.

5. **PV industry**: Carry out the SolarNL program and help build PV industry in the Netherlands with a PV manufacturing potential of 7 GWp/year. Support the development of European PV value chain. Expand LMPV with a major research program (funded by the SolarNL grant) supporting the involved PV companies.

6. **Outreach**: Develop further targeted outreach activities.

Infrastructure

Our research program builds on the developments of unique equipment in electron and optical microscopy, (electrochemical) scanning probe microscopy, and many dedicated forms of spectroscopy and materials fabrication. Several of these new techniques have been commercialized and successfully brought on the market. The added value of these sales to the Dutch economy is 20 M€ so far (2023) and will continue to grow with further sales and additional innovations that LMPV will make in the coming years (Roland Berger analysis, 2023).

Connections within AMOLF and Amsterdam Science Park

LMPV has many links with the Nanophotonics center, as it was created as a spin-off from that program; we hold a bi-weekly joint poster session. LMPV also has links with research groups in Chemistry and Spectroscopy with which a monthly meeting is held. LMPV has research links in the Amsterdam Science Park with ARCNL (SEM/tomography), the University of Amsterdam (photovoltaics, nanophotonics, electrochemistry), and CWI (AI), and co-teaches the photovoltaics course in the AMEP master's program of University of Amsterdam and Vrije Universiteit Amsterdam and at the University of Groningen. LMPV group leaders are members of many leading national committees relevant for PV and materials research.

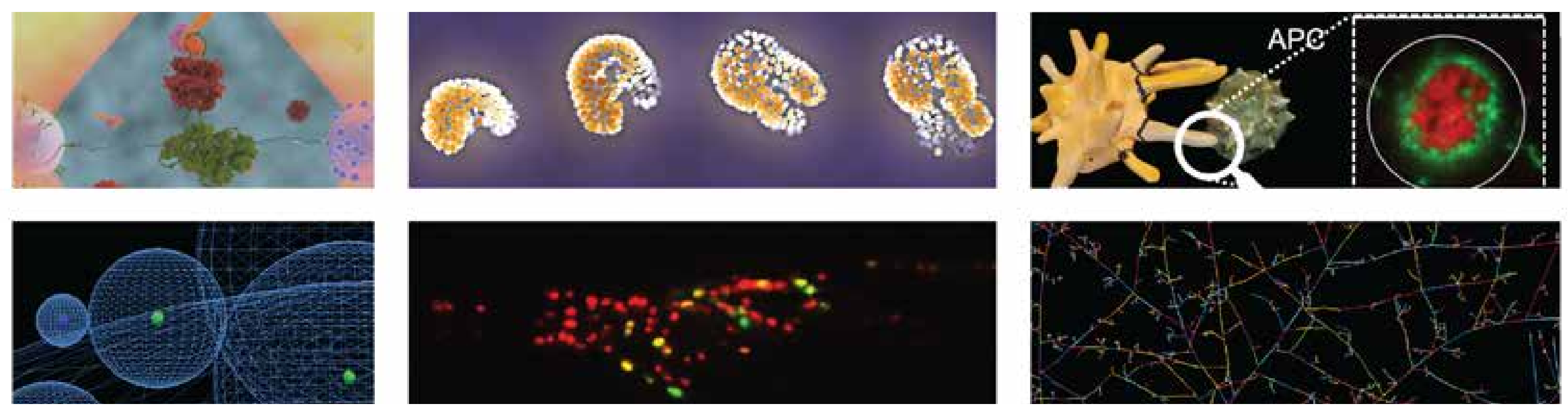
7.5 Living Systems

The Living Systems center develops and applies a broad range of physics-based approaches – experimental, theoretical and computational – to enable innovative studies of living systems. From the folding of single protein molecules to organism-scale processes such as development, immunity and behavior, we explore the design principles of living systems across multiple levels of biological complexity and physical scales.

Specific activities of the center

The core activity of the center is a bi-weekly series of internal meetings, at which a pair of junior scientists present their recent work for in-depth feedback. In addition to providing

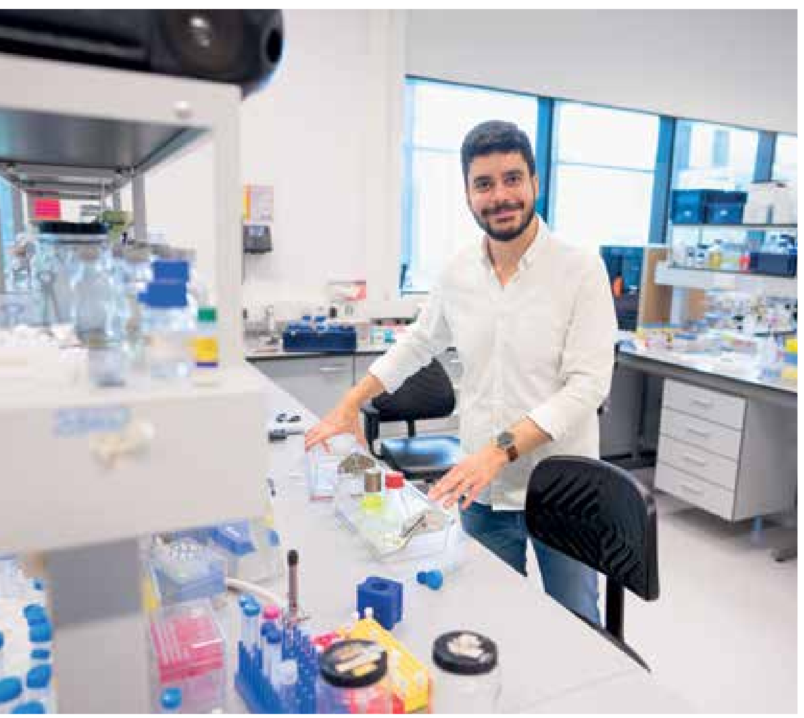
Research in the Living Systems center is pushing the frontiers of physics-based approaches to studies of living systems across scales – from molecules through cells, to multicellular systems and whole organisms.



a foundation for regular scientific exchange, these meetings also serve an educational purpose – speakers receive feedback not only on scientific content but also presentation style and technique, considering not only the specific content of each presentation but also the 'bigger picture' of their long-term trajectory as an individual scientist. Twice yearly poster sessions provide further opportunities for candid exchange at a personal level. Annual retreats are held to enhance social interactions across both PIs and junior scientists of the center. In addition to these regular events, PIs of the center organize ad hoc workshops (on average 1-2 per year) and seminars (on average 5-6 per year) featuring external speakers from both within the Netherlands and abroad.

Infrastructure

The laboratory infrastructure of the Living Systems center features state-of-the-art optical microscopes (often bespoke setups fabricated at AMOLF) for single-molecule imaging and optical tweezers / force spectroscopy, super-resolution imaging, FRET microscopy, stroboscopic widefield imaging (2D and 3D) and multiphoton confocal imaging. Our biochemical labs are equipped for both in vitro work with purified DNA and proteins, as well as in vivo work with cells (both ML-I and ML-II), organoids, and select model organisms such as the nematode C. elegans, as well as plant-microbe symbiotic systems. Experimental work in the center is supported by four specialist technicians with expertise in molecular biology, genetics, as well as purified protein work.



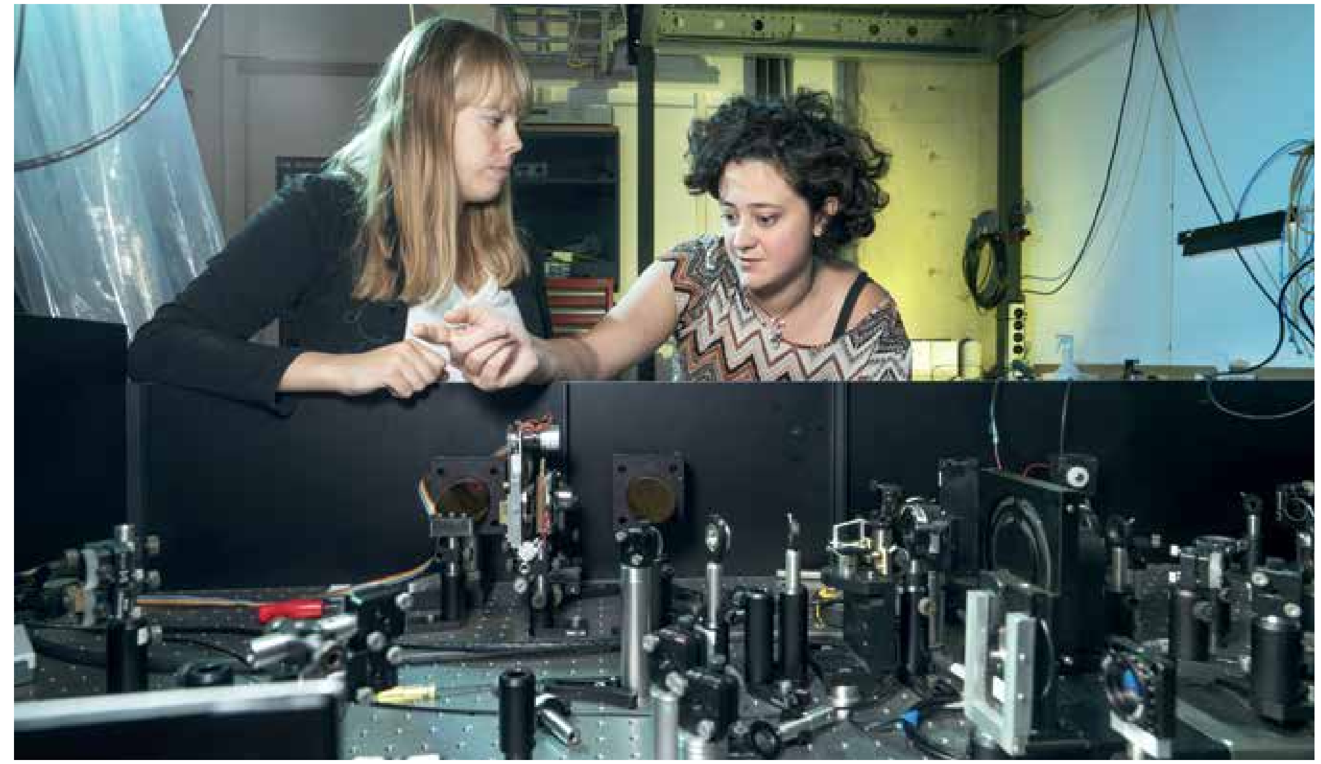
Connections

With the three research themes at AMOLF: Groups of the Living Systems center engage scientifically with all three of AMOLF's research themes. Three members (Tans, Van Zon, Ganzinger) are part of the Autonomous Matter theme, and are exploring the how organizing principles of living matter can be applied to developing novel chemical and soft robotic matter systems with previously unimagined designs and functions. Two members (Ten Wolde, Shimizu) are part of the Information in Matter theme and are investigating how biological information processing is implemented at a fundamental physical level, and exploring how the general design principles of emerging from that work can be applied to design new classes of optical and mechanical information-processing matter. Increasingly active interactions are being forged also with Sustainable Energy Materials through a shared interest in Computational Imaging, which is rapidly becoming a key enabling approach for studies of both living systems and sustainable energy materials.

With the other expertise centers at AMOLF: Interactions with other centers occurs mainly at the level of infrastructure and expertise sharing, but also at the level of education/training of junior scientists. Experimentalists of the Living Systems center make extensive use of the NanoLab Amsterdam (hosted by the Nanophotonics center), primarily for microfluidic design fabrication, 3-D printing infrastructure of the Modern Mechanics center, chemical characterization infrastructure of the Chemistry and Spectroscopy center, and electron microscopes of the Nanophotovoltaics center. In turn, in addition to sharing biochemical infrastructure and expertise with other centers, the Living Systems center hosts an annual multi-day scientific computing (python) course for members of all centers.

National: Within the Netherlands, the Living Systems center plays a prominent role in the national physics and biophysics landscape. Our members regularly participate in the organization of the annual NWO Biophysics Conference in Veldhoven (2022/2023 Organizing Committee member: Ten Wolde). In addition, Living Systems member Kristina Ganzinger becomes in 2023 the chair of NWO's Research Committee Physics of Life and also a member of NWO's disciplinary consultation committee (Round Table) for Physics, and also member of De Jonge Akademie of the Royal Netherlands Academy of Arts and Sciences (KNAW). In 2023, Sander Tans and Jeroen van Zon launched a new national initiative OrganoidNL, which kicked off with a one-day symposium in March 2023 with ~200 participants, now scheduled to be an annual event. Tom Shimizu is developing a rapidly growing line of research on the biophysics of symbiosis with Toby Kiers (Vrije Universiteit Amsterdam).

International: Members of the center host ad hoc workshops: in 2022 (Future of the Physics of Life, organizers: Ten Wolde, Shimizu & Tans) and 2023 (Physics of Behavior, organizers: Shimizu & G. Stephens, Vrije Universiteit Amsterdam), collaborate with numerous institutions abroad, including Harvard University, Princeton University, Yale University, University of Michigan, University of Utah (USA), the University of Heidelberg (Germany), ETH Zurich (Switzerland), University of Edinburgh (UK), ESPCI and ENS Lyon (France).



7.6 Chemistry & Spectroscopy

The Chemistry & Spectroscopy (ChemSpec) center applies a wide range of physical and chemical techniques to synthesize and characterize complex functional matter. We study the self-organization of simple molecular and nanoscopic building blocks to tailor-made nanocrystals, complex emulsions, patterned nano- and microcomposites, including out-of-equilibrium processes leading to directed self-assembly and spontaneous symmetry breaking. Moreover, we investigate the interaction between different molecules and nanoscopic materials in complex hybrid nanostructures and the emergence of complex behavior, using analytical chemical techniques and advanced spectroscopy and microscopy techniques.

Specific activities of the center

Activities within ChemSpec are aimed at maximizing the sharing of knowledge between the research groups. Biweekly, ChemSpec organizes activities such as presentations and posters about current research, technical tutorials and problem-solving sessions. Moreover, lab visits and hands-on technical and equipment demos are organized such that students can share expertise on chemistry and spectroscopy. The ChemSpec expertise center also assists in the chemical safety training and organizes the annual chemical safety meeting.

Infrastructure

The infrastructure within ChemSpec features a wide range of chemical and optical characterization techniques such as femtosecond polarization-resolved and two-dimensional vibrational spectroscopy, heterodyne-detected vibrational surface sum-frequency generation spectroscopy, scanning probe microscopy including scanning electrochemical microscopy, advanced electron microscopy including tomography, (time-resolved) single particle microscopy and spectroscopy techniques and high performance liquid chromatography. Moreover, we have developed customized equipment for synthesis and assembly of complex molecules and nanomaterials ranging from CVD and Schlenk line setups to microfluidic devices, ALD, nanocube imprint lithography and 3D nanophotochemistry.

Connections

With the three research themes at AMOLF: ChemSpec is connected to all three research themes. Since ChemSpec groups are affiliated with Sustainable Energy Materials and Autonomous Matter, there are also many connections to Information in Matter.

With the other expertise centers at AMOLF: Three of the ChemSpec groups also participate in Nanophotonics and Nanophotovoltaics, thereby strongly connecting the three expertise centers. Regular meetings with all expertise centers are set to evaluate and learn best practices.

National: The ChemSpec expertise center is connected nationally via a range of academic and industrial collaborations. Three of the five groups at ChemSpec have professorship affiliations with the Faculty of Sciences at the University of Amsterdam (van 't Hoff Institute for Molecular Science and Institute of Physics) with shared PhD and MSc projects. Moreover, research within ChemSpec fits well in the NWA Materials, and is part of a larger national ecosystems (e.g. ARC-CBBC, AMCEL, DACG). This connectivity is also reflected in a range of research collaborations within national consortia and projects (e.g. KIC, ENW-PPS, Topsector, Growth Fund). These collaborations also involve companies (e.g. ASML, DELMIC, Symeres, TNO) with a strong interest in chemistry and spectroscopy research.

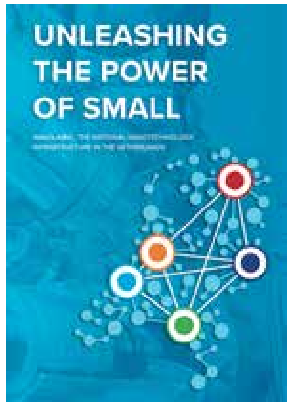
International: Formal international collaboration exists through FET-Open and Pathfinder European consortia. In addition, there are many small-scale collaborations of the ChemSpec groups with international academic groups.

8. National facility NanoLab Amsterdam

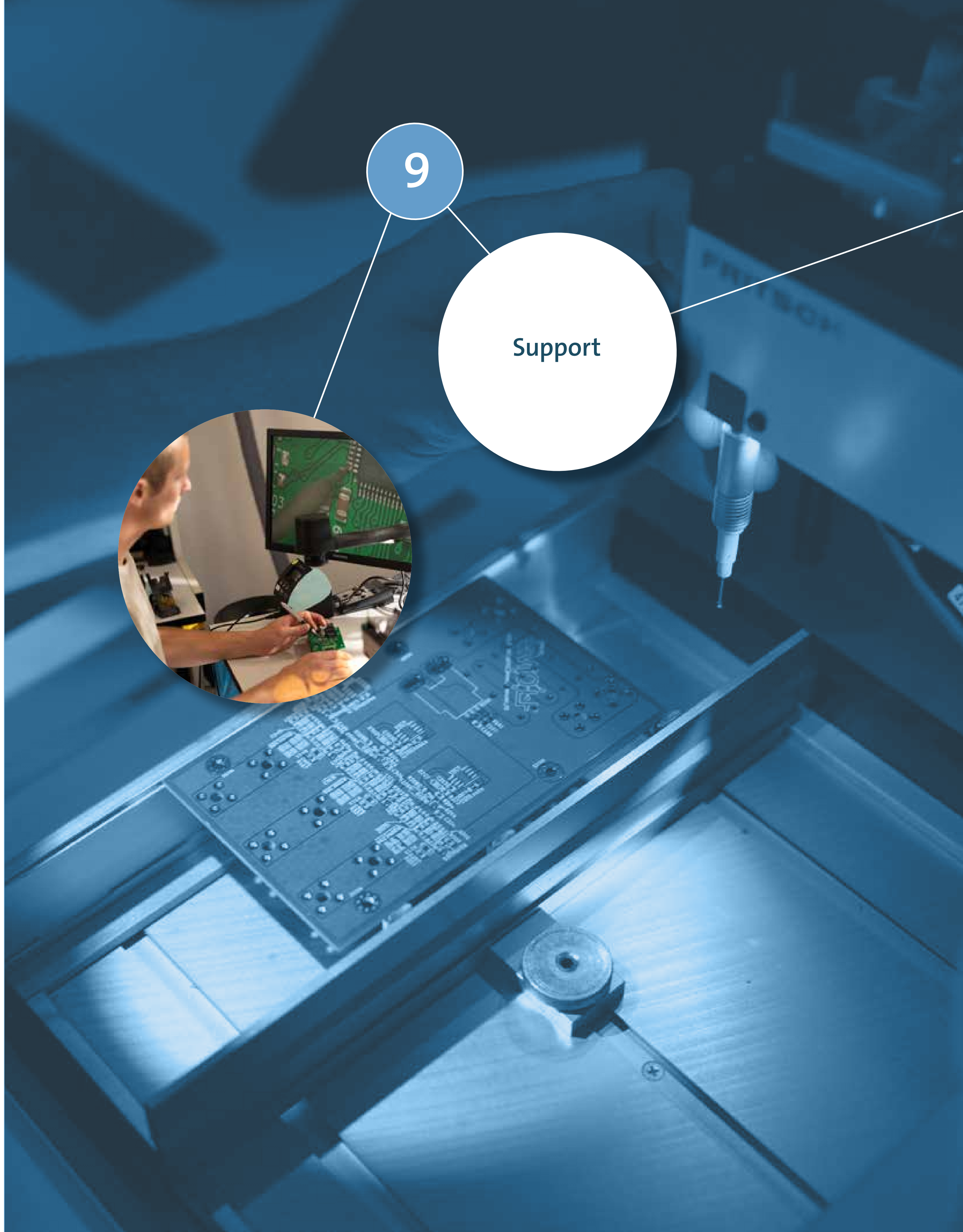
AMOLF houses the NanoLab Amsterdam, a cleanroom facility for fabrication and characterization of materials and devices down to the nanometer scale. It aims to service both the scientific community and industrial R&D users in nanoscience and technology by providing access and support to its state-of-the art infrastructure. The NanoLab Amsterdam is part of NanoLabNL (www.nanolabnl.nl), the Dutch national facility for nanotechnology research that provides a full-service and open-access infrastructure for R&D in nanotechnology. Amsterdam forms one of the five hubs of NanoLabNL, besides Twente, Delft, Eindhoven, and Groningen. Each of the five hubs provides high-end broad-purpose cleanroom infrastructure for nanofabrication, including optical and electron-beam lithography, dry and wet etching, and material growth and deposition techniques as well as characterization facilities such as electron and atomic force microscopy. The NanoLab Amsterdam specializes in several key expertises, including metamaterials, nanophotonics, energy conversion materials, and nano- and micromechanics. These benefit a range of application fields from photovoltaics and photonics to quantum technology. AMOLF researchers and their partners develop specialized protocols and forefront techniques. An example is the development of advanced characterization techniques that combine electron microscopy with optical spectroscopy, in collaboration with Delmic and ThermoFisher.

With approximately 100 users each year, the AMOLF NanoLab Amsterdam takes an important role in facilitating nanotechnology R&D. The past years have seen the development of nanotechnology as a scientific discipline to an enabling tool for a wide range of scientists, from quantum engineers and smart material designers to biomedical scientists. Without state-of-the-art infrastructure, they could not even dream of doing new research or developing new devices. The opportunities offered by nanotechnology are emerging from the continuous and uniquely rapid development of high-end equipment. This requires continuous investment in equipment that is at the absolute forefront of performance. NanoLabNL stimulates and coordinates the availability of these essential capabilities in the Netherlands. It laid out its vision in a Manifesto in 2021.[1] Currently, a major re-investment program is being carried out by NanoLabNL, as part of the national Growth Fund subsidy QuantumDeltaNL. This allows the NanoLab Amsterdam to invest 12 M€ by 2028 to strengthen its basic infrastructure and ensure state-of-art equipment can be made available to its users in the coming years. As part of this renewal, a restructuring of the cleanroom and upgrade of its air handling system will be carried out in 2024. Moreover, AMOLF will host from 2024 a unique new aberration-corrected TEM integrated with optical excitation, funded by a Research Infrastructure: national consortia grant from NWO. This strengthens the capabilities that the institute offers in the area of light-integrated electron microscopy and establishes AMOLF as an important partner within the Netherlands Electron Microscopy Infrastructure (NEMI) network.

The NanoLab Amsterdam functions as a user facility, with users trained and supported by the NanoLab group that is headed by Hans Zeijlemaker. Scientific coordination is performed by Ewold Verhagen, who is also Board member of NanoLabNL. The coming years will see, besides the aforementioned infrastructure renewal, a continued push for professionalization of the services offered by the NanoLab and its staff. Part of this is an improved distribution of the responsibilities of management, training, and representation between the NanoLab group leader and lab manager, as well as better sharing of protocols and process information both within the facility and with the national partners. The latter is facilitated by the recently deployed NanoLab Information System (NIS), a software platform that is developed and shared by all NanoLabNL hubs. With these expansions and improvements, AMOLF aims to continue to take its responsibility in providing a reliable solid and high-quality national facility for nanotechnology, meeting the growing demand from the scientific community.



1 'Unleasing the power of small', NanoLabNL, the national nanotechnology infrastructure in the Netherlands (https://nanolabnl.nl)



9. Support

9.1 Technical engineering groups

AMOLF strives to supply excellent technical support. The in-house facilities at AMOLF for the design and manufacturing of measurement equipment, electronics, and software engineering are essential for setting up new, innovative research directions, which is central to AMOLF's mission. AMOLF has four technical engineering groups: Software Engineering, Electronics Engineering, Design Engineering, and Precision Manufacturing. These groups support both AMOLF and ARCNL. The dynamic nature of AMOLF in starting new research directions requires that the technical support divisions are well-equipped, are able to accommodate new methods and techniques, and receive adequate training to pick up new developments.

Besides the technical engineering divisions, AMOLF employs 10,7 FTE research technicians. Research technicians are members of the scientific research groups and provide direct scientific support for the research setups. These technicians do not work for one single research group but flexibly divide the work within the team according to demand and expertise. Some technicians are specialized in a specific scientific field, e.g. laser technology or microscopy. The group technicians generally also serve as intermediaries between the scientists and the technical support divisions to coordinate complex projects. In the AMOLF NanoLab Amsterdam, 5,8 FTEs of specialized technicians are employed, in addition to 0,8 FTE facility project management.

9.2 Administrative support groups

High quality administrative support is vital for creating a productive research environment. Administrative support is provided by ICT, Facilities Services, Health & Safety, Finance, Communications, Secretarial office and Human Resources. All administrative support divisions, except the secretarial office, support both AMOLF and ARCNL.

Since 2017, several processes within the administrative divisions were digitized and administrative software systems were updated or replaced. This includes amongst others a renewal of the financial administration software, a new online repository for our publications, and an electronic system for documenting and planning maintenance and renovation of the building. A new personnel administration system has been set up for implementation in 2023. We updated our online IT tools by implementing Microsoft Office 365 and encouraging the use of Microsoft Teams for a safe and readily accessible online collaborative environment. In the coming years, the

goal is to optimize these systems and make them part of the regular workflow, resulting in a professional software support environment.

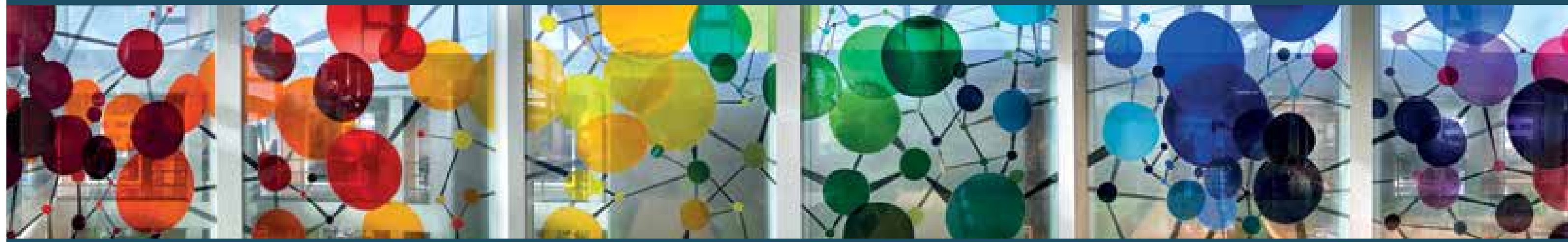
An important recent development is the increased attention for safeguarding knowledge security. Breaches of knowledge security mainly concern the unwanted transfer of (sensitive) information and technology to state actors which can threaten Dutch national security and can covertly influence Dutch research. In the coming years, several initiatives will be developed within AMOLF and NWO-I to comply with the Dutch National Knowledge Security Guidelines. These initiatives are both of technical nature, to increase the level of cybersecurity maturity, and of educational nature, to create better awareness.

AMOLF is part of the NWO-I Foundation. NWO-I supports the NWO institutes by serving as back office for several administrative services and expertise. Also, NWO-I provides support for long-term strategic planning and serves as a liaison with external stakeholders. The scope of the back-office services that will be provided by NWO-I is currently being reviewed. The outcome of this process will to some extent impact the (front office) administrative services at AMOLF.

Colofon

AMOLF
Science Park 104
1098 XG Amsterdam

Phone: +31 (20) 7547100
E-mail: info@amolf.nl
www.amolf.nl



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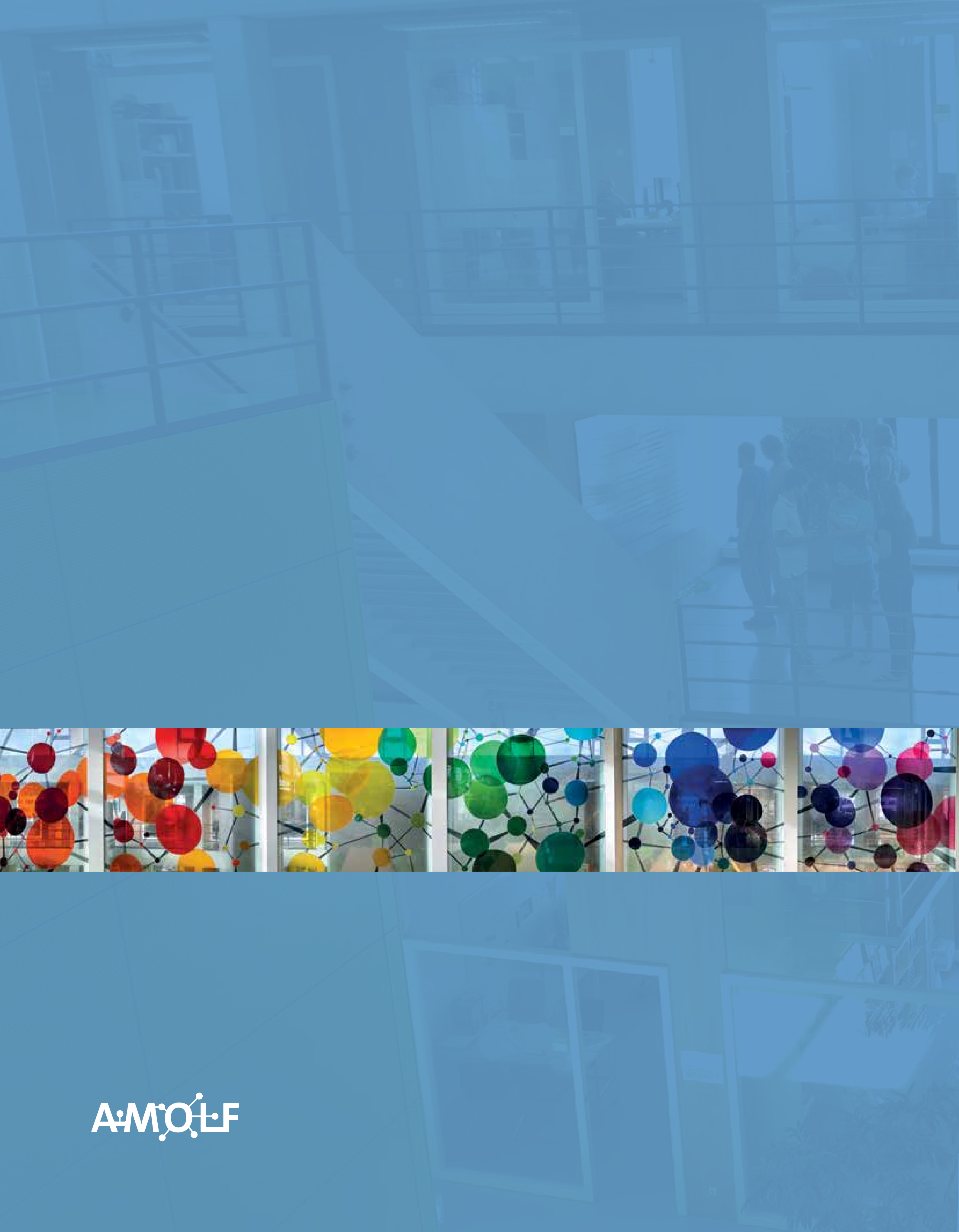
Petra Klerkx, Amsterdam

Printing
BenF, Zeist

Photos
Ivar Pel
Wouter Jansen
Erik Bronkhorst
Lukas Helmbrecht
Nout Steenkamp
Petra Klerkx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