2022

2017

AMOLF **Self evaluation**

AMOLF

Data as of September 2023

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AMOLF is part of the Netherlands Organisation for Scientific Research

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1 General introduction

1. General introduction

1.1 Introduction and mission

AMOLF is one of the nine scientific research institutes of the Netherlands Organization for Scientific Research (NWO) and employs about 135 researchers (19 research group leaders, 65 PhD students, 25 postdocs, and 25 undergraduate students), as well as 75 employees for technical and administrative support.

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.

Examples of functional complex matter systems studied at AMOLF are metamaterials to control light, sound and motion, nanostructured solar cells, shape-morphing mechanical metamaterials, and life-like and living adaptive systems. AMOLF uses the obtained knowledge to create novel functional materials and to find new solutions to important societal challenges in renewable energy, the production and use of sustainable materials, health care and sustainable information technologies, often in collaboration with industry. AMOLF pursues these goals by being a flexible and dynamic research institute that works with teams of highly qualified scientists in focused research themes. The research program of AMOLF comprises three highly interdisciplinary themes:

- Sustainable Energy Materials;
- Information in Matter;
- Autonomous Matter.

The themes are built on disciplinary strengths in:

- Nanophotonics;
- Chemistry & Spectroscopy;
- Living Matter;
- Modern Mechanics;
- Light Management in Photovoltaics .

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

- initiating and developing new research directions;
- recruiting and training high-level scientific talent;
- fostering a strong international position;
- initiating and coordinating national research programs;
- innovating techniques and devices in collaboration with industry and society;
- providing a national facility for nanofabrication and characterization.

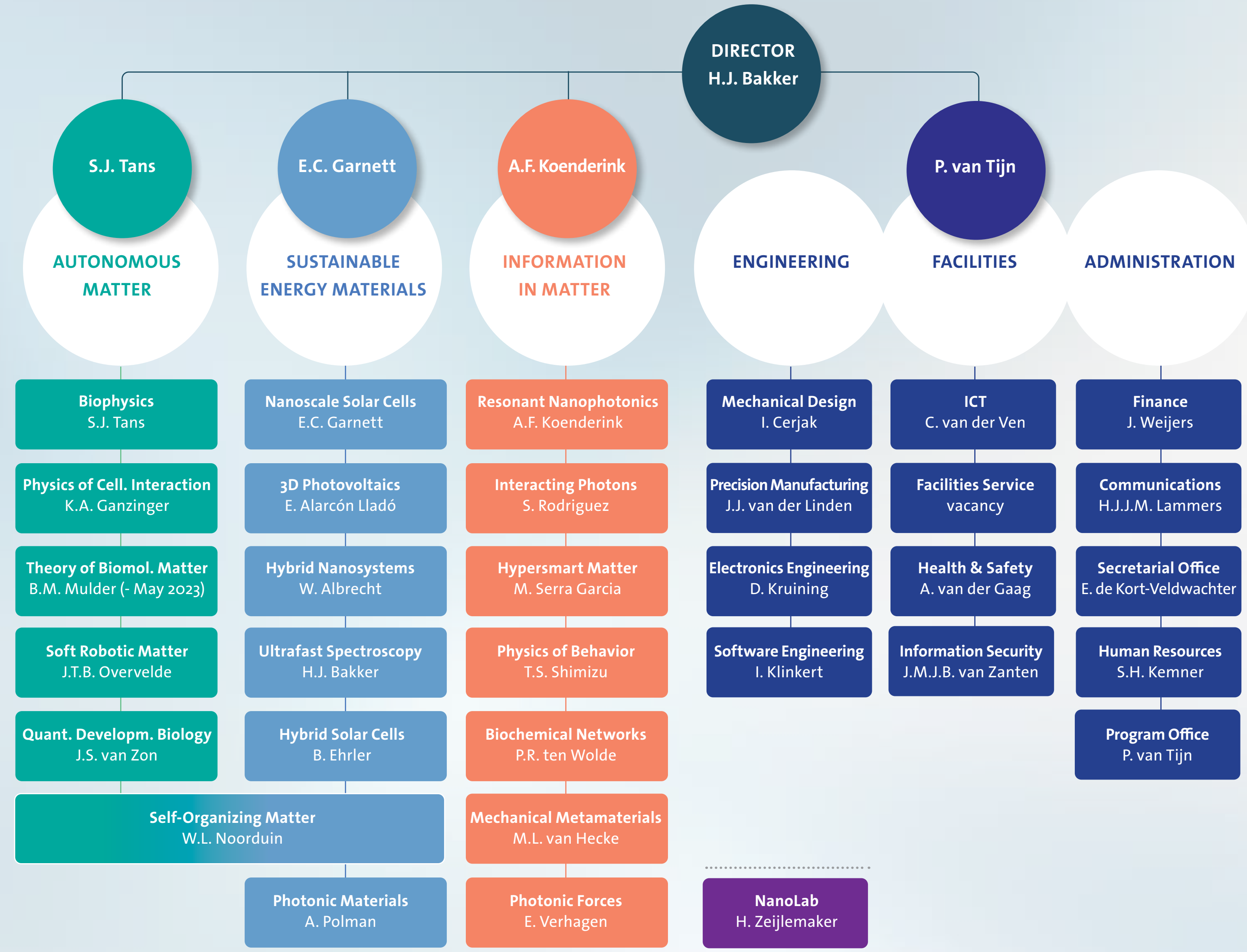
1.2 Organization

AMOLF has a flat organizational structure with short communication lines. The institute houses 19 research groups, each headed by a single PI, with a size of 5-10 scientists per group. The research groups are organized within three departments that carry out the three research themes. The technical and general support divisions of the institute, which also support the Advanced Research Center for NanoLithography (ARCNL), are organized in groups that are directed by the institute manager. The organization of scientific and support departments is shown in Figure 1.

The institute governance is as follows:

- **AMOLF is directed** by Huib Bakker (2015-present).
- **The management team** (MT) of AMOLF consists of the director (Huib Bakker), the institute manager (Paula van Tijn) and the three department heads (Femius Koenderink, Erik Garnett, and Sander Tans) lead the three research departments. The MT meets every week and discusses strategic and operational topics, and advises the director.
- **The three research departments** address highly interdisciplinary research themes and each consist of 6-7 research groups. The department is led by one of the scientific group leaders who is also member of the MT. The research departments organize biweekly colloquia with internal and external speakers and annual international workshops.
- **The scientific group leaders** and the heads of the support departments meet every four weeks in a staff meeting. The staff advises the MT and the director on matters concerning the institute. All important strategic developments are discussed in the staff meeting. The staff also has an advisory role in hiring decisions for scientific staff, and in establishing new lines of research.
- **Disciplinary knowledge** is organized in five expertise centers (Nanophotonics, Chemistry & Spectroscopy, Living Matter, Modern Mechanics, and Light Management in Photovoltaics). The centers train PhD students and post-docs in these fields, link up groups to provide world-class technical and scientific expertise, and position AMOLF strategically in discipline-oriented national and international networks.

Figure 1 ⟷ AMOLF organizational structure



- **The technical support departments** work in close collaboration with the research groups to develop unique scientific instrumentation and new experimental set-ups.
- **The facilities and administration departments** provide a wide range of services for all AMOLF employees and develop and maintain internal systems to facilitate the research being performed.
- The director receives external advice from the **Institute Advisory Committee** (IAC). The IAC comprises 8-9 leading persons from academic institutions, industry, and society (see Appendix 7.2). The IAC meets twice per year at AMOLF to discuss AMOLF's strategy and long-term policy, and to advise the AMOLF director in these matters. Another prime task of the IAC is to give advice on tenure decisions of scientific tenure-track group leaders.
- **The Works Council** is a legally enshrined organ consisting of AMOLF employees. Its advice or approval is requested when the management intends to make major policy decisions, as mandated by the Dutch Works Councils Act. The Works Council is a highly valued body within AMOLF, as it helps to improve the AMOLF workplace by voicing the viewpoints of the employees.

Table 1 ⟷ Total funding and expenditure in k€ per year over 2017-2022

	2017		2018		2019		2020		2021		2022	
Base funding [1]	9.167	59%	9.757	62%	9.931	64%	10.412	62%	10.475	64%	10.800	58%
Research grants national [2]	3.179	21%	2.992	19%	2.743	18%	2.783	17%	2.181	13%	2.904	16%
Research contracts other [3]	3.083	20%	2.909	19%	2.840	18%	3.538	21%	3.032	18%	4.391	24%
Other [4]	73	0%	8	0%	24	0%	3	0%	709	4%	393	2%
Total funding	**15.502**	**100%**	**15.666**	**100%**	**15.538**	**100%**	**16.736**	**100%**	**16.397**	**100%**	**18.488**	**100%**
Personnel costs	10.587	70%	10.204	70%	10.460	70%	10.563	71%	10.632	72%	11.616	69%
Material + Other costs	4.602	30%	4.278	30%	4.505	30%	4.332	29%	4.038	28%	5.339	31%
Total expenditure	**15.189**	**100%**	**14.482**	**100%**	**14.965**	**100%**	**14.895**	**100%**	**14.670**	**100%**	**16.955**	**100%**

Note 1: Direct funding NWO-I (base funding / lump-sum budget).

Note 2: Research grants obtained in national scientific competition (e.g. grants from NWO and KNAW).

Note 3: Research contracts for specific research projects obtained from external organizations, such as industry, governmental ministries, European organizations, and charitable organizations.

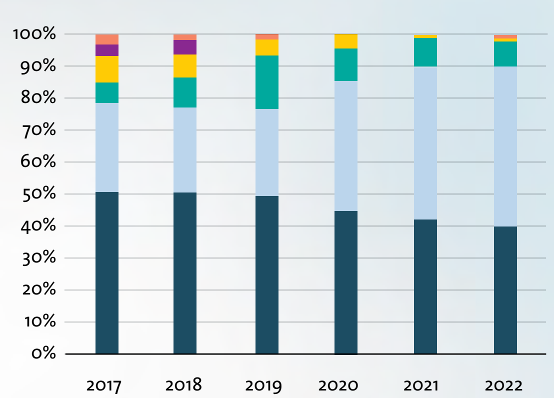
Note 4: Funds that do not fit into the other categories (specific covid-related funds: 2021 +700 k€; 2022 +334 k€).

1.3 Funding

The NWO-I base funding (direct funding) covers the salaries of scientific group leaders, group working budgets, start-up packages of new tenure track group leaders, and most of the indirect and overhead costs, i.e. the technical and administrative support, the acquisition and maintenance of part of the technical and scientific infrastructure, and the exploitation of the building. The running costs and investments costs of nearly all research projects and ~90% of the junior scientific personnel positions (PhD students and postdocs) are paid from grants obtained in national and international competitions. The fraction of this external funding obtained in competition has been quite steady over the last years at approximately 40% of the total funding (Table 1).

Over the last six years, AMOLF has been highly successful in attracting national and international competitive funding in individual grant schemes, like the NWO Talent Scheme (Veni, Vidi, Vici), the ERC Starting, Consolidator and Advanced Grants (Section 3.2.3), and in large collaborative programs with multiple partners, such as the NWO funding schemes for collaboration with industrial partners (NWO OTP, NWO KIC), and the European EIC Pathfinder scheme (formerly known as FET OPEN). Notably, our tenure-track group leaders have been very successful in obtaining competitive personal funding to further develop their research groups. In 2021, the AMOLF cleanroom facility NanoLab Amsterdam was awarded 12 M€ within the National Growth Fund (Groeifonds) program QuantumDeltaNL, to renew and strengthen its basic infrastructure, including nanolithography, material deposition, material etching, and advanced characterization techniques. Over the last 6 years, the distribution of external funding has increasingly shifted from national (NWO) grants to European funding, such as the ERC and the FET funding schemes (Table 2).

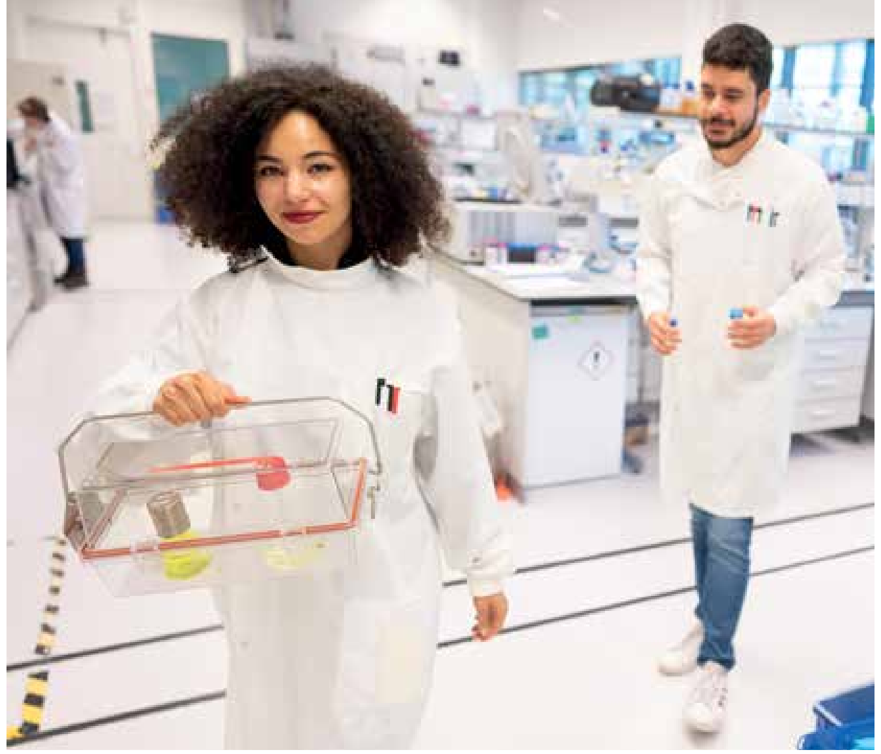
Table 2 ⟷ External research funding over 2017-2022



	2017	2018	2019	2020	2021	2022
Total research funding in k€*	6.262	5.901	5.583	6.321	5.213	7.295

*see also table 1: total of Research grants and Research contracts

1.4 Personnel



The composition of the AMOLF staff is detailed in Table 3. Over the last six years, the number of employees at AMOLF increased, mainly due to an increase in scientific staff from 120 FTE to almost 140 FTE, largely attributable to a higher number of PhD students. The number of research groups increased from 17 to 19. The number of tenure track group leaders gradually declined from five in 2017 to three in 2022. One of our national roles is to attract and train talented scientists, and we will expand our pool of tenure track group leaders in 2023/2024. The number of guests increased over the last six years. This group is mainly comprised of PhD students and postdocs who are jointly supervised by a group leader from AMOLF and a group leader from another knowledge institute or university in the Netherlands.

The support staff consists of technical and general support staff. The technical staff is comprised of technicians who are embedded in the research groups, and in specialist teams focused on Mechanical Design, Precision Manufacturing, Electronic Engineering, Software Engineering, and providing technical support for the NanoLab cleanroom. AMOLF also provides the administrative and technical support for the neighboring institute ARCNL. At the end of 2022, ARCNL had 73 FTE of scientific personnel, for which AMOLF employed an equivalent of 11,2 FTE support personnel.

Our scientific staff is quite diverse in nationality and age. As of December 31, 2022, our group leaders encompass 5 nationalities, with an age distribution spanning from 36 to 66 years old. Among our postdocs and PhD students, 22 different nationalities are represented. The support staff is predominantly Dutch. The age distribution of the support staff is evenly dispersed over all age groups. Demographic data on gender diversity is given in more detail in Section 4.4.2.

Table 3 ⟷ Staff over 2017-2022

	2017		2018		2019		2020		2021		2022	
	#	FTE	#	FTE	#	FTE	#	FTE	#	FTE	#	FTE
Tenured group leaders	12	11,5	12	11,5	13	12,5	13	12,5	15	14,5	16	15,5
Non-tenured group leaders	5	5,0	6	6,0	4	4,0	4	4,0	4	4,0	3	3,0
Postdocs	27	26,9	18	17,6	19	18,6	18	17,4	14	14,0	23	22,9
PhD students	49	47,8	59	58,0	59	57,8	56	55,8	63	62,8	65	64,8
Undergraduate students	23	20,3	20	18,7	27	26,2	29	25,4	27	25,9	24	21,3
Visiting fellows	7	0,9	8	1,1	10	1,4	10	1,3	7	0,8	5	0,7
Guests	18	6,9	20	9,0	22	9,2	18	7,8	28	11,7	27	10,8
Total scientific staff	***141***	***119,3***	***143***	***121,9***	***154***	***129,6***	***148***	***124,2***	***158***	***133,7***	***163***	***138,9***
Technical support	36	34,7	36	34,9	33	31,3	35	33,6	36	34,1	40	8,8
General support	40	32,1	36	29,1	36	29,0	39	30,5	34	27,6	35	28,9
Support staff ARCNL	12	10,2	13	11,6	13	11,4	13	11,7	14	12,8	13	11,2
Total support staff	***88***	***77,0***	***85***	***75,6***	***82***	***71,7***	***87***	***75,9***	***84***	***74,5***	***88***	***79,0***
Total Staff	**229**	**196,3**	**228**	**197,5**	**236**	**201,3**	**235**	**200,1**	**242**	**208,2**	**251**	**217,9**

"AMOLF's research program has always been very dynamic, which is enabled by qualities that are highly constant, namely the great interest of everyone at AMOLF in each other and each other's work, and the strong will to help one another. We should cherish these qualities."

H.J. Bakker
DIRECTOR

"A research institute should be much more than the sum of the separate parts. It is heartwarming to see how at AMOLF researchers and people in technical and administrative support closely collaborate, and together achieve world-class research. That makes AMOLF a truly special place."

P. van Tijn
INSTITUTE MANAGER

"Autonomy is such a fascinating concept, in science as well as in society. Simple on the surface yet highly complex under the hood, and incredibly powerful in drawing disciplines together. The appeal for me is also its urgency and promise – mastering autonomy will be critical to future material systems."

S.J. Tans
AUTONOMOUS MATTER

"The energy transition is the greatest challenge facing humankind in the 21st century. We are investigating more sustainable ways to make renewable electrticity, chemicals and materials while also coordinating national efforts, for example in the SolarNL growth fund program."

E.C. Garnett
SUSTAINABLE ENERGY MATERIALS

"Building the Information in Matter department is very inspiring: we bring together very different experimental platforms and yet jointly build a new language and understanding of physics of information. AMOLF is ideal for collaboration without disciplinary walls."

A.F. Koenderink
INFORMATION IN MATTER

2. National role and strategy

2.1 National role

AMOLF has an important national role in initiating and developing research directions that are new to the Netherlands. To enable a fast and successful start of new research themes, AMOLF strives to be an outstanding and attractive place for tenure track group leaders and offers an optimal environment for research and training. The institute also places a strong emphasis on the development of new scientific instrumentation, as this is key to performing research in new fields. AMOLF thus serves as an incubator for Dutch science in starting new research themes, in attracting and training of scientific talent, and in developing scientific instrumentation. To develop new research themes further on a national level, AMOLF initiates and coordinates national research programs, in which the institute closely collaborates with universities and other research institutes. AMOLF also regularly starts public-private partnership projects, to maximize the societal impact of its research. Examples of this model of incubating and coordinating directions are for instance biophysics (nucleated at AMOLF as a national strategy choice in the physics domain ca. 20 years ago, now departments in Delft, Leiden, Utrecht, Amsterdam Free University), photovoltaics research (started 10 years ago as strategic NWO focus groups at AMOLF, Groningen, and now a nationwide endeavor), and nanophotonics (e.g., all technical universities have groups led by AMOLF alumni in this field). As example of public private partnership coordination, AMOLF developed the new NWO institute ARCNL (Advanced Research Center for Nanolithography), in response to a call for bids initiated by ASML and NWO. The recently formulated research themes Sustainable Energy Materials, Information in Matter, and Autonomous Matter were identified as strategic directions in national research agendas, such as the MaterialenNL agenda (Narrative 6.1, writing co-led by AMOLF, with broad input from Dutch academia and industry). In line with our mission, these themes are highly instrumental in the incubation of new research topics (e.g. by tenure track hires, see section 2.3), and in the national coordination of research (see section 3.3.3).

The national and international roles of AMOLF were well recognized by the 2019 Committee Frenkel, which reviewed the entire portfolio of all national institutes. This committee defined three important potential national roles for an institute, being:

1. driving new (inter)disciplinary scientific fields by stimulating science at the national and international level, and by playing a connecting and coordinating role in the relevant research field in the Netherlands;
2. providing sustainable access to (inter)national heritage, unique collections and (large-scale) infrastructure or facilities;
3. attracting excellent scientists and feeding Dutch universities and knowledge institutions with talent. According to the committee, each national institute should at least fulfill the first role and preferably also the second or the third role.

The committee noted that AMOLF fulfills clear national and international roles as a driver of new scientific fields and as coordinator of the scientific agenda for materials research. They qualified AMOLF as "a spider in the web" that connects various parties, including research-intensive companies, in larger initiatives. In the opinion of the committee AMOLF also pursues a conscious and thorough tenure track policy, which means that it quickly attracts excellent researchers to start new programs. The committee concluded that AMOLF offers clear added value in the national research field because it fulfills the driving role and the magnet function. These roles are also perfectly in line with NWO's strategic ambitions 25, 27 and 29 (Science Works! NWO strategy 2023-2026): to develop more strategic research themes with bottom-up organization from the field in collaboration across the knowledge chain, organized via the NWO institutes.

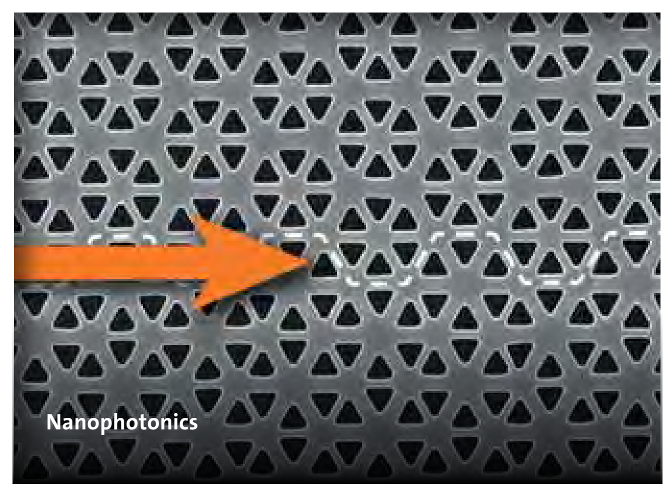
Figure 2 ⟷ Connectivity to Dutch academic research institutes and main industrial partners.

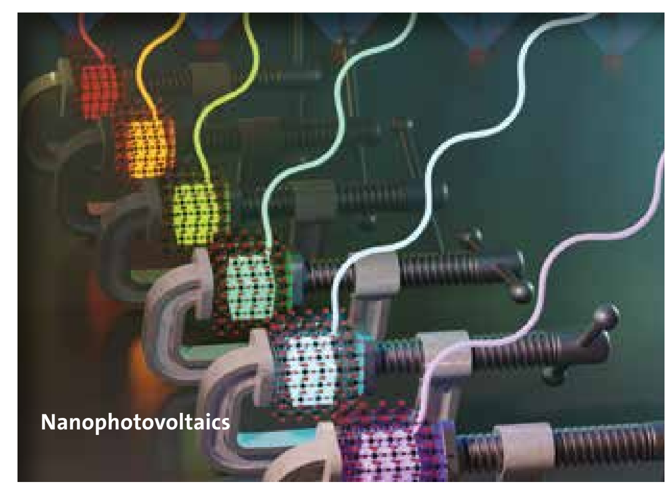
2.2 AMOLF research of past and present

At the start of the previous strategic period 2017-2022, the research program of AMOLF comprised four research directions: Nanophotonics, Nanophotovoltaics, Designer Matter, Physics of Living Matter. These directions were connected by the central aim of understanding how function emerges in complex matter and leveraging this understanding to create new forms of adaptive and responsive (smart) materials. Below is a summary of the main developments.

⟷ **Within Nanophotonics** we investigated new physical phenomena and functionalities emerging from exquisitely tailored interactions of light and nanoscale matter, exploiting nonlinearity, non-hermiticity, fluctuations, quantum correlations, and nonreciprocity, as resources for measurement, transport, conversion, and processing of energy and information. For instance, we developed tiny strings that co-localize resonances for light and sound as a platform for on-chip non-reciprocal photonics and phononic devices, with unique potential for quantum sensing and transduction. By strongly coupling open-access microcavities to exciton polaritons, we developed a platform to study noise, bistability, and stochastic resonances, as resources for a wide range of optical applications. We demonstrated that in such systems noise can be harnessed as a resource to improve optical sensing. Moreover, we developed resonant metasurfaces for lighting (structured light for LEDs and lasers, with Signify, Lumileds), for metrology (with ARCNL, ASML), and extremely strong light-matter interaction. A highlight includes the development of resonators with mode volumes below $\lambda^3/10^6$, yet possessing high optical quality factors, that have a unique potential for molecular optomechanics, and the study and use of strong coupling. Our research also targeted information technology with optical metasurfaces, finding applications in analogue optical computation, and in optical metrology for wafer manufacturing.

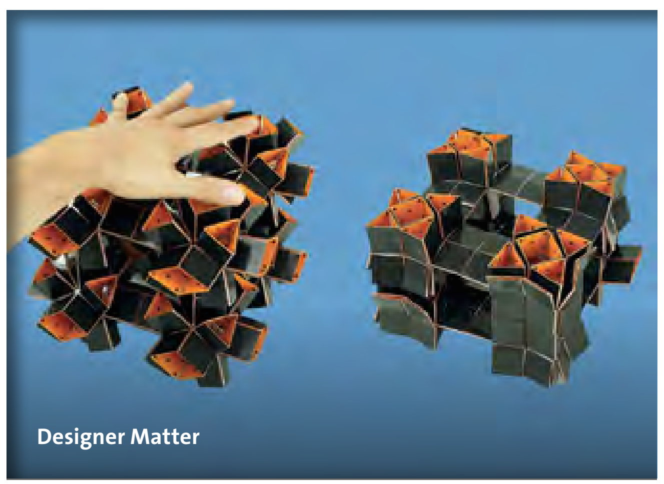
⟷ **Within Nanophotovoltaics** we developed novel materials and photonic architectures to create photovoltaics (PV) with enhanced performance and functionality. We applied these concepts to create a wide range of solar cells, from lightweight ultrathin films to ultra-high efficiency tandem solar cells. We strongly expanded our research program on perovskite solar

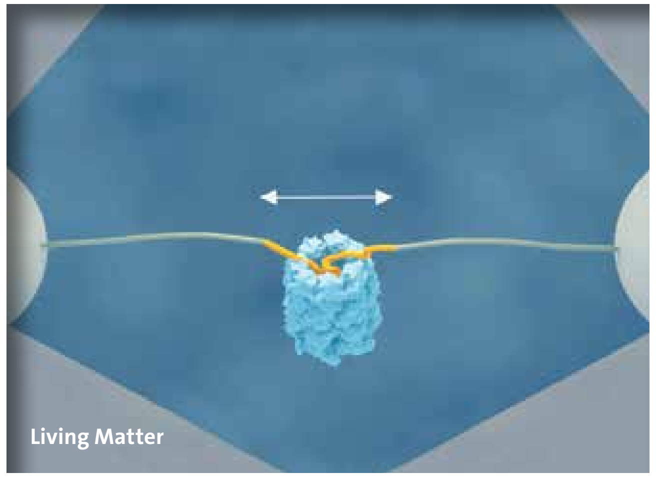




cells, developing novel synthesis methods and carrier collection geometries. In parallel, we developed dedicated spectroscopic tools to study the structure and dynamics in perovskite PV materials. We developed nano-electrochemistry as a technique to grow PV materials and contact layers with tailored shape and composition. We further developed electron microscopy techniques dedicated for PV materials analysis, including time-resolved cathodoluminescence spectroscopy and electron backscattering diffraction for the analysis of sensitive PV materials. The rich insights in plasmonics developed at the interface of Nanophotonics and Nanophotovoltaics triggered the start of a new research direction in which we use light to locally drive and probe chemical reactions. Our materials programme also has impact in a broader sustainability context, for instance in using perovskite materials for energy efficient lighting and computing.

⟷ **Within Designer Matter**, new soft robotic concepts were discovered that transform a continuous flow of air into pulsating actuation, leading to programmable behavior in walking robots and the potential to control the beating of a soft artificial heart. Moreover, embedded decentralized algorithms have helped soft robots learn how to move in specific directions, even when undergoing changing environments and damage. Furthermore, large progress in the design of metamaterials based on concepts such as spin-ices, frustration, and topological defects, enabled the fabrication of programmable shape-shifting and self-folding materials, and a new research line on interacting material bits led to the realization of metamaterials that count and processes sequential information. We also developed new concepts to produce new functional materials using ion exchange reactions and to steer self-organization with user-defined light-patterns. By combining the expertise on mechanically responsive materials and reaction-diffusion processes, a new strategy for generating highly regular band patterns was developed.


Designer Matter


Living Matter

⟷ **Within Living Matter** several major discoveries were made on cellular organization and information processing. At the molecular level, it was shown how proteins can pull on protein loops to dissolve protein aggregates and to combat neurodegeneration, and how proteins can actively form protein dimers by two coupled ribosomes. At a higher level of organization, protein regulation networks were shown to optimally process information, enabling new research in information processing costs and links to other forms of information processing. The quantitative biophysical know-how present at AMOLF also turned out to be increasingly useful for the study of multi-cellular systems. The spatial organization of different bacterial strains was shown to be key in the functioning of multi-bacterial systems such as our gut microbiome. Organoids, which are self-organizing organ-like systems, have been identified as a major new direction for biophysics research. With a key and expanding role, artificial intelligence (AI) methods were used to study tissue dynamics at the cellular level, which is key to understand how cells autonomously organize and grow, but also how this can fail, for instance in tumor growth.

During the last strategic period, these four intertwined research lines produced multiple research projects that crossed disciplinary boundaries and a similarity in their research questions and theoretical descriptions. For instance, the research on photonic systems showed an increasing interest in nonlinearities, noise, and limits to sensing and computing, thereby becoming connected to the thermodynamics of information in biophysical systems. Similarly, research on the organization of biological systems showed a growing overlap with questions asked within our research on supramolecular chemical systems and soft robotics.

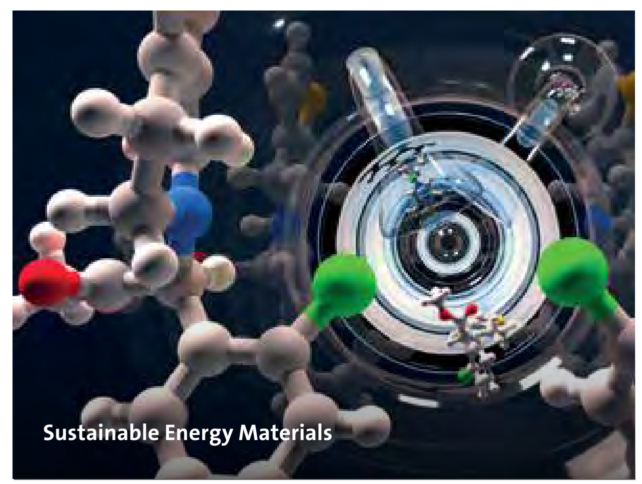
These internal developments coincided with important national developments, for instance in the 'National Agenda on Materials', which appeared in 2020, and which was authored by a broad national committee for the coordination of research on materials. This committee consisted of representatives from universities, NWO and technology institutes, and companies, and of policy makers. The 'National Agenda on Materials' stressed the importance of the research and development of energy materials, metamaterials, information materials, soft and responsive biomaterials, and materials for a circular economy, and the importance of developing high-tech infrastructure for fabrication and characterization.

Following the internal and external developments outlined above, we decided in 2021 to rearrange our research organization into three new, highly interdisciplinary research themes: Sustainable Energy Materials, Information in Matter, and Autonomous Matter. A detailed description of these themes can be found in the next subsection and in the AMOLF Strategic Plan 2023-2028. This reorganization also aligns with NWO's strategic ambitions 25, 27 and 29 (Science Works! NWO Strategy 2023-2026).

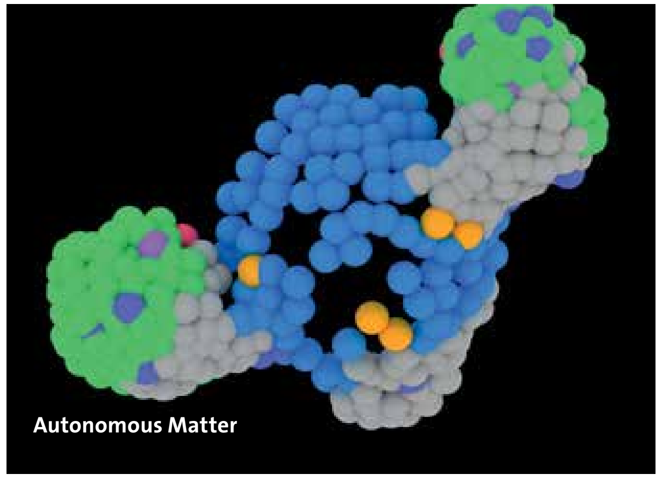
2.3 The three new research themes in short

The new theme Sustainable Energy Materials is a natural evolution of the Nanophotovoltaics research, adding in light-driven chemistry and spectroscopy as well as topics from Designer Matter. The strongly collaborative team of 7 groups share an interest in the discovery and understanding of light-driven processes and in the use of fundamental insights in (nano)photonics and (nano)materials to efficiently convert sunlight to electricity, chemicals, materials and heat. The recent rise of the world-wide interest in halide perovskites – highly efficient, dynamic, and reactive ionic semiconductors - clarified that it is increasingly important to understand (electro)chemical processes within the perovskite and at interfaces with contacts. Recent developments in time-resolved spectroscopy (e.g. cathodoluminescence and sum-frequency generation) offer new opportunities to understand these critical interfaces in great detail. Some of the recently developed schemes envisioned for enhancing photovoltaics, such as plasmonic nanoparticles for light concentration and trapping, appear to be also highly promising for chemistry and spectroscopy applications, but both their fundamental understanding and practical implementation require extensive research and development. This expansion beyond Nanophotovoltaics into chemistry and spectroscopy was also inspired by our close contacts with research groups at universities, companies and other institutes, and the recognition of their interests and needs. For example, discussions with the (electro)catalysis groups at the universities of Utrecht, Amsterdam and Leiden, together with the need for green chemistry and fuels in the future, led to large collaborative grants focused on using light and electrons to drive and monitor catalytic reactions.

The new theme Information in Matter comprises groups from the former Nanophotonics, Designer Matter, and Living Matter research directions that have a strong joint interest in information processing. These groups have their roots in quite different physical systems, e.g. nanophotonic resonator systems driven by light, macroscopic mechanical metamaterials that are highly nonlinear, and biophysical systems that include biochemical networks up to full organisms (C. Elegans, fungi). The common thread in these systems is that they sense, gather, and process information, and that they (can) operate at fundamental limits of performance, e.g., set by thermodynamics, reciprocity, quantum mechanics, or energy resources. The close collaboration of groups coming from very different fields will lead to new insights in how systems can process information. It can also lead to new designs, for instance concepts well-known in living systems may find new applications in photonic and mechanical systems (e.g., hardware AI implementations). This theme is well matched to national developments at the universities in Groningen, Twente, Nijmegen and Eindhoven, that primarily focus on neuromorphics and electronics, as we pursue complementary paradigms and systems, yet have related goals in reaching the fundamental limits of information materials and physical systems that process information.


Sustainable Energy Materials


Information in Matter



Autonomous Matter

The new theme Autonomous Matter combines research groups of the former Living Matter department with soft robotics and self-organized assembly and chemistry research of the former Designer Matter department. A key driver was our realization that this research, both at AMOLF and beyond, was moving towards understanding how systems autonomously organize and sustain themselves, which indicated untapped future synergies. The autonomy in these diverse systems is characterized by stochasticity, feed-backs, spatial organization, energy consumption, and optimization strategies. Living and engineered systems highlight different facets, with the former having autonomy in abundance but in poorly understood fashion, while the latter are well understood by bottom-up design but still have numerous autonomous functions to gain. For instance, concepts known from organoids, which represent an important new strategic direction for AMOLF, may inspire new designs for soft robots. Vice versa, mechanisms that have been developed and that are well understood for soft robots, may turn out to be also present in living systems, thus providing a better understanding of these systems. This theme synergizes with several complementary national trends, like the development of bio-inspired chemistry in the Institute for Complex Molecular Systems, the interdisciplinary expansion of organoid research, which has a strong basis in the Netherlands, as well as the Robotlab and Basyc minimal cell programs in which AMOLF participates. The Autonomous Matter program represents a key physics perspective in these current advances.

To define and strengthen the three novel research themes, AMOLF hired three highly talented tenure track group leaders, one in each theme:

Wiebke Albrecht (2021) with her group Hybrid Nanosystems takes a central position in Sustainable Energy Materials.

Marc Serra Garcia (2021) with his group Hyper-smart Matter is at the core of Information in Matter.

Kristina Ganzinger (2018) with her group Physics of Cellular Interactions is at the core of Autonomous Matter.

The highly interdisciplinary character of the new themes implies that they combine different disciplines in which AMOLF holds great expertise and possesses a strong track record. To push the frontiers of these disciplines, we established expertise centers for: Chemistry & Spectroscopy, Light Management in Photovoltaics (LMPV), Modern Mechanics, Living Systems and Nanophotonics. The mission of the expertise 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 national and international collaborations and networks, for instance LMPV plays a leading and coordinating role in the national collaboration SolarLab on photovoltaics. Together, the expertise centers form the foundation for AMOLF's research themes. The combination of disciplinary strengths and interdisciplinary themes puts AMOLF in an excellent position to connect researchers, governments, politics, knowledge institutions and industry, thus carrying out one of its key national roles (Science Works! NWO Strategy 2023-2026).

2.4 What has been achieved? Strategic goals of the past strategic period

Developing new cross-disciplinary research directions. We saw a range of opportunities for the scientific landscape in the Netherlands and beyond by combining current trends in biology, physics, chemistry, and engineering. The Designer Matter program that we initiated in the previous strategic period, through the recruitment of Martin van Hecke, Wim Noorduin and Bas Overvelde, was key to this development. In the present strategic period, it forms a crucial part of all three new themes:
- Sustainable energy materials,
- Information in Matter,
- Autonomous Matter.

To further expand in personal grants. In the past, AMOLF group leaders have been very successful in obtaining grants from the Dutch personal granting schemes (Veni, Vidi, Vici). Over the last strategic period, we aimed to extend this success to other sources, in particular to the ERC. With explicit policies including extensive tenure tracker mentoring, critical proposal reading by several colleagues, and grant presentation 'grill sessions', we managed to obtain 17 ERCs and the equivalent Dutch Vidi/Vici/WISE personal grants over the last period.

Innovation of scientific instrumentation. We introduced several new instruments in our cleanroom, including E-beam lithography, Electron backscatter diffraction (EBSD), and inductively coupled plasma enhanced chemical vapour deposition (ICPECVD). The unique EBSD detector that we developed at AMOLF is now commercialized by ASI/EDAX. We furthermore developed several instruments in house, including picosecond time-resolved cathodoluminescence imaging, and Open Source multicolor single-molecule TIRF microscopy.

Introducing an advanced data management policy. All research groups developed data management plans, we organized several workshops on data management, we started a pilot for groups to switch to electronic logbooks, and we started the creation of replication packages for our published papers. This is in line with ambition 8 of the NWO strategy, setting the groundwork for more effective open science (Sience Works! NWO Strategy 2023-2026).

Improving the gender balance among our scientific staff. Over the last strategic period we hired 4 new tenure track group leaders of which 50% were women. One female group leader (Gijsje Koenderink) left AMOLF for a prestigious position at the TU Delft. Her transition forms a logical and desirable implementation of our role of transferring successful research and successful talent to other academic institutions in The Netherlands, consistent with ambition 3 of the NWO strategy (Science Works! NWO Strategy 2023-2026).

Enhancing national collaborations with university groups and other institutes. We started several PhD projects together with University of Amsterdam (UvA) groups at the Institute of Physics and the Van 't Hoff Institute of Molecular Science, and with the Applied Physics department at the Eindhoven University of Technology (TU/e). We also initiated a collaborative program which allows group leaders to apply for a 50/50 financing of joint PhD projects together with other academic institutions in the Netherlands. We also managed to get several KIC projects granted in which we intensely collaborate with groups at other national academic institutions and with companies.

Continue to take a leading role in the Dutch National Science Agenda (NWA). We are a partner in the recently granted NWA NL-ECO national consortium on energy efficient computing, in which we lead the work on metasurface based computing. We are also a partner in the NWA consortium Holland Hybrid Heart that was recently granted. Polman and Ehrler have managing roles in the NWA Materials route and NWA Energy Transition route. In addition, we are very active in setting up and participating in several very large national Growth Fund initiatives. The Growth Fund was not yet created at the time of the last Strategic Plan and is in its scope similar in character to the NWA.

Broadening the scope of collaboration with industrial partners. We expanded our Public-Private Partnership (PPS) activities, which mainly engaged large companies, with a program of small-scale postdoc projects targeting close collaboration with small and medium-sized companies. Examples are LUMICKS, Seaborough, and Amsterdam Scientific Instruments. In national Growth Fund applications, we have worked closely with companies and made plans for large-scale public private partnerships that include many players including SMEs, multinationals, and societal stakeholders.

Enhancing international collaborations and partnerships. We started several collaborations with international academic partners. We started a post-doc exchange program with the University of Cambridge, an intense collaboration on photovoltaics research with the Fraunhofer Institute for Solar Energy Research in Freiburg, and we are setting up a collaboration and exchange program with ESPCI in Paris. In addition, we participated in several EU FET-Open consortia (SoFiA, THOR, Hybrid Heart, Repressit, Chiralforce, SolarUp, Reactor), and in two FET Proactive consortia (Ebeam, HOT). These efforts comply well with NWO's ambitions 25, 27 and 29 to coordinate knowledge networks around strategic research topics (Science Works! NWO Strategy 2023-2026).

2.5 Recommendations of last SEP evaluation

In the last institute evaluation in 2017, AMOLF was graded the highest mark ('excellent') in all criteria, i.e., research quality, relevance to society, and viability. The evaluation panel also made a few specific recommendations for AMOLF. In the following paragraph we describe how we have addressed these recommendations during the past strategic period.

- **Maintain and extend the strong links between the four departments.** Over the last strategic period, the four original departments became indeed even more strongly connected. The strong connections inspired us to define three new interdisciplinary themes and departments. To further strengthen the cross-disciplinary connections within each of the new themes, we have started AMOLF-funded postdoctoral projects on interdisciplinary topics within each theme.

- **Explore further opportunities for start-ups, especially in the domain of physics instrumentation.** Over the last strategic period we have promoted awareness for valorisation by establishing a targeted valorisation workgroup. We also now have a renewed IDF policy which makes it more stimulating for AMOLF employees to begin a start-up. We have also expanded our internal PPS program that enables the appointment of post-docs on collaborative projects with industrial partners. Recently, one of our group leaders (Wim Noorduin), together with a former AMOLF PhD student, began a start-up, named Lumetallix, based on an AMOLF invention (see Narrative 6.2). This start-up also made use of specific regional (IXA Amsterdam Physics-to-Market) and national funding programs (NWO TTW Take-off) for enhancing start-up activities. We continued our strong links with external startups like Delmic and Lumicks. The products of Delmic are largely based on AMOLF inventions and we continued the co-development of new products with Delmic.

• **Safeguard the AMOLF model and maintain the limit on the size of the research groups**. The limited size of the research groups strongly stimulates the interaction and collaboration of different groups. Over the last strategic period we have continued our policy in restricting the number of group members and available lab space per group. In this collaborative environment, in which exchange of knowledge is stimulated, new collaborations arise between research groups and the interaction between the research groups and the support departments is augmented by the low barrier to connect to each other. Moreover, restricting the group size forms a stimulus for group leaders to leave AMOLF when they have become very successful and can run a bigger operation elsewhere. This also creates space for new (tenure track) group leaders that bring in new research topics, thus contributing to the implementation of our national roles, being the attraction of international scientific talent, and the start and development of new research directions for the Netherlands. During the last strategic period, two group leaders have left AMOLF.

• **Monitor diversity in all aspects and maintain managerial focus on gender policies and hidden biases**. We have continued our policy in improving the gender balance, especially among the scientific staff. As an example, our new hiring policy for tenure track staff includes extensive scouting, setting minimum gender balance targets for the candidate shortlist, and extending the application deadline if that target is not initially met. This decision has had the desired effect of attracting new excellent female talent into the candidate pool. Of the four new hired tenure track group leaders over the last period, two are women. Over the last years we have expanded our policy of improving the gender balance to a more general promotion of diversity and inclusivity. For this purpose, we have established a new Inclusivity and Diversity Team (IDT). The IDT has written a diversity and inclusivity plan for the years 2022-2026 that is embraced by the management team. At present we are carrying out the proposed actions of this plan. Our broader policy regarding inclusivity and diversity got national recognition from the Dutch Physical Society by awarding us the National Diversity Award in 2022.

2.6 Where can we do better?

Several of the goals that we defined at the beginning of the last strategic period were not completely reached. In addition, we have identified some additional aspects that we would like to improve. Below we outline these points:

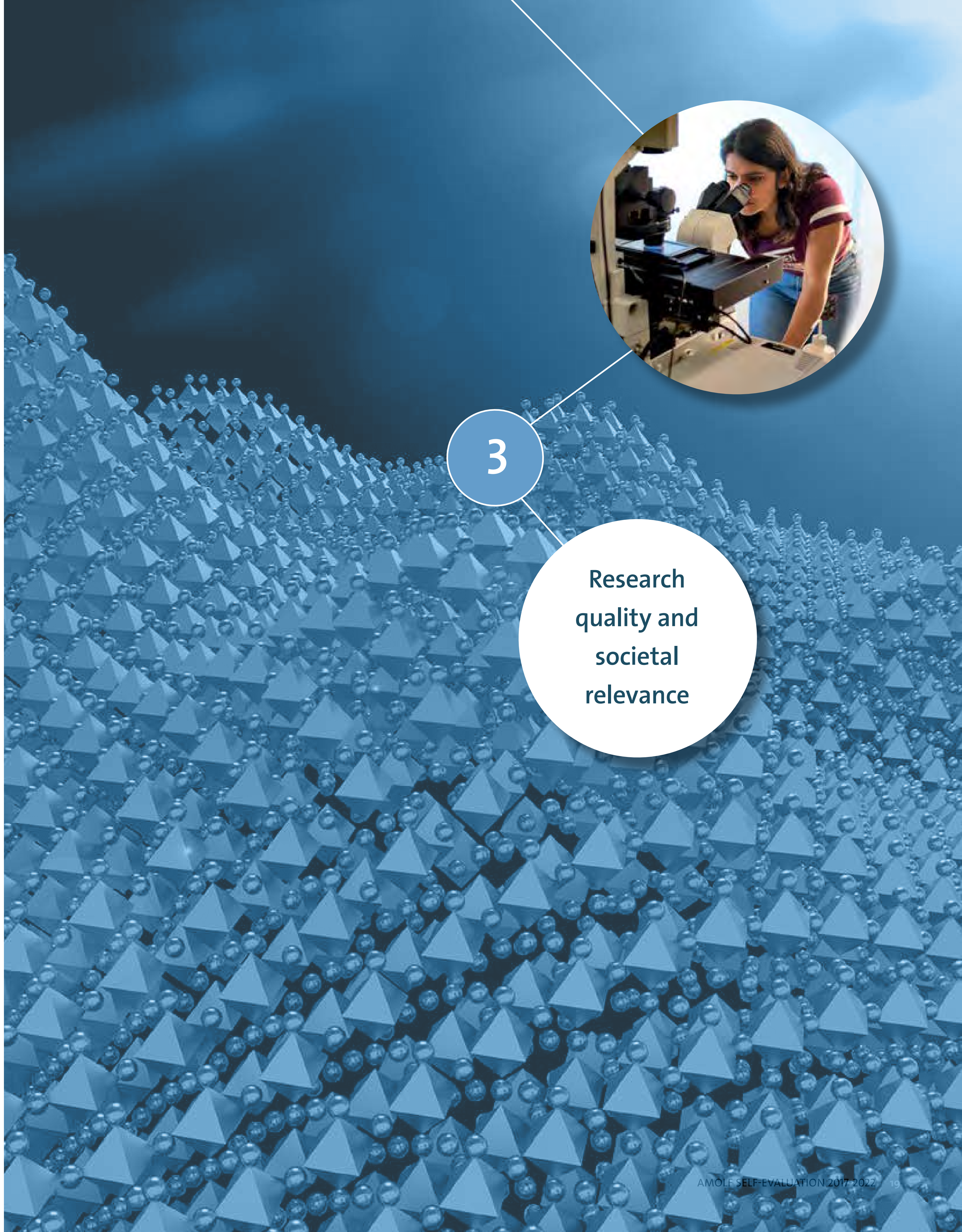
• **Towards gender balance in scientific and technical staff.** Our target of a 25% representation of women among our scientific group leaders was not reached. Although we realized a 50:50 gender balance in new hires as targeted, this was offset by the departure of Gijsje Koenderink to the TU Delft. While we celebrate this as a success in light of our role to transfer research and talent to Dutch academia, the consequence is that at present only 3 out of 19 group leaders are female (16%). Among some of the technical staff divisions, the gender is even more unbalanced, and strongly limited by the candidate pool (very low percentages of women study in applied technical disciplines, e.g., below 10% for ICT-related studies). Nevertheless, we have been able to increase the percentage of female technical staff in some areas, such as in our cleanroom team.

• **International collaborations at the institute level**. We have many international collaborations via individual groups and in larger-scale collaborations, especially within European consortia. However, we do not have many international collaborations at the institute level. The Covid pandemic was most certainly hindering in setting up these collaborations in the last strategic period. We are now setting up such a collaboration with ESPCI in Paris, and in the coming strategic period we aim to set up more of these institute-wide exchange programs and collaborations.

• **Limited visibility with students**. AMOLF is well-known among the international research community. However, AMOLF is relatively unknown among students and junior scientists, even at the national level. Here we should do better, especially as the competition to find excellent junior scientists (PhD and postdoc candidates) has been getting stronger over the last years.

• **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 most pressing societal problem now is global warming and climate change. In that perspective we should do much more in reducing the CO_2 footprint of our own (research) activities. This also aligns with NWO's strategic ambition 14 of the NWO strategy 2023-2026, which strives to make the organization climate neutral by 2030 (Science Works! NWO Strategy 2023-2026).

The plan for improving these points is outlined in chapter 4 (Institute Culture and Policy), in section 5.2 (Strategic Actions), and in our Strategic Plan 2023-2028 (separate document).



3 Research quality and societal relevance

3. Research quality & societal relevance

3.1 Choice of performance indicators

Based on our mission and strategy, AMOLF has selected the following performance indicators to evaluate its research quality and societal relevance (Table 4).

These indicators clarify to which extent AMOLF:
- performs high-level fundamental scientific research, with high impact in the international scientific community;
- provides an excellent environment to nurture talented PhD students, postdocs and tenure track PIs;
- has a national coordinating role;
- contributes knowledge to society by working together with industry and societal partners;
- engage the public by communicating our research work and results.

We discuss these indicators quantitatively in the following subsections, and in chapter 6 we provide six case studies (narratives), each of which highlight the interplay between our research achievements and our strategy to impact science and technology, by initiating new directions, crossing disciplines, and by working in partnership with academia and industry.

Table 4 ⟷ Choice of performance indicators for research quality and societal relevance, based on AMOLF output, their use by others, and recognition

	Research quality	Societal relevance
Demonstrable products	• Scientific results, published in refereed journal articles and reviews • Theses defended • Science organization through research agendas, consortia & events	• Industrial & societal collaborations and their output • Inventions and prototypes • Coordination of public-private partnerships and societal networks • Outreach
Demonstrable use of products	• Citations of articles • Reach of agendas, consortia & events	• Delivered PhDs to society • Tech transfer, i.e., licensed/adopted patents, spin-offs • Open Science • Visitors exposed to outreach activities
Demonstrable marks of recognition	• Talent grants recognizing personal or collaborative quality • Thesis and early-career awards • Honorary memberships, awards	• Funding awarded in PPS schemes • Societal funding & awards • Highlighted outreach

3.2 Research quality

3.2.1 Research output

Products: In the period 2017-2022, AMOLF published 574 papers in internationally peer-reviewed journals (registered in Web of Science). AMOLF delivered 66 PhD theses and 72 other types of publications, such as book chapters (14), conference papers (37), editorials, technical reports, etc. (21). Table 6 shows an annual break down. 89% of our refereed papers were published open access (see section 4.1)

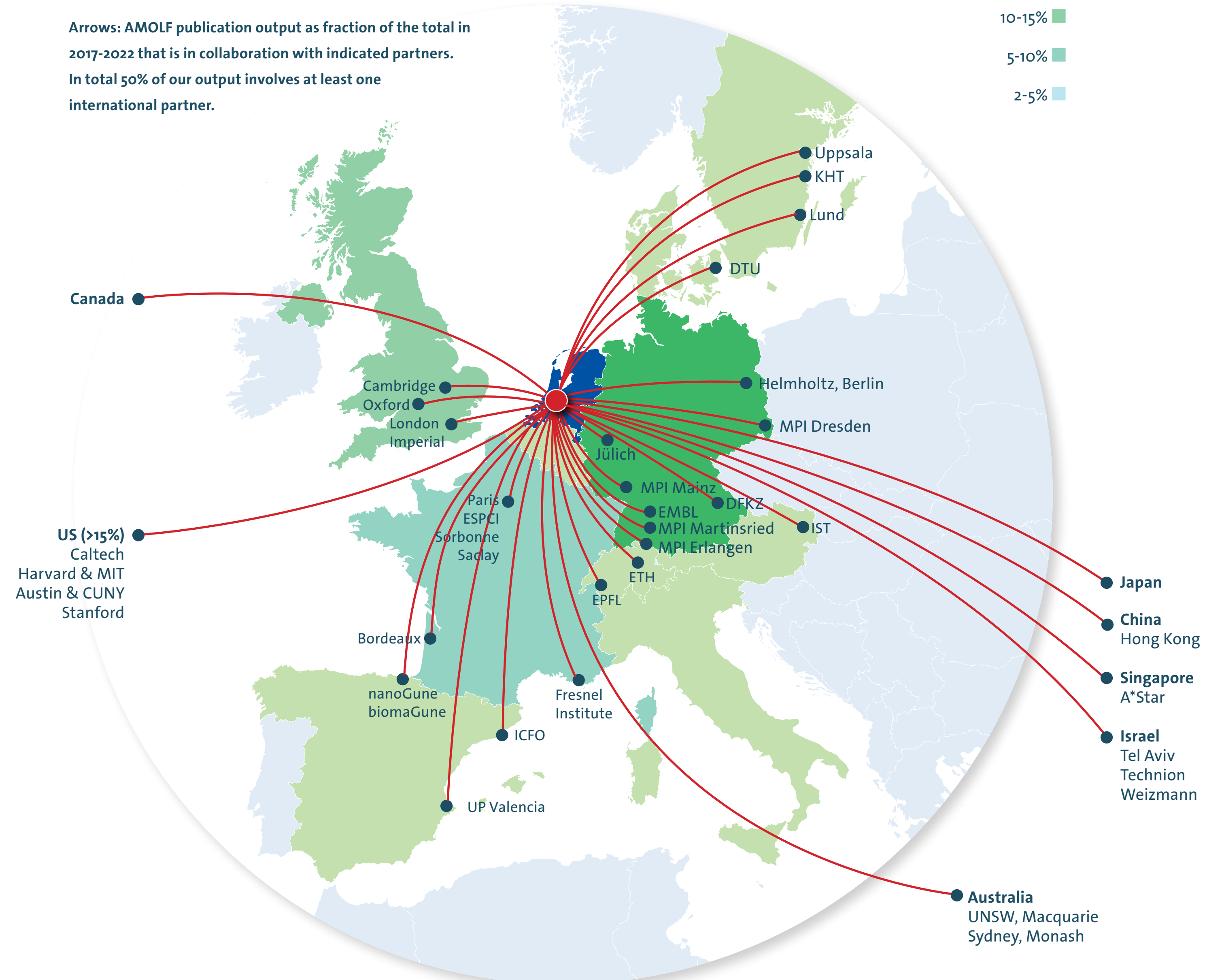
An analysis of the journals in which we publish shows that international professional societies like APS, ACS and OSA account for approximately 50% of our publication volume, and the Nature family and AAAS journals for 15%. Our research output reflects the ambition for interdisciplinary research, with a strong focus on journals that serve a broader audience. Nearly 40% of our papers appear in journals with a broader readership, such as PRL, PRX, ACS Nano, Nano Letters, Science, Science Advances, PNAS, and the Nature family of journals. We also contributed to many reviews and perspectives, spanning the full breadth of our research. These reviews, in journals such as the Nature Review family, ACS Photonics, ACS Nano are often written together with main international players, and many of them are the basis for new research partnerships and activities. Figure 3 shows our international collaborative publication network. Our primary collaborators are at leading institutes in the US, Germany, UK, France, Switzerland, and Spain.

Our publication portfolio illustrates the strongly collaborative nature of AMOLF research in the national and international research landscape. Only 20% of our papers are published without collaborating partners, with 50% of our papers including at least one Dutch partner institution. Also, 50% of papers include at least one international collaborator, mainly located in Germany (Fraunhofer Institutes, FZ Jülich, Max Planck Institutes), the US (Harvard, Caltech, CUNY), France (ESPCI), the UK (Cambridge University, Imperial College), Switzerland (ETH, EPFL) and Australia (UNSW). This distribution is in line with our strategic goal to build topical research networks with key institutes.

Table 5 ⟷ AMOLF output over 2017-2022

	2017	2018	2019	2020	2021	2022	Total
Refereed publications	105	85	98	103	95	83	**574**
PhD Theses	8	9	13	12	16	8	**66**
Other (book chapters, proceedings, ...)	9	12	10	12	15	14	**72**
Total	**122**	**106**	**121**	**127**	**126**	**104**	**712**

Figure 3 ⟷ Connectivity to international academic partners



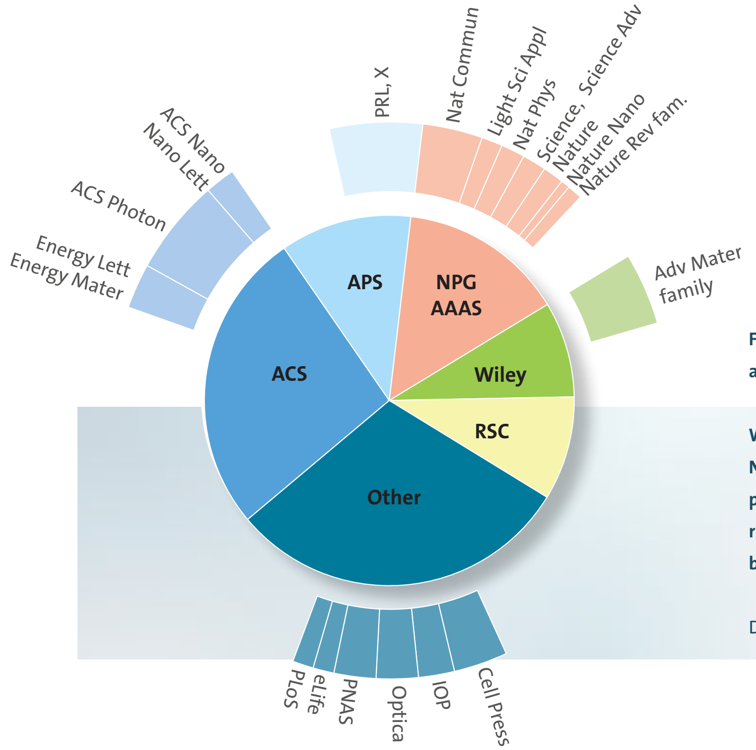


Figure 4 ⟷ International scientific journals in which AMOLF publishes, analyzed by the distribution over publishers.

We primarily publish in society journals (ACS, APS, IOP, OSA, AAAS, National Academy of Science, RSC). Our output is distributed over physics, chemistry, materials science and life science titles. As our research is interdisciplinary, we aim for visibility and output in mainly broad-audience journals, as broken down on the outer perimeter.

Data analysis on March 1, 2023 WoS output.

Use of products: Citation habits vary strongly across fields, and it is well known that as a single metric, citations for a paper set or for individual papers, are not a full representation of their multifaceted impact. According to ISI web of science, the papers we published in the reporting period were cited 14.182 times. This amounts to >24 citations on average per paper. To gain more insight into the use patterns, we have commissioned an analysis from the bibliometric expertise center CWTS. This analysis does not use journal-based metrics like the journal IF, but is based instead on a per-paper citation analysis, where the impact of each paper is normalized to its research field. CWTS uses a citation-network analysis to cluster papers in research fields. According to CWTS, the MNCS (mean-normalized citation score) of papers from 2017-2019 (over 2 full citation accumulation years to ensure relevant citation statistics) is 1,81, quantifying the mean impact that our papers have according to citation patterns. For comparison, according to the CWTS Leiden ranking of over 1300 major universities, Dutch universities in the physical / natural sciences are reported to have an MNCS of 1,5 +/- 0,2. It is remarkable that 22% of our papers belong to the top-10% of most frequently cited papers in our fields (so-called pptop10% metric). This value is on par with values quoted in the annual CWTS Leiden Ranking for the top-10 of international universities.

CWTS also provides an analysis of how the various fields that we are active in grow, as normalized to the overall growth in worldwide scientific output in all fields. Growth factors as large as 2 to 4 are reported for many of our directions, such as metasurfaces, mechanical metamaterials and optomechanics, perovskites, organoids and synthetic biology. These are also fields in which we have a high impact, as measured by MNCS and pptop10% values for those fields that are at, or exceeding the institute mean performance. These metrics are consistent with our ambition to develop new and interdisciplinary research topics, in which we aim for a strong international impact.

3.2.2 Coordinating science

An important national role of AMOLF is to stimulate the Dutch scientific landscape by engaging other academic partners in new research directions, and by initiating and nurturing national consortia in important research directions. In section 3.3.3 we will describe our contributions to the writing of national research agendas and to the organization of large grants and grant calls within the Netherlands. We also stimulate the formation of national networks and collaborations by organizing symposia and workshops around our research themes that typically take place at AMOLF, with international and national invited speakers, and to which we invite Dutch academia and industry partners. In the past period, AMOLF hosted >20 such events. Examples include the annual LMPV symposium - now a major annual event for the Dutch solar research community, symposia on soft matter biomimetics (2018), designer matter and soft robotics (2021), light-driven chemistry for sustainability (2022), physics of information (2022), organoid research (2023), autonomous matter (2023), and summer schools (Nanophotonics, 2019 & 2022). These symposia have a large reach, engaging the breadth of Dutch academia in our disciplines.

Approximately 40% of the events that we organized were specifically aimed at including non-academic partners in new consortia. These for instance included a sequence of 4 workshops for developing the NWA (Dutch National Science Agenda, seeding research programs that include academia, industry, and societal partners).

3.2.3 Marks of recognition

European H2020 ERC grants awarded between 2017 and 2022:

- ERC Starting (5):
  E. Verhagen (2017)
  S.R.K. Rodriguez (2019)
  B. Ehrler (2020)
  J.T.B. Overvelde (2020)
  M. Serra Garcia (2022)
- ERC Consolidator (2):
  E.C. Garnett (2022)
  W.L. Noorduin (2022)
- ERC Advanced (3):
  P.R. ten Wolde (2020)
  A. Polman (3rd, 2021) and
  M.L. van Hecke (2021)
- ERC Synergy (1):
  S.J. Tans (with B. Bukau (Heidelberg) and N. Ban (ETH)) (2022)

NWO Vidi, WISE and Vici grants

- NWO Vidi (3):
  B. Ehrler (2017)
  W.L. Noorduin (2018)
  K.A. Ganzinger (2021)
- NWO WISE (2):
  K.A. Ganzinger (2017)
  W. Albrecht (2021)
- NWO Vici (1):
  G.H. Koenderink (2019)

Postdoc level grants:

- European Marie Skłodowska-Curie fellowships (2):
  F. Wruck (2017)
  A. Bhattacherjee (2019)
- NWO Veni (Dutch equivalent of Marie Skłodowska-Curie) (6):
  S.R.K. Rodriguez (2017)
  J.T.B. Overvelde (2017)
  C. Martinez-Torres (2017)
  S.R. Waitukaitis (2017)
  S.H.C. Askes (2019)
  E.M. Hutter (2019)
- NWO Rubicon (5):
  S.A. Mann
  H.M. Doeleman
  A.S. Meeussen
  M.J. Avellaneda Sarrio
  M. Futscher

Royal Netherlands Academy of Science and Arts (KNAW) memberships during 2017-2022

- KNAW:
  H.J. Bakker
  A. Polman
- DJA (Young Academy of the KNAW):
  A.F. Koenderink
  K.A. Ganzinger

National physics and young talent prizes

- Physica prize (annual prize, Netherlands Physical Society):
  M. van Hecke (2020)
- KNCV Gold medal (annual prize, Netherlands Chemical Society):
  E.C. Garnett (2022).

Marloes Bistervels wins Young Speakers contest at the annual national Dutch Physics conference.

Andrea Cordaro celebrates his cum laude PhD with the committee

- KNAW Early Career Award (Royal Academy of Sciences):
  S.R.K. Rodriguez (2018)
  J.T.B. Overvelde (2022)
- KHMW Early Career Award (Pieter Langerhuizen baten):
  K.A. Ganzinger (2020)
- Techniektalent 2020 (De Ingenieur):
  J.T.B. Overvelde
- Minerva award (recognizes young excellent female and non-binary scientists):
  F. Burla (2019)
  W. Albrecht (2021)
- PhD thesis prizes: annual Physics Thesis Award (for best Dutch physics thesis, NWO and NNV –Dutch Physics Society):
  H.M. Doeleman (2019)
  A.S. Meeussen (2021)
- Dick Stufkens Prijs (Holland Research School of Molecular Chemistry):
  S.H.C. Askes (2017)
- Martinus van Marum prize (KHMW) for best thesis**:**
  E.M. Hutter (2019)
- MSc thesis prize: Tata Steel Afstudeerprijs voor Werktuigbouwkunde en Materiaalkunde:
  S.A. Rigter (2019)
- Young Speakers Contest (yearly prize at FYSICA NNV):
  S.R. Waitukaitis (2018)
  A.S. Meeussen (2020)
  M.H. Bistervels (2022)
- Best article of a PhD student in Nederlands Tijdschrift voor Natuurkunde (NNV):
  W.J. Smit (2018)
- NWO Physics Valorisation Prize (2019):
  R.M.A. Heeren (former AMOLF group leader, prize awarded for research largely conducted at AMOLF)

Selection of international recognitions in reporting period

- Fellow APS:
  M.L. van Hecke (2022)
- Fellow Optica/OSA:
  A.F. Koenderink (2022)
- EPS Prize for Research into the Science of Light:
  A. Polman (2017)
- Pierre-Gilles de Gennes Prize:
  G.H. Koenderink (2018)
- WIN (Waterloo Institute for Nanotechnology, Canada) Rising Star Award:
  B. Ehrler (2018)
- ACS Photonics Young Investigator Award Lectureship:
  A.F. Koenderink (2018)
- Highly cited researcher of Web of Science (top 1%):
  A. Polman (2018 and 2019)
- Rising Stars of Light Award (by Nature journal Light, Science & Applications):
  C.E.A. Cordaro (2022)
- Young Academy of Europe:
  B. Ehrler, member since 2022

3.3 Societal relevance

Our results in fundamental science often provide promising routes to industrial and societal impact. We see five main routes to generate impact:

Collaborative projects with industry and societal partners. These projects are often the first step towards broader impact of our research results and allow for further development of our scientific discoveries and their potential valorization. Approximately 35% of our grants include industrial or societal partners, corresponding to 14,3 M€ total research budget since 2017. These grants are described in more detail in section 3.3.1 below. Furthermore, a recent analysis by Roland Berger estimated that electron microscopy and spectroscopy products developed by AMOLF together with Delmic, ThermoFisher and EDAX over the past 10 years, are already providing an added value of 12 M€ per year to the sector, with an estimated increase to 16-20 M€ per year by 2032.

High-level training of scientists. Over the last strategic period we have trained and delivered approximately 325 scientists (210 MSc students, 65 PhDs, 50 postdocs), who contribute to the human capital needed for technical innovation in society. A recent Roland Berger analysis estimated that these high-level people are already adding 50 k€/person/year in value to the economy, bringing the total value added to the economy resulting from training by AMOLF to 16,25 M€/year.

Inventions, tech transfer and spin offs. We have a keen eye for possibilities to patent our research, to start new companies, and to develop new products, particularly novel instrumentation that can be useful to the broader research community outside AMOLF. Section 3.3.2 presents some examples.

National and international coordination efforts. As a national research institute, one of our goals is to connect scientists with each other and with societal partners. We do this by organizing workshops, setting up governing structures and forming large interdisciplinary consortia, which are detailed in Section 3.3.3. Roland Berger recently estimated that by 2032, one of these consortia led by AMOLF (SolarNL) will lead to a future added value to the Dutch economy of 422 M€ per year, a cumulative CO_2-eq savings of 24 million ton.

Outreach. We regularly communicate to people outside academia the importance and impact of scientific research on their daily lives. We give talks in public settings, such as in radio interviews, in podcasts, and in museums and theatres, we collaborate with artists and museums to make exhibits that highlight both the beauty and utility of our research, we communicate our scientific results in the press and social media, and we organize every year an open day that attracts about 1.000 visitors. Section 3.3.4 provides several examples.

3.3.1 Industry and societal collaborations and their output

Since 2017 AMOLF has established 35 new collaborative projects with companies, technology transfer institutes and societal partners. We have a long-standing collaboration with Delmic, a spin-off company from Albert Polman's research on cathodoluminescence microscopy, and within this collaboration new instruments were developed. Furthermore, we set up industry-co-funded collaborations on microscopes for crystallographic mapping with EDAX, on nanoelectrochemistry with Bruker and Nanonics, and on ultrafast electron microscopy with ThermoFisher. These collaborations illustrate that we are valuable partners for some of the world's leading developers of analytical instruments. Our expertise in nanophotonics has led to productive collaborations with Philips and, more recently, with the Philips spin-outs LumiLEDs and Signify on solid-state lighting. Our expertise in optics has led to collaborations around metrology, particularly with our sister-institute ARCNL and ASML, through jointly funded PhD students (2 defended, 4 ongoing) and NWO grants. Our optics expertise has also led to applications in photovoltaics and major collaborations with both energy and photovoltaics companies such as Shell and HyET Solar. With the rise of new types of chemical reactors driven by light, we are also leveraging our expertise in photonics to collaborate with chemical companies such as ExxonMobil, BASF, and Toyota. Our fundamental research on crystallization has enabled collaborations with pharmaceutical companies Symeres and Innosyn, that are interested in producing enantiopure chemical compounds. Our expertise in biophysics at the single-molecule and cellular level has led to industrial partnerships in medical applications, like immunotherapy for cancer with Lumicks. In recent years, important progress has been made in developing AI driven analysis of single cells within organoids, which has led to partnerships on drug screening with the Hubrecht Institute in Utrecht. Finally, the highly interdisciplinary nature of AMOLF's research has led to partnerships with several medical companies, such as those interested in developing soft-robotic hearts that beat without electronics, like Evos and Xeltis. The first successful implantation of such a synthetic heart has now been achieved in a goat. Combined, these new collaborations represent a research budget of 14,25 M€ (8,5 M€ since 2021), have led to 76 publications, 4 patent applications by AMOLF, 6 patent applications by our collaborating industrial partners, 1 startup and 6 commercial products with a total of 120 units sold and >60 M€ in turnover.

3.3.2 Inventions, tech transfer and spin offs

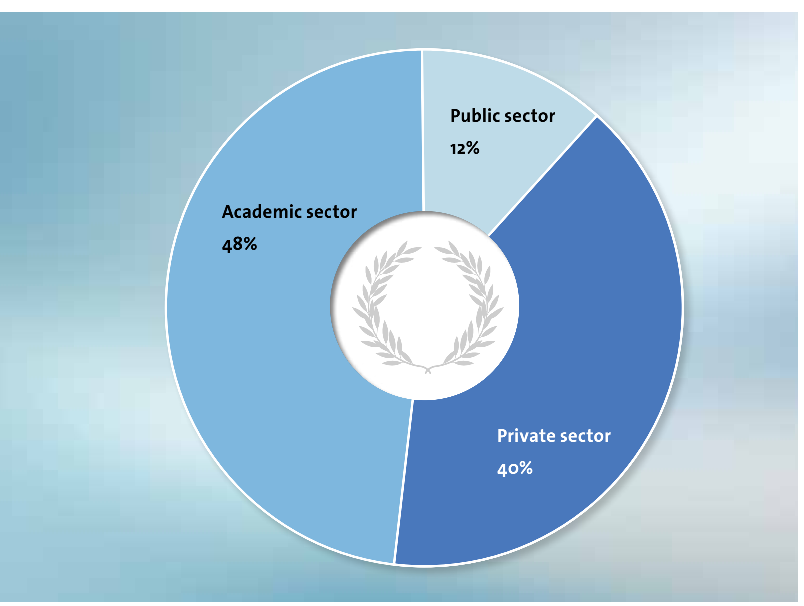
To promote our patent output, AMOLF offers a financial bonus to employees that file an 'invention disclosure', when it is deemed to be potentially successful by a dedicated committee. Of the 19 invention disclosure forms submitted from 2017-2022, 4 have led to patent applications by AMOLF and 6 patent applications were filed by our industrial partners. One patent concerned the detection of lead pollution using rapid chemical conversion reactions leading to highly emissive compounds. This patent led to a spin-off company – Lumetallix – which was a finalist in the competition of the most innovative new startup in the Netherlands in 2022, and currently has projects in India and Ivory Coast (see Narrative 6.2 for more detail).

Our efforts to develop new instrumentation for our own research led to commercialization of several novel scientific instruments. One such example is our partnership with Amsterdam Scientific Instruments and EDAX which led to the commercialization of the world's first direct electron detector for electron backscatter diffraction (https://www.edax.com/news-events/amolf). This product was developed in cooperation with AMOLF (starting in 2015), with the first research prototype designed and built at AMOLF, and the first commercial product installed at AMOLF, in the context of a public-private partnership research program that started in 2022.

3.3.3 National and international coordination efforts

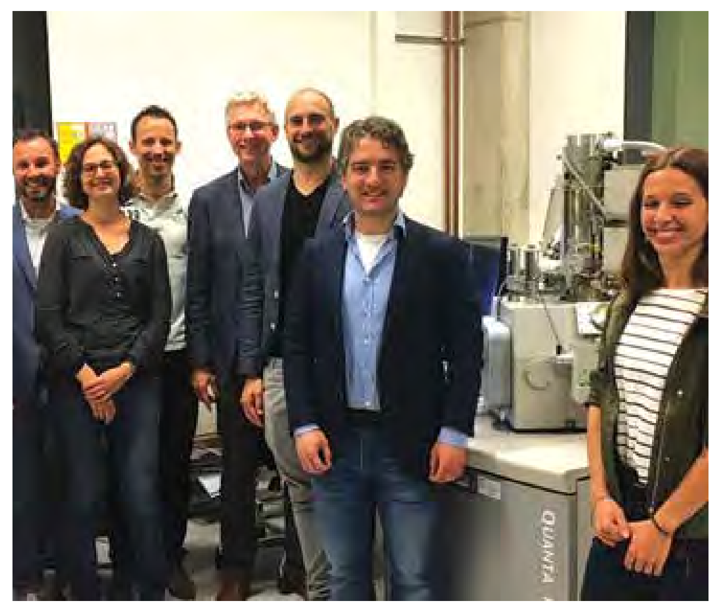
AMOLF plays a key role in organizing the Dutch scientific landscape by developing large national and international research programs and by writing national research agendas. In the 2017-2022 period, AMOLF has focused on several new directions in materials research, now included in our new research themes Sustainable Energy Materials, Information in Matter and Autonomous Matter. In 2015, AMOLF initiated the writing of research agendas on materials research, which led to the foundation of the Dutch Materials platform (chaired by Albert Polman) in 2019, which defines the funding priorities for the materials research community in the Netherlands. This initiative led to the Dutch Materials Agenda, and more recently to various National Growth Fund programs. The Growth Fund is a new funding scheme launched in 2020 that finances investments in research and development that lead to structural and durable economic growth of the Dutch economy. AMOLF has led, and has been heavily involved in four Growth Fund proposals: SustainableMaterialsNL (900 M€), The Revolution of Smart Molecular Systems (97 M€), QuantumDeltaNL (615 M€) and SolarNL (898 M€); these initiatives have all been granted (see Narrative 6.1).

Figure 5 ⟷ Fields entered by PhD laureates of AMOLF.



Paradiso lecture by Gijsje Koenderink in 2019.

Thermofischer electron microscopy collaboration project opening at AMOLF.



Collaboration between AMOLF groupleader Bas Overvelde and the Bartlett School of Architecture in London, called 'Edge of Chaos'.

AMOLF has played an important role in organizing the research community within our focus areas. For example, AMOLF took the lead in establishing SolarLab, which coordinates photovoltaics research projects, photovoltaics grant applications, and facilities for photovoltaics research in the Netherlands. Another example is the recently granted NL-ECO program focused on information processing with a radically lower carbon footprint. AMOLF played a key role in establishing this grant, which was awarded within the National Science Agenda (NWA). NWA is a funding scheme that started in 2015, designed to answer questions raised by the public and to address their biggest concerns about the future. AMOLF has coordinated the Materials Route within the NWA since 2015, and is now also coordinating the Sustainable Energy route. Yet another example is the OrganoidNL platform that has been launched at AMOLF in coordination with various other national partners, to develop the Dutch ecosystem of research labs and companies within the field of organoid research. Organoids are identified as a major new biomaterials direction, which is traditionally strong in the Netherlands. Together with Delft University of Technology, AMOLF is establishing a Testbed for Mechanical Quantum Sensors, as part of the QuantumDeltaNL Growth Fund initiative, which is a national facility for the development of novel optomechanical sensor technologies and a springboard for public-private collaborations.

AMOLF has also been active in organizing consortia at the international level. The LMPV expertise center runs large programs with leading photovoltaics centers in the world: with the Fraunhofer Institute for Solar Energy Research in Germany, with Cambridge University in the UK, with Stanford and Caltech in the US, and with UNSW in Australia. Bas Overvelde is leading a European program on soft-robotic artificial hearts and Kristina Ganzinger initiated a successful EU program on new cancer treatments, involving the University of Oxford, the Universitätsklinikum Bonn, the University Medical Center Utrecht, the Karolinska Institute, and the private partner Vycellix Sweden.

3.3.4 Media and Outreach

AMOLF puts large emphasis on outreach activities, with about 130 reports in newspapers, magazines, radio & blogs, including items in top-tier national newspapers (NRC and de Volkskrant), and over 50 expert appearances and interviews on radio and television, over the last strategic period. Every year we open our labs for one day to the public, participating in the Science Park 'Open Day', and typically host 1.000 visitors. The event targets both adults and children, with special children's workshops forming the most popular activities. We also broadly communicate our research results, with over 40 presentations and debates by AMOLF group leaders and junior scientists in Science Cafes, high schools, primary schools, and regional TEDx events. We developed a program to host student projects on our solar energy test field. On this field, energy yield and weather data are constantly collected to study photovoltaic panel performance under realistic test conditions. We have already realized 14 projects (http://www.lmpv.nl/solar-field/).

For the large number of people who are not regularly in touch with science, we discovered that the combination of art and science can be particularly effective in creating a first contact. One example is the collaboration with the Bartlett School of Architecture in London, called 'Edge of Chaos', which was funded by an award from the Cinekid art Festival in Amsterdam, and subsequently went on tour to Paris, Namur (Belgium) and Lomé, Togo, reaching a total of 62.000 visitors. Other examples include a permanent art installation showing self-assembled materials research at the NEMO science museum (570.000 visitors in 2022), 'RainMaker' at FabLearn and Maker Faire, 'Frankie - The artificial starfish' and 'Morphing Crystals', both located at the Rijksmuseum Boerhaave.

AMOLF Open Day: young scientists fascinated by light.

4 Institute culture and policy

4. Institute culture and policy

4.1 Open science

4.1.1 Open Access to publications

AMOLF has a long-standing policy to publish its output as open access (OA). Since 2021 we are implementing NWO's adoption of PlanS (2021), meaning that we strive to publish all our papers as either:

- **Gold/diamond OA**, with immediate access and CC-BY license, where such journals are available and considered an adequate publication platform for the work at hand;
- **Hybrid OA**, in case NWO has a transformative agreement with the journal;
- **Green OA**, with no embargo on the author-accepted manuscript.

In addition, AMOLF makes all PhD theses available OA through its repository with no embargo as standard. In exceptional cases, temporary embargoes can be installed if group leaders have a clear motivation (e.g., grant agreements, jeopardizing IP or publication).

Practically all our research output is available open access through these three routes to OA. The total fraction OA has saturated at ca. 90%. Analysis of the remaining papers show that a small further improvement to 95% may be possible, beyond which lie a few papers beyond our span of control, such as collaborative papers where we are not lead author, and conference papers. We also note a clear shift from green OA to gold/hybrid open access with CC-BY license. AMOLF is a strong supporter of the idea that scientific communities are best served by professional societies, which organize the field through their journals, conferences, prizes, and scholarships. We hence believe in an OA publishing policy that supports such journals as they transition to fully OA. This explains the shift towards hybrid OA, and the decrease of green OA. The route of green OA nonetheless remains important for AMOLF, since current NWO regulations explicitly forbid us to pay for hybrid OA, unless a transformative agreement with the publisher is in place. Unfortunately, NWO-I is left out of most transformative agreements, as most of these are negotiated by the Dutch universities without NWO. The only transformative agreement that we are in [ACS - OA since 2017, and OA with a CC-BY license since 2022] is strongly contributing towards our PlanS compliance. However, at the same time, this deal implied a doubling of the net total cost for reading plus publishing of ACS content. If this trend extrapolates to all our output, the budgetary implications of high-level OA will be significant.

Table 6 ⟶ Journal articles of AMOLF published open access.

	2017	2018	2019	2020	2021	2022	Total
Total fraction OA (%)	**86**	**93**	**93**	**85**	**89**	**89**	**89**
Of which Green (%) (arXiv, institute repository)	33	46	33	24	14	19	**23**
Hybrid (%)	38	35	35	50	54	52	**49**
Gold (%)	15	12	25	11	22	18	**19**
Fraction of total papers published with CC-BY license (%)	**25**	**17**	**31**	**26**	**38**	**51**	**31**

4.1.2 Data management and Open Data, software, blueprints

In 2018, AMOLF together with ARCNL launched the implementation of a new Research Data Management policy (RDM), with the dual goal of improved accountability/ integrity, and ultimately FAIR Open Data. In the Dutch physics landscape, this policy has been ahead of policies at universities. Aided by the small size of AMOLF as compared to the disciplinary breadth of science faculties, we can provide concrete and practical tools to our researchers.

The main pillars of this policy are:

- training for all scientists and technical support in data management tools, in the form of periodically held symposia with motivational and instructional talks;
- data management plans for all researchers and projects. Junior researchers need to write and sign these plans, which describe data handling and storage for all steps in the research process. We ask scientists to keep the plans up to date as research evolves, which is monitored in the yearly evaluation cycle;
- individually traceable paper logbooks with clear logbook instructions, centrally archived at AMOLF;
- 'replication packages', defined as a structured and annotated collection of data files, logbook entries, processing scripts and blueprints to reconstruct the research results reported in a published paper.

In spring 2022, we have expanded this toolset to:

- possibility of electronic logbooks as an alternative to paper logbooks. While groups are free to choose different electronic solutions, our policy provides clear requirements on their features and archiving;
- training in improved coding practices, open data formats and use of version control;
- offering an AMOLF portal at Zenodo to deposit data sets as Open Data.

The AMOLF Data Management policy is available on the AMOLF SEP website.

We have the dual goal of improving our scientific process accountability - from the viewpoint of research integrity, and to move towards making all (valuable) data open access. Our philosophy for Open Data is that deposited data sets must be publication-quality datasets that are 'as FAIR as possible'. We have therefore first further improved our research practice towards FAIR standards internally. In the first implementation phase, we have focused on creating awareness and offering tools. Since 2021, we have the ambition to deposit replication packages corresponding to each paper for which AMOLF has lead authorship in a closed institute archive, or openly accessible in Zenodo. Group leaders are asked to report on the implementation of this responsibility in the annual planning and control meeting with the director on their group. The number of deposited replication packages currently covers circa 25% of our papers. We expect this number to rise to circa 60%, bounded by the fact that for many collaborative papers, (part of) the data responsibility lies outside AMOLF.

In 2022 we have taken the next step to stimulate researchers to make data sets and replication packages openly accessible through Zenodo. Looking forward to 2024 and beyond, we will move to making OA deposition of data sets mandatory for all papers for which the lead author comes from AMOLF, unless disclosure hampers international collaborations, IP creation, or working with industry. A large stimulus for our researchers is that our Open Science role models are spotlighted at AMOLF and externally – see e.g. the Ganzinger Gitlab and Open Microscopy initiative.

4.2 PhD policy and training

We have a strong focus on high-quality training of junior scientists, from undergraduate students to PhD students and postdocs. Our research groups purposely have a moderate size of 5-10 researchers, which allows intense and frequent supervision by the group leader, and we follow a 'shared office' policy that mixes students from different labs, which creates an open and collaborative spirit that often yields new projects initiated by the students. AMOLF provides high-level courses on scientific skills and career development, and continuously organizes seminar series where junior scientists improve their presentation skills. A key policy aim over the past period was to further strengthen this aspect, as well as our recruitment strategy and guidance for future careers. These aspects are contained in the 'AMOLF PhD and postdoc training program'. Key novel elements are:

- 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 a Dutch university;
- a high-level mentoring program including annual performance interviews and an evaluation process involving also external PIs to maximize student potential and to allow the early identification of issues;
- a 'prospectus talk' after one year in which students present the plan for their PhD to other students and PI's;
- a dedicated '18 months till PhD manuscript submission' interview with the group leader and the department head to get an overview of what has already been achieved, and to plan what still needs to be done;
- new initiatives focused on mental health and work happiness, 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;
- new initiatives to help students to orient on their future career, through 'towards a new position' interviews and talks by ex-AMOLF employees about their diverse jobs, which we will strengthen by organizing an 'AMOLF Career day'. The full 'AMOLF PhD and postdoc training program' is available on the AMOLF SEP website.

Table 7 ⟷ Duration of the PhD period of AMOLF PhD students until the date of graduation.

Starting year	2014	2015	2016	2017	2018	2019	2020	2021	2022
Enrolement male	7	6	12	8	13	13	10	14	9
Enrolement female	3	6	8	2	7	4	4	7	8
Total	10	12	20	10	20	17	14	21	17
Graduated in 4 years or less	0	0	0	2	0				
Graduated between 4-5 years	6	6	15	8	8				
Graduated between 5-6 years	4	4	1	0	0				
Graduated after 6 years	0	2	0	0	0				
Not yet finished					11	15	13	20	17
Discontinued	0	0	4	0	1	1	1	1	0

Table 7 shows the duration of the PhD period until graduation for our PhD students over the last 9 years. It should be noted that the indicated PhD periods include the purely administrative time delay between finishing the manuscript and the actual PhD thesis defense (graduation date), which amounts to an average of 3-4 months. The duration of an average PhD period at AMOLF of 56 months between the start of the PhD and the defense is short by ca. 3 months compared to that at Dutch universities. The excellent performance of our junior researchers is indicated by the various prizes and awards they received, as outlined in section 3.2.3.

4.3 Academic culture

4.3.1 Social safety, inclusivity

At AMOLF we are convinced that working with a diverse team of researchers with mutual respect is essential to create an environment and organization that is effective in performing creative, cutting-edge research, and that forms an inspiring and safe working place. In our view, creating an inclusive environment is a prerequisite to attain high diversity at all levels in the institute, from group leader to technical support, and from MSc student to PhD student and postdoc. AMOLF has taken measures to enhance social safety and inclusivity from both the top-down (institute-wide) and bottom-up (smaller group) approaches, with a few examples provided in more detail below.

Diversity Day - discussion panel.

• **Fostering personal interactions**. At AMOLF we have the tradition to gather every day at 10:45 for coffee in the canteen for 15-20 min. The coffee break is the perfect moment to meet new people, have informal chats and come up with new ideas. This informal contact lowers the barrier to approach people for work-related issues later.

• **Introduction of new employees**. Every other Thursday during the coffee break, the AMOLF director takes the stand to give announcements, which include new policies, awards, thesis defenses, and the explicit welcome of new employees, where they are given the microphone to introduce themselves.

• **Cultural initiatives**. AMOLF annually organizes an international lunch (highlighting cuisine from the wide variety of cultures at AMOLF, and in previous years a monthly 'language cafe', initiated and organized by foreign students, who teach others within the institute their native language over drinks and snacks. A large proportion (66%) of AMOLF's PhD students and postdocs come from outside the Netherlands (mainly Europe and USA).

• **Inclusivity events**. AMOLF periodically organizes inclusivity events such as the bi-annual Women in Science Day for female scientific staff from AMOLF and ARCNL, co-organized by a diversity-team representative, a female group leader and two female PhD students. Our most recent diversity event addressed a broader perspective on gender, and we organized this event in collaboration with TransAmsterdam.

• **Going beyond the gender binary**. At AMOLF we acknowledge that gender is more diverse than just male/female. We have thus introduced new policies targeted at non-binary and transitioning people. These include the explicit signposting of gender-neutral toilets and the possibility to sign up in the HR database as male, female, or non-binary. Our HR department also facilitates processes in which a person's chosen name at AMOLF differs from that on official documents.

• **Possibility of anonymously reporting of discrimination and harassment**. In 2022, we created an anonymous consultation form on the AMOLF intranet which allows for reporting of any systemic undesirable behavior and suggestions to improve current policies. For discussing more personal issues, AMOLF also has two confidential advisors.

• **Confidential advisors**. AMOLF has an internal and an external confidential advisor, one male and one female, who can be contacted in case of problems concerning undesirable behavior, or working conditions that negatively affect the performance. We have also introduced an LGBTQ+ confidential advisor.

• **Public action**. Following the awarding of the National Diversity Award 2022 to AMOLF, the Nederlandse Tijdschrift voor Natuurkunde (Journal of the Dutch Physical Society) published an article in which AMOLF director Huib Bakker and group leader Esther Alárcon Lládo were interviewed on our policy on diversity and inclusion. AMOLF group leaders also support this policy with their own bottom-up public actions. Concrete examples are explicit remarks on diversity that Erik Garnett gave during his KNCV medal award plenary talk at CHAINS 2022 (annual Dutch chemistry conference with 1.600 attendees), an interview about diversity with Said Rahimzadeh Kalaleh Rodriguez in the Newsletter Inside NWO-I (March, 2022, https://www.nwo-i.nl/en/artikel/interview-with-said-rodriguez/), and the public rejection of invitations for plenary/invited talks at conferences that disregard gender balance (see the tweet of Albert Polman below).

4.3.2 Research integrity

Scientific integrity is taken very seriously at AMOLF. The basis is a strong culture of transparency about data and procedures maintained in all the individual groups and actively pursued in the weekly group work discussions. On the training and awareness front, all incoming scientific employees are given a copy of the National Academy of Sciences publication On Being a Scientist: A Guide to Responsible Conduct in Research. Post-covid, AMOLF has started a series of mandatory and recurrent training sessions for the whole scientific staff in which internal and external speakers address case studies on scientific integrity issues, information on how to respond to perceived scientific integrity issues, and discuss in smaller groups a variety of issues using the Dilemma Game developed by the Erasmus University of Rotterdam. Finally, the AMOLF Confidential Advisor is regularly explicitly announced as a first contact point in case of scientific integrity issues. The AMOLF Confidential Advisor serves as a gateway to communicate with the upstream NWO-I Scientific Integrity Advisors, with the supervisor(s), and/or the AMOLF management. We note that our Data Management policy reinforces our research integrity efforts, for instance by traceable logbook keeping and publishing all data and data conversion scripts in replication packages.

4.3.3 Recognition and reward

Highlighting the wide variety of potential contributions to science is important to the academic culture at AMOLF. AMOLF strongly supports the national 'Recognition and rewards' initiative, which aims to modernize the way in which we give

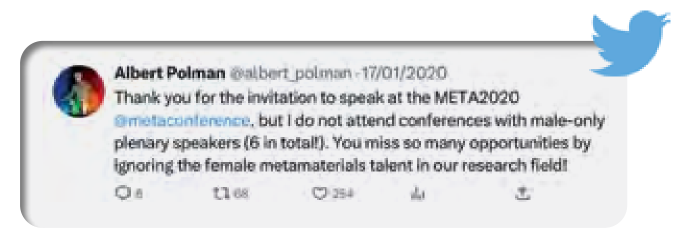


Figure 6 ⟷ Picture from the KNCV medal award speech of Erik Garnett and tweet from Albert Polman emphasizing the importance of diversity and inclusion in science. See also interview with Erik Garnett at C2W, https://www.sciencelink.net/features/kncv-gold-medal-2022-erik-garnett/20764.article.

credit and measure success (recognitionrewards.nl), related NWO-I efforts, and the DORA initiative in the United States. This includes highlighting the crucial roles of the support departments at AMOLF, the recognition of activities beyond research, such as in Open Science, in forming new networks in the Dutch academic landscape, in societal outreach activities, knowledge transfer to companies, and career path vitalization. We have for instance adjusted our appraisal interview and tenure decision process forms to take these aspects more explicitly into account, and we highlight them in our mission documents. Importantly, the wide variety of contributions and roles are frequently discussed in the bi-weekly institute-wide speech by the AMOLF director.

4.4 Human resources policy

4.4.1 Talent management

A central component of our mentoring philosophy for tenure track group leaders is intensive mentoring by senior group leaders, while preserving full scientific autonomy and independence. To guide the tenure decision, we developed a multi-step tenure track policy, including annual meetings to provide detailed advice and feedback, transparent criteria, for instance on scientific output, group management, data management, open science, gender balance, and a portfolio document detailing the progress that is updated every year by the tenure tracker. Tenure is assessed normally after 4 years, with the entire scientific staff in an advisory role. In the 2017-2022 period, we have strengthened our mentoring policy. The present policy includes early aid in the writing of grants and manuscripts, more formalized roles of mentors, for instance in guiding the tenure tracker through the annual evaluation cycle (see below), complete upfront transparency about the evaluation criteria (documented on intranet), and the offering of a 'manual for new group leaders' with all institute-related aspects. In addition, we offer tenure trackers, and in fact all staff, an intensive grant interview prepping, known internally as 'grill sessions'. We have seen strong positive impact of these sessions, evidenced by high success rates in ERC grants and in NWO personal granting schemes. AMOLF tenure trackers typically become affiliated with a Dutch university within a few years after getting tenure, which promotes the Dutch scientific network and provides new routes to explore collaborative relations. Another new element in our mentoring policy is the formation of tenure tracker social groups, which get together regularly to discuss their challenges and opportunities. We further offer professional development courses that focus on group management, leadership, and communication.

The attraction of talented PhD students and postdocs is crucial for AMOLF but increasingly competitive. Hence, we developed an 'AMOLF recruitment day' to inform candidates on open positions, to help students make their choice, to achieve a better match between students and research groups, and more generally to improve the visibility of AMOLF among students. This policy is tightly coordinated with our new PhD and postdoc training program, as described in section 4.2. The 'AMOLF PhD and postdoc training program' is available on the AMOLF SEP website.

In the technical and administrative support departments, we also offer our employees a broad range of opportunities to stimulate their professional development. In the annual appraisal interviews, professional education and growth is actively discussed. AMOLF offers a variety of activities, which can vary from attending focused courses to learn specialist skills, to general leadership training for department heads.

Over the last years, the cost of living has steeply increased in the Netherlands, and in Amsterdam in particular. This puts pressure on our ability to attract talent at the PhD and postdoc level. The availability of affordable housing in the Amsterdam area has also declined. AMOLF has a contract with the non-profit student housing agency DUWO for renting out apartments to PhDs and postdocs coming from abroad. Even though we were able to increase the number of apartments at our disposal, the demand for affordable housing exceeds what we can offer. The expensive housing situation also affects our ability to attract new personnel in the support departments. In addition, the pay gap between public institutions and the private sector has increased over the last years due to a national shortage of qualified technical personnel. These factors combined have made it challenging to retain our highly skilled support staff and to attract new people to fill our vacancies.

The Dutch Physical Society recognized AMOLF's accomplishments with respect to inclusion and diversity and awarded AMOLF with the National Diversity Award 2022

NNV-Diversiteitsprijs 2022

4.4.2 Diversity

AMOLF's ambition for diversity and inclusion is described in the newly developed Diversity and Inclusion Plan 2022-2026, which is built on the experiences of the preceding 2018-2022 Gender Equality Plan. In the 2018-2022 period our efforts focused on ensuring an equally safe and supportive working experience for all genders, and to improve gender balance at all function levels. AMOLF promotes an inclusive, family-friendly working environment, with flexible institute-wide employment regulations for maternity and parental leave, institute funding for PhD extensions to accommodate maternity, working part-time to accommodate child-care duties, and working flexible hours from home (policy extended after Covid, aided by improvements in video-conferencing tools). These opportunities are used by many employees at all function levels, with group leaders with young children serving as role models. For tenure track group leaders, our tenure track policy foresees flexibility in the timing of the tenure track decision, so that parental/maternity leave does not lead to undue pressure.

Unfortunately, physics in the Netherlands is subject to the 'leaky pipeline' effect whereby many more women than men leave the academic system at each career step. This is also visible at AMOLF: we currently have 33% representation of women at the PhD level, ca 20% at the postdoc level, and 20% at the senior level (3 scientific group leaders and the institute manager). A selection of our implemented policies:

• Our 2017 ambition was to raise female representation among PIs to 25% (from 12%) by 2022, through gender balanced tenure track hires. While the departure of Gijsje Koenderink has moved the 25% target out of sight, our tenure track hires (4 total) have been gender balanced (50%).

• All our senior staff have followed unconscious bias training, we organized a Women in Science Day (2019) and a Diversity Day (2023), and regularly draw attention to the leaky pipeline problem, for instance on the UN International Day of Women and Girls in Science. In institute seminars and symposia that we organize at AMOLF, we ensure a significant fraction of female role models as speakers (averaging 40% over the last 5 years).

• We are improving our onboarding program and installed a 'buddy' system where new employees get an already experienced "buddy" to learn the ropes of life at AMOLF and in Amsterdam.

These efforts were found to lead to sustained impact at the PhD and postdoc level. The LMPV expertise center was for instance traditionally male oriented but is now fully gender balanced

at approximately 50%. Although for some other disciplines at AMOLF the seed pool of applicants is less diverse to start with, we aim to extend this success.

Our new Diversity and Inclusion Plan also formulates our efforts to promote diversity in a broader context, extending to several target groups at risk of discrimination beyond gender. This new plan has tremendously benefitted from bottom-up input, which for instance highlighted the international/cultural dimension of diversity and inclusion, particularly for new employees. The AMOLF Diversity and Inclusion Plan 2022-2026 is available on the AMOLF SEP website.

4.5 Sustainability

AMOLF has had an active sustainability workgroup that aims to reduce AMOLF's environmental footprint. In 2021, we defined a roadmap for becoming climate neutral by 2030, with input from the sustainable engineering and consulting company Arcadis. The AMOLF CO_2 footprint is calculated annually since 2018. Highlights of current AMOLF policy include encouraging more local conferences, reusing cardboard boxes and packaging chips, effective separation of different types of waste, monitoring waste production, energy and water usage, an aquifer system for thermal storage, replacing conventional lighting with LED lighting, and installing energy monitoring in all renovated lab spaces. Some of the envisioned actions to be taken by 2025 include: installation of solar panels on the roof, reducing emissions due to commuting by 30%, and reducing residual waste by 50%.
The full AMOLF Sustainability Roadmap 2030 is available on the AMOLF SEP website.

5 Viability and future strategy

5. Viability and future strategy

5.1 SWOT analysis

Strengths

S1 ⟷ High scientific and technical quality. AMOLF and its staff are of high international standing, and AMOLFs scientific contributions as well as technological innovations in instrumentation are recognized to address forefront questions in science and society. The AMOLF technical infrastructure has a secured strong (>15 M€) investment agenda.

S2 ⟷ Agile research program and organization. As a compact non-hierarchical organization with diverse in-house disciplines, AMOLF can rapidly develop new cross-disciplinary research fields, as exemplified by our three new themes and department structure. This agility is enabled by a strongly collaborative spirit, excellent technical support, and shared responsibility for common goals.

S3 ⟷ Excellent training ground for scientists. AMOLF is attractive to international researchers at most levels (undergraduate, graduate, postdoc and tenure track). AMOLF provides tenure trackers excellent technical support, a generous start up, and scientific independence.

S4 ⟷ Coordinating role. AMOLF is active in bringing together academia, industry, and societal partners up to the national level. Examples are the national innovation agenda MaterialsNL, the Dutch Growth Fund initiatives on Sustainable Materials, SolarNL and The Revolution of Smart Molecular Systems, as well as our contributions in national policy committees (e.g., NWO Table of Physics, and Table of Chemistry, community committees that oversee disciplines (nano-quantum, life science, …) at NWO).

Weaknesses

W1 ⟷ Tension between ambition and footprint. With 19 group leaders, an ambitious secured infrastructural investment agenda, and the newly acquired project portfolio, the building is filled to its limits. As there is no guarantee of group leader outflux to create space, our ambitions for new research directions are likely to be realized with tight space constraints.

W2 ⟷ Diversity imbalance and limited control over diversity targets. Currently only 16% of our scientific group leaders are women, despite a 50% hiring ratio over the last strategic period. This indicates that reaching diversity targets will be slow and are not fully in our control.

W3 ⟷ Insufficient capacity in commercialization and IP. Effective commercialization and filing IP require a larger organization than AMOLF alone. AMOLF would ideally rely less on industry to file IP and would profit from consistent access to business development services.

W4 ⟷ AMOLF is relatively unknown to potential PhD and PD candidates. Circa 40% of AMOLF staff teach in Leiden, Delft, Amsterdam (University of Amsterdam and Vrije Universiteit Amsterdam), Groningen and Eindhoven in mainly the physics curriculum, but our existence is less well known to students outside the physics domain. As our research is increasingly interdisciplinary, it becomes harder to access the full pool of talented PhD and PD candidates.

Opportunities

O1 ⟷ Use new themes to gain scientific and societal traction. Sustainable Energy Materials is a mature, yet pressing theme for science and society, while Information in Matter and Autonomous Matter are new fields that are rapidly growing internationally.

O2 ⟷ Growth Fund (Groeifonds) as a new scientific and societal funding and collaboration scheme. The major Dutch Growth Fund initiative to invest large sums (>102 M€) in major societal and economic challenges such as sustainability, quantum technology, and materials, provides a completely new route to collaborate with industry, academia, and societal stakeholders. AMOLF has taken a leading role in several Growth Fund initiatives and can further profit from these and future initiatives.

O3 ⟷ New themes broaden collaboration scope. The new research themes open a much wider spectrum of potential collaborations beyond the traditional physics scope, including collaborations in sustainability, materials science, quantum technology, and the medical domain. An additional interesting novel opportunity for collaborative research is with experts in Artificial Intelligence (AI), in the design of new material systems and in communication and information processing.

O4 ⟷ Graduate training program. Our reforming of the PhD training program to a graduate school format with course credits, personal development trainings, and AMOLF-wide hiring cycles, give the opportunity to enhance our talent influx and improve their training.

O5 ⟷ Open science and open data. As a small and focused organization, we have an advantage in quickly developing practical research data management strategies that translate abstract Open Data and Data management ambitions in actual outcomes, which can define best practices for others.

O6 ⟷ Grants enabling to quickly test ideas for science and utilization. The recently introduced grant schemes Kiem / Lift / ENW XS and Amsterdam IXA provide low-barrier and short running-period funding for testing of ideas for startups, commercialization, and PPS research collaborations.

Threats

T1 ⟷ Level-playing field for funding increasingly out of sight. Current and future policies increasingly exclude AMOLF from funding streams that are only available to universities. This includes 'Sector plans' (for attracting talent) and rolling grants (proposed to enable continuity). AMOLF has a key coordinating role for national research lines, yet is excluded from leading NWO's largest collaborative grant called 'Zwaartekracht' (Gravitation).

T2 ⟷ Attracting talent in an expensive city. The steeply increased cost of living and housing in Amsterdam puts pressure on our ability to attract talent at the PhD and postdoc level, and to attract and keep technical support staff. In addition, the pay gap between public institutions and the private sector has increased over the last years due to a national shortage of qualified personnel.

T3 ⟷ Non-optimal governance of the NWO Institute organization. The board of the foundation NWO-I is the same as that of the much larger NWO organization, which makes the institutes relatively vulnerable in case of conflicts of interest between the overall NWO organization and the NWO institutes.

T4 ⟷ Unfavorable ratio of direct to project funding. Limited direct funding means that, with exception of funding tenure track start-ups, the majority of AMOLF's strategic aims are realized through project funding. This implies that funding for strategic directions is volatile, and subject to project call boundary conditions that are outside our control, and that particularly jeopardize blue-sky research directions.

T5 ⟷ Large projects and programs involve large administrative burden. There is a clear trend towards larger collaborative projects and programs. Especially EU funding has a serious administrative burden, and it is hard to attract suitable personnel to assist in this work, especially because the temporary nature of these grants.

5.2 Ambitions, concrete strategic actions, and viability

For the coming strategic period, we envision the following concrete strategic actions, inspired by the SWOT of the previous section.

1. Further develop our three new interdisciplinary research themes.
SWOT: S1 ⟷ S2 ⟷ O1 ⟷ O3
We aim to further develop the three research themes by initiating and developing cross-disciplinary collaborative projects. It is our strong belief that the combinations of different disciplines within each of these themes will yield many highly interesting opportunities for new science, in particular in the understanding and development of new matter and materials that harvest and store energy, that process information, and that function autonomously. We will also promote the new themes in a national and international context by organizing annual workshops and by coordinating new national and international research programs of similar interdisciplinary character.

In these new programs we will closely collaborate with university groups and other research institutes, thus transferring this interdisciplinary philosophy to other academic institutions, in accordance with our mission of initiating new research directions for The Netherlands.

2. Attract world-class scientific talent.
SWOT: S1 ⟷ S3 ⟷ W4 ⟷ O4 ⟷ T2
We will continue with attracting the best people at all levels 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 inclusive 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 also 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 deploy actions to enhance our visibility among students and further develop our training and mentoring program (see later points).

3. Coordination of large national research networks and research consortia.
SWOT: S4 ⟷ O2 ⟷ T5
An important task of AMOLF as a national NWO research institute is the coordination of national research networks and research consortia. We will continue taking a leading role in the coordination of large national research programs. Recently we took a leading role in setting up the national Growth Fund initiative proposal SolarNL on sustainable photovoltaic materials (312 M€ awarded), granted in 2023. AMOLF will have a central role in the coordination of the fundamental research

program of this proposal and will take responsibility for the central administration. Furthermore, we will improve our internal organization to facilitate the writing and coordination of large collaborative research proposals on the national and the EU level.

4. Expanding national collaborations with universities and other national institutes.
SWOT: W4 ↔ O3
To strengthen our research program and national position we will intensify our national collaborations by establishing shared PhD and postdoc positions with university groups, by initiating and coordinating large national research consortia, and by actively participating in existing large-scale national collaborations like the ARC-CBBC, ARCNL, and the Growth Fund initiatives The Revolution of Smart Molecular Systems and QuantumDeltaNL.

5. Further development of international collaborations.
SWOT: S1 ↔ S2 ↔ O1 ↔ O3
To further develop our research and to strengthen our international position, we will explore and develop international scientific collaborations at the institute level. We are in close contact with ESPCI in Paris, and we will explore other large-scale collaborations at the institute level, for instance with the Fritz Haber Institute in Berlin, and the Sonderforschungsbereich on Intelligent Matter in Münster.

6. Implementation of a renewed data management plan.
SWOT: O5
To further stimulate and develop open science, we will implement our recently updated data management policy. This policy includes the long-term storage of data, metadata and logbooks underlying publications, the filing of replication packages for all articles where AMOLF is in the lead, and the organization of regular trainings and informative workshops to AMOLF researchers to provide instruction how to store data and how to make data publicly accessible in replication packages.

7. Improving diversity and inclusivity.
SWOT: W2 ↔ T2
To promote an inclusive and diverse working environment we have recently formulated a new inclusivity and diversity plan that outlines several concrete actions. These actions include the improvement of the on-boarding of new employees at AMOLF, the improvement of the gender balance among all AMOLF employees, the organization of awareness events, like a diversity day and gender-bias awareness trainings, and the organization of institute-wide activities that stimulate diversity, like the AMOLF international lunch and the language café.

8. Implementing our new PhD and postdoc training program.
SWOT: S3 ↔ W4 ↔ O4
We will implement a new PhD and postdoc training program. Key novel elements of this program are outlined in section 4.2.

9. Further implementation and development of the Amsterdam NanoLab.
SWOT: S1 ↔ S4 ↔ O2
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. Thanks to the granted Growth Fund initiative QuantumDeltaNL AMOLF can invest ~12 M€ in cleanroom infrastructure in the coming strategic period. We will also invest in dedicated personnel who can assist in the operation and maintenance of the cleanroom equipment. It should be noticed that the budget required for the operation and maintenance will have to come from other means.

10. Invest in and develop state-of-the-art infrastructure.
SWOT: S1 ↔ W1
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, we will invest in several scientific set-ups spanning all AMOLF research areas. We will furthermore develop a facility that combines transmission electron microscopy (TEM) with light-incoupling to study light-induced processes at the atomic scale, using funding from the NWO Research Infrastructure funding scheme. In the support departments, we will invest in several state-of-the-art machines for the technical departments and in IT infrastructure. All investments will be accommodated within the limited space available in the building.

11. Preserve and develop industrial collaborations and startups.
SWOT: S3 ↔ W4 ↔ O6
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 wish to preserve and expand our collaborations with industrial partners, for which we have outlined several initiatives, including:

- collaborative joint small projects with companies (financed by at least 15% (in-kind + cash) by the company);
- the organization of Industrial contact days;
- the stimulation and support of start-ups that originate from research discoveries at AMOLF;
- the organization of so-called valorization colloquia given by AMOLF alumni who are now working in a company;
- the setting up of large-scale collaborations with big industrial partners, for instance within the NWO national funding schemes for public-private partnerships.

12. Reducing our CO_2 footprint.
We wish to contribute to a sustainable society, not only through our research but also in how we perform our (research) activities. Therefore, in the coming strategic period we aim to strongly reduce our CO_2 footprint, by reducing and changing travel, by stimulating the use of public transport, and by installing large arrays of solar panels.

6. Narratives

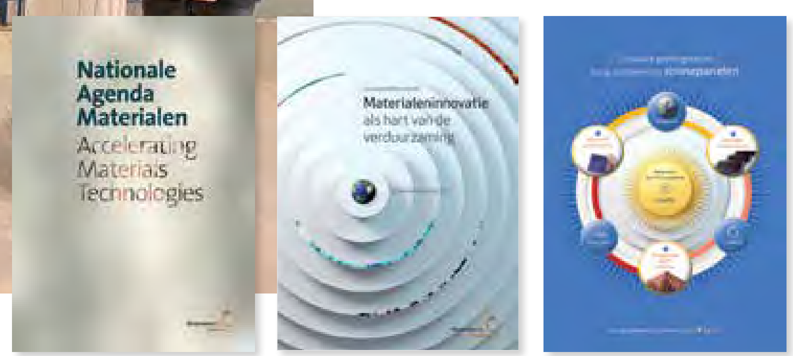
6.1 Coordination of research

National Agenda Materials

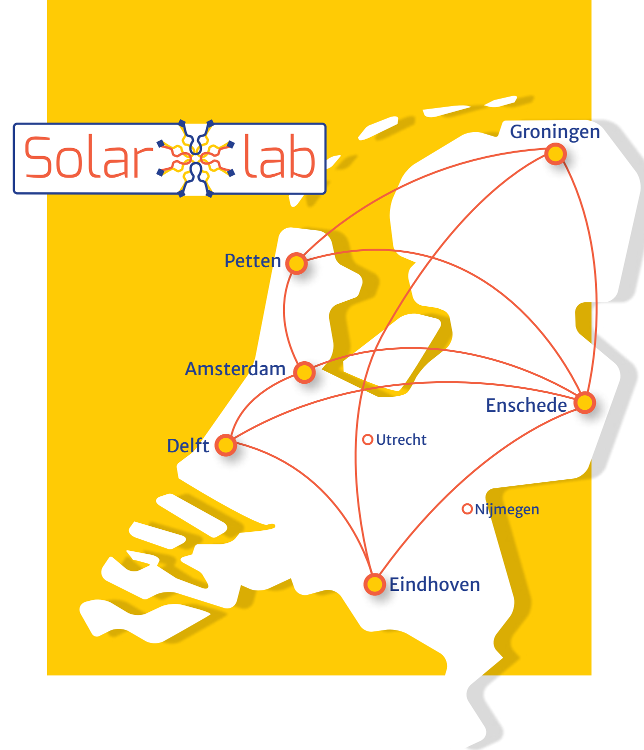
Together with colleagues in the materials field, organized within the National Materials Platform, we created a ‘National Agenda Materials – Accelerating materials technologies’, that describes promising research directions in the materials field in which the Netherlands plays a key role. An economic analysis by Roland Berger Consulting was part of the agenda. The agenda formed the basis for an application for the Dutch National Growth Fund for a program on Sustainable Materials (photovoltaics, batteries, building materials and circular plastics). The program for circular plastics was funded in 2022; the programs for photovoltaics, batteries and sustainable steel were funded in 2023. The total budget of the innovation programs for the four programs is 2.4 billion €; the total Growth Fund subsidy for the four programs is 952 M€, of which 163 M€ is for academic research. For details, see: www.materialennl-platform.nl and www.nationaalgroeifonds.nl.

SolarLab national PV research network

In 2016, we founded the national photovoltaics (PV) research network SolarLab (www.solarlab-nl.org) that connects the research groups working on PV in the Netherlands. A total of 55 PIs and some 180 PhD students and postdocs are involved in PV research in the Netherlands today. SolarLab is governed by a steering committee with representatives from the six main PV research hubs: AMOLF, University of Groningen, TU Delft, TU/e, University of Twente and TNO. In the period 2017-2023 the SolarLab collaboration has written several joint research and investment grant applications with NWO and the National Science Agenda (NWA). Unfortunately, none of these were funded so far. The SolarLab consortium has further developed a roadmap for collaborative PV research between the Dutch PV groups working on perovskite solar cells.
Building on the network created in SolarLab, AMOLF played a leading role in coordinating the granted National Growth Fund application for photovoltaics mentioned above: ‘SolarNL: Circular, integrated high-efficiency solar panels’. This program brings together many industrial partners, TNO, and academic partners and presents an ambitious plan to create a new PV industry in the Netherlands. The program has a budget of 898 M€, of which 586 M€ is covered by private funding and 312 M€ is granted from the National Growth Fund. It aims at
1. building a Si heterojunction solar cell factory with a manufacturing capacity of 3 GW_p/year PV,
2. a perovskite solar foil factory,
3. several fabrication facilities producing innovative integrated PV products, with a total of > 7 GW_p/year production capacity (see www.SolarNL.eu).



National Agenda Materials - accelerating materials technologies, **offered to state secretary for economic affairs Mona Keijzer (2020) by Albert Polman. Follow-up applications for the National Growth Fund:** ***Sustainable Materials*** **(2021, 220 M€ awarded) and** ***Circular integrated high-efficiency solar panels*** **(312 M€).**



The program also contains a major program for fundamental research that will be carried out by the academic SolarLab consortium (41 M€). The SolarLab network has been instrumental in coordinating this part of the program. AMOLF plays a central role in the management of the SolarNL program, that will have its central office in Amsterdam Science Park. This office will help organize workshops and attract visitors and PV companies to AMOLF and the Amsterdam Science Park.

6.2 Lumetallix

from fundamental science to societal impact

In 2017, the group of Wim Noorduin explored how minerals can be converted into different chemical compositions. One of the first conversions that the group developed was a reaction towards perovskite semiconductors that can emit bright light. PhD student Helmbrecht then also demonstrated how these conversion reactions can be used to make LED’s.

At the beginning of 2020 this research took a different turn: inspired by local news on lead problems with water pipes in Amsterdam, the idea was born to exploit the formation of light-emitting perovskite as an indication for the presence of lead. Exploring this idea was initially halted by the start of the COVID19 pandemic. But while stuck at home, with help of Helmbrecht, Noorduin started testing his house and neighborhood for lead traces using the perovskite formation. By coincidence it was discovered that this reaction could not only be used to find lead in water pipes, but also for paint and other common sources of lead. Further extensive testing was done in the lab and real-world environments. Surprisingly, despite the notoriously limited stability of perovskites, it was found that real-world environments can be tested for lead traces in a reliable and quantitative manner by transferring them to perovskites, as was convincingly demonstrated for a wide range of systems including paints, soil, waterpipes, dust, glass and plastic. In parallel they learned that lead pollution was a very large problem with large societal impact, with 1 in 3 children suffering world-wide from lead poisoning, and that there was an urgent need for simple and scalable testing for lead. The idea of a startup company was born!

To start the company, the first step was patenting the invention with the support of AMOLF. Then a team had to be formed for the startup. Building upon Noorduin’s previous connections with the ACE ventures program on founding startups at the Science Park, a business developer was found, and early 2022 the company Lumetallix was formed with Helmbrecht and Noorduin as co-founders. To turn the invention into a product, the first step was to verify the technical and commercial feasibility, an activity that was funded by a NWO Take Off Phase 1 grant. With the help of students at the Business school of the University of Amsterdam, they identified that NGO’s working on lead pollution where very excited to help with the validation of the test, while the US real-estate market provided the largest commercial impact potential, because there is a clear awareness of the dangers of lead poisoning, as 1 in 3 houses potentially still contain lead paint. Based on this market research, Lumetallix obtained a NWO Take Off Phase 2 grant to bring the test kit to the market.

Currently, Lumetallix is providing test kits to NGO’s working in Asia and Africa, and already more than 10.000 tests have been performed to detect lead in houses, playgrounds, toys and on four different continents. Also, the first steps are taken to enter the US market by negotiating distributor deals and applying for grants with local governments. Moreover, new collaborations are

Use of the Lumetallix test kit in the field.

set up with academic partners (Columbia University, University of Amsterdam) working on environmental pollution, lead poisoning, and forensic science (Netherlands Forensics Institute) to maximize the societal impact of this invention.

6.3 Hybrid Heart

There are approximately 26 million people worldwide with heart failure (HF) with a predicted increase of 25% by 2030. In general, curing results for patients with HF are unacceptably low and in advanced stages can be poorer than for many forms of cancer. Beyond the mortality risk, HF has a huge and lasting impact on patient's quality of life and wellbeing. For patients with advanced HF, current treatment options include intravenous inotropic drug support requiring hospitalization, donor heart transplantation and implantation of a long-term mechanical circulatory support device. With only 5000 heart transplantations globally per year and the high morbidity and mortality that accompany current support devices, there is an urgent need for alternatives. For paediatric patients, the situation is even more distressing due to the rarity of young donor hearts or well-sized support devices.

To develop an alternative solution for HF patients, the Soft Robotic Matter team of Bas Overvelde obtained a Future and Emerging Technologies (FET) Open grant in 2018 together with cardiothoracic surgeons (Amsterdam Medical Center AMC), tissue engineers (TU/e), soft robotic engineers (SSSA), and industry (EVOS, Xeltis) to build a soft, totally artificial heart that could be powered wirelessly (www.hybridheart.eu). The main goal of the project is to ultimately improve the quality of life of patients. The replacement of the heart with a bioinspired soft robotic reproduction with biocompatible surfaces would better mimic the natural behaviour of the heart, as the soft robotic technology is key in mimicking the natural contraction of the heart, while also enabling the much-needed mechanical intelligence that regulates the left-right balance via the Frank-Starling mechanism.

Within this project, AMOLF has focussed on the development of the soft robotic technology that uses soft pneumatic muscles to mimic the contraction of a natural heart. When activated, these muscles contract two internal chambers that in return expels blood in the left and right circulation. From a mechanical point of view, there are significant challenges in achieving the needed physiological behaviour (blood pressure and flow), durability and efficiency of the artificial heart. To achieve this, AMOLF has used its facilities to fabricate various prototypes, and performed in vitro experiments together with the project partners to characterize the heart. Moreover, AMOLF has also focussed on the control of the soft robotic heart, i.e., to create a heartbeat. To limit the dependency on electronics and software, AMOLF focussed on the development of so-called fluidic circuits that provide pulsatile pressure to the pneumatic muscles. By incorporating a hysteretic valve (inspired by the valve you also

Sputtering of ketchup is used as an inspiration to build fluidic circuits that generate a heartbeat in a soft totally artificial heart.

find in ketchup bottles) we were able to provide a heartbeat with minimal components (only a pump, pre-volume, and valve were needed), thus potentially improving the reliability of the device after implantation.

The first *in vivo* acute animal studies have been performed in 2022 and 2023, which demonstrated the concept of a soft and totally artificial heart, and several prototypes are now being patented within the consortium. Given these positive results, we have received NWA-ORC funding to continue our efforts with a fully Dutch consortium to build the Holland Hybrid Heart (HHH) and to take the step towards chronic animal experiments.

6.4 Birth and first steps of Information in Matter

In 2020, AMOLF organized itself in departments or 'Themes' based on ideas and functionalities rather than on physical systems. One of these newly created departments is Information in Matter (Infomatter), which brings together researchers investigating biological, mechanical, and optical systems processing information. How did researchers working on so seemingly disparate systems together establish a new interdisciplinary department?

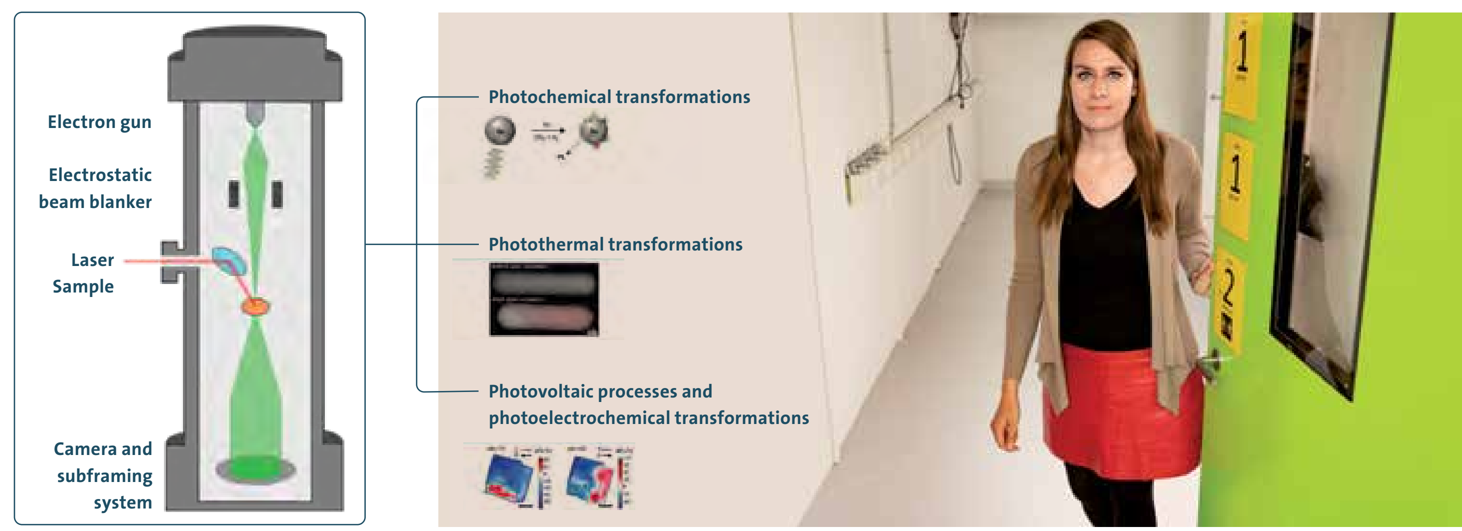
The seed of Infomatter was planted around 2018-2019, when Rodriguez, Ten Wolde and Van Hecke realized that several groups had increasingly been thinking of their systems in the context of information processing. At a staff retreat in 2019, they pitched these ideas to the entire AMOLF staff, and decided to launch a series of brainstorm sessions with interested group leaders to further analyze their strength, as well as their place in the context of national and international developments, for instance in energy efficient computing, physics of emergent systems, and data-driven approaches to physics. Although this meeting series had to proceed online because of Covid, it was a big success: It became evident that despite working on very different physical systems, many AMOLF groups were increasingly speaking the same language. Terms like mutual information, entropy, gain, noise, and memory, were increasingly voiced at AMOLF and various groups focused their research on understanding fundamental limits to sensing and computing. All these developments triggered new questions and insights, and thus the realization emerged that the physics of information in matter could bring together many groups at AMOLF, and inspire a vision of optical cavities, living cells, and springs, as information processing machines.

These internal events coincided with important external developments. For instance, AI was rising to prominence, largely thanks to the ability of computers to process more and more information. This brings not only many opportunities, but also challenges, such as how to contain the tremendous growth in energy consumption of our information society. This realization was becoming apparent in various stratifications in Dutch academia, for instance the influential national roadmap 'MaterialsNL', written by a broad committee representing Dutch academia and industry, which identified 'information materials' as a primary target. This confluence of events convinced us that the enthusiasm around Infomatter was not only a common thread within AMOLF, but also presented an opportunity to take up the baton to address pressing issues arising in the information area, where AMOLF is complementary to other partners in Dutch academia (such as the neuromorphic community, integrated photonics, and quantum information).

It has been a very exciting experience to build the Infomatter department: we are now in the rewarding process of training the first generation of students through tutorials, student talks, poster sessions, and foreign speakers, where presenters are challenged to transcend their discipline, and focus on cross-cutting concepts. Moreover, new collaborations have been established between groups from different disciplines. For example, Rodriguez, Ten Wolde and Shimizu are now studying how cooperativity, a well-known mechanism in cellular sensing, can be exploited to enhance optical sensing. These developments were further propelled by the hiring of Marc Serra Garcia, who is fascinated by providing a universal computing toolbox based on mechanics. Also, putting the question 'What fundamental limits does physics impose on X information processing?' (with X replaced by optical, biological, and mechanical) center stage is strongly accelerated by the ERC research projects of Rodriguez, Serra Garcia, ten Wolde, van Hecke, and Verhagen. We already see that this theme lands well in Dutch academia: the Dutch Infomatter symposium that we organized at AMOLF last fall, with speakers from AMOLF and Dutch institutes, was a big success. In addition, three Infomatter groups are in the lead for so-called 'wave-based computing' in the national NWA project NL-ECO on novel energy-efficient computing, and we have co-leading roles in two gravitation consortium proposals with information processing at their core.

6.5 Shining light on atomic-scale processes (SHINE)

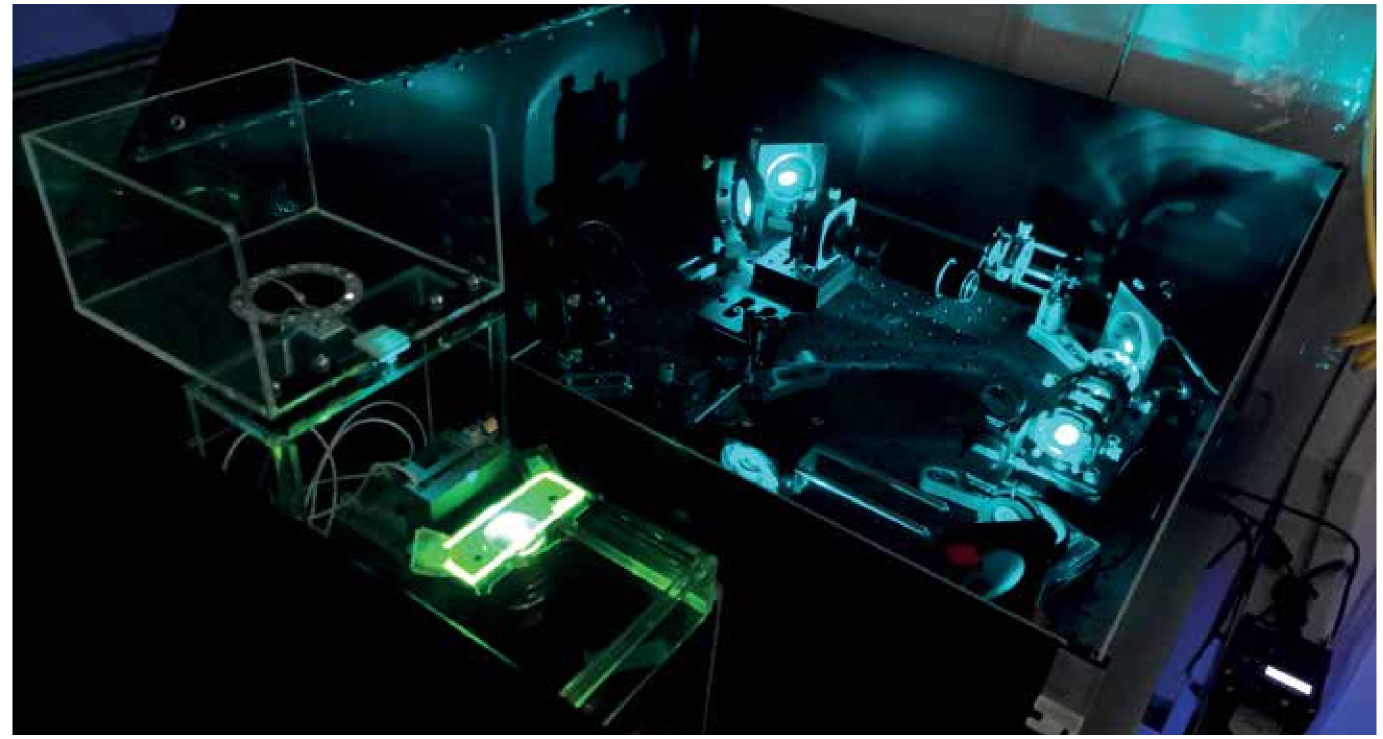
Recent developments in the fields of nanophotonics and plasmonics make it possible to concentrate light nearly to the atomic scale within picoseconds, opening up unprecedented control over where, when and how energy is injected into a material. Understanding how this new world of atomic-scale energy conversion affects photovoltaic, photochemical and photothermal transformations is crucially important to develop new pathways for the energy transition. Modern transmission electron microscopes (TEMs) are now able to routinely visualize



Wiebke Albrecht coordinates the SHINE proposal.

materials all the way down to the atomic level, but until now not under optical illumination in operando and with high time resolution. The SHINE infrastructure recently granted by NWO (3 M€) will create a new research infrastructure at AMOLF that is unique in the world and enables us to make movies of how materials change at the atomic scale during optical illumination, under real operating conditions (gas, liquid, electrical bias) and with nanosecond time resolution. This initiative is the culmination of long-term planning by AMOLF to bring the existing expertise in nanophotonics and in situ electron microscopy (e.g., time-resolved cathodoluminescence microscopy) to the atomic level and apply it to materials and devices relevant for the energy transition. To acquire the necessary expertise, we hired tenure tracker Wiebke Albrecht, who is a world expert in advanced (atomic-scale) electron microscopy including electron tomography under in situ conditions, and laser-induced photothermal transformations. Albrecht coordinated the SHINE proposal with input from the Netherlands Electron Microscopy Infrastructure (NEMI) materials science roadmap with the aim to develop a new NEMI node in Amsterdam focused on light and electron microscopy.

The infrastructure will support Dutch and European researchers working on photoconversion processes, including 15 M€ in recently granted large programs at AMOLF on photovoltaic, photothermal and photochemical transformations as well as 2 new tenure track positions in photovoltaics and photochemistry at the Free University of Amsterdam (VU) and the University of Amsterdam (UvA). SHINE will setup partnerships with electron microscopy companies, to complement our long-standing partnership with FEI (ThermoFisher Scientific). We will also strengthen our existing partnership with Amsterdam Scientific Instruments (ASI) by incorporating their unique direct electron detector into the TEM to allow for the nanosecond time resolution and unprecedented electron sensitivity. Our earlier partnership with ASI led to the world's first direct electron detector in a commercial electron backscatter diffraction (EBSD) instrument, the EDAX Clarity system, which is currently being used in an industrial partnership program with EDAX and ASI to bring light and electrical bias into in operando EBSD measurements of photovoltaic devices. This project is complementary to SHINE because it provides large-area microscopy and crystallographic imaging in addition to the atomic-scale information gathered by SHINE. This latest investment in equipment and personnel to combine nanophotonics and electron microscopy makes AMOLF a world-leader in the field and provides a unique focal point for our Sustainable Energy Materials theme as well as the LMPV and Chemistry & Spectroscopy expertise centers.



K2: an open-source, simultaneous triple-color total internal reflection fluorescence (TIRF) microscope (left) developed by the team of Kristina Ganzinger. See also https://ganzingerlab.github.io/K2TIRF/K2TIRF/index.html.

6.6 Swapping mountains for the sea: starting the Ganzinger Lab at AMOLF

Kristina Ganzinger

I still remember where I was standing when my phone rang: on a parking lot close to the Max Planck Institute for Biochemistry in Munich, it was a cold sunny day. The suspense was killing me when I picked up the call because the number displayed had the Amsterdam prefix. When I heard that I was offered to start my tenure-track group at AMOLF, this was the ultimate Christmas present. My position was linked to the "Women in Science Excel" (WISE) program of NWO, and at the time that funding was awarded in a two-step process: candidates were first pre-selected by the institute, and then invited for an interview for the WiSE program. It was an interesting experience as it meant tables were turning very soon: right after I was informed of the positive interview outcome at AMOLF, AMOLF was helping me to prepare for the WISE interview, including a proper mock interview! This made me feel very well supported right from the start, and certainly contributed to the successful outcome.

Starting a research group is a jump into the unknown for any scientist, and no less so if it means moving to a new country with a different scientific landscape. AMOLF's mentoring system for tenure trackers has made a big difference to my learning the ropes: my mentors guided me along my tenure 'track', from explaining funding structures to being a sounding board for my ideas. The yearly evaluations were also useful reflection points: putting together my portfolio each year and discussing it with the AMOLF management team and mentors helped me appreciate achievements, shift priorities if needed and set new targets for the coming years. What I find even more remarkable, however, is that there is barely any AMOLF group leader who has not given me useful advice or feedback at some point in the past five years, across all our departments. This did not only help me practically with setting up and growing my group – it also made me feel like everyone wanted me to succeed. Talking to my peers at other institutions made me realize that this is not what most tenure trackers experience, but very much the special 'spirit of AMOLF'.

It is always important to work with a good team and have a pleasant group atmosphere. Luckily, my lab started on a good foot, with motivated master students joining my two first PhD students to form a bubbly nucleus. In the first years, my group spent much time on methods development, including designing a TIRF microscope and a device to produce lipid vesicles for our research on reconstituting cells from their basic building blocks. With the excellent contributions from the support departments and my lab's commitment to open science, we managed to make both projects fully open access, including everything from design drawings, part lists and building instructions to user instructions and data analysis – to much acclaim by the respective communities.

Since I joined AMOLF in 2018, my group has tripled in size, and we are now also well connected to other Dutch research groups with complementary interests. Funded by programs such as NWO Vidi and EIC Pathfinder Open, we study how the spatiotemporal patterning and coordination of signaling molecules on the nanoscale defines how cells process information. Our portfolio now spans from basic research projects to projects closer to application in which we use our methods to help finetune cancer immunotherapies. Looking back, it has been an intensive five years – also marked by two years of Corona pandemic and interrupted by two maternity leaves. Looking forward, I am committed to actively shaping research policies to make our research landscape as inclusive, fair, and productive as possible. This starts with our own research integrity and data management policies at AMOLF, but I also want to make use of my time as chair of the NWO working group 'Physics of Life', member of the NWO Table Physics and the Young Academy of KNAW. I am more excited than ever to continue my scientific journey at AMOLF!

7. Appendices

7.1 Scientific groups

Group Leader	Group Name	Start	Departure	University Affiliation
Polman, A.	Photonic Materials	Mar-91	-	UvA
Mulder, B.M.	Theory of Biomolecular Matter	Jan-92	May-23	UU
Bakker, H.J.	Ultrafast Spectroscopy	Jan-95	-	UvA
Tans, S.J.	Biophysics	Oct-01	-	TUD
Wolde, P.R. ten	Biochemical Networks	Nov-02	-	VU
Koenderink, G.H.	Biological Soft Matter	Oct-06	Aug-19	VU
Koenderink, A.F.	Resonant Nanophotonics	Feb-08	-	UvA
Shimizu, T.S.	Physcis of Behavior	Apr-09	-	VU
Zon, J.S. van	Quantitative Developmental Biology	Mar-12	-	
Garnett, E.C.	Nanoscale Solar Cells	Sep-12	-	UvA
Verhagen, E.	Photonic Forces	Jan-13	-	TU/e
Hecke, M.L. van	Mechanical Metamaterials	Sep-14	-	LEI
Ehrler, B.	Hybrid Solar Cells	Nov-14	-	RUG
Noorduin, W.L.	Self-Organizing Matter	Aug-15	-	UvA
Alarcón Lladó, E.	3D Photovoltaics	Feb-16	-	UvA
Overvelde, J.T.B.	Soft Robotic Matter	May-16	-	TU/e
Rodriguez, S.R.K.	Interacting Photons	Nov-17	-	
Ganzinger, K.A.	Physics of Cellular Interaction	Sep-18	-	
Albrecht, W.	Hybrid Nanosystems	May-21	-	
Serra Garcia, M.	Hypersmart Matter	Oct-21	-	

UvA: University of Amsterdam
LEI: Leiden University
RUG: University of Groningen
TUD: Delft University of Technology
TU/e: Eindhoven University of Technology
UU: Utrecht University
VU: Vrije Universiteit Amsterdam.

7.2 Committees and boards

AMOLF Management Team members in 2022

Prof. H.J. Bakker ⟷ Director, chair
Prof. E.C. Garnett ⟷ leader Sustainable Energy Materials
Prof. A.F. Koenderink ⟷ leader Information in Matter
Prof. S.J. Tans ⟷ leader Autonomous Matter
Dr. P. van Tijn ⟷ Institute Manager

AMOLF Expertise Center Leaders in 2022

Prof. E. Verhagen ⟷ Nanophotonics
Prof. W.L. Noorduin ⟷ Chemistry&Spectroscopy
Prof. T.S. Shimizu ⟷ Living Matter
Prof. M.L. van Hecke ⟷ Modern Mechanics
Prof. A. Polman ⟷ Light Management in Photovoltaics

AMOLF Institute Advisory Committee in 2022

Prof. C.H. van der Wal ⟷ chair, University of Groningen
Dr. B. Broers ⟷ Authority for Consumers and Markets
Prof. M.L. Groot ⟷ Vrije Universiteit Amsterdam
Prof. R.A.J. Janssen ⟷ Eindhoven University of Technology
Prof. P.E. de Jongh ⟷ Utrecht University
Prof. A. van Oudenaarden ⟷ Hubrecht Institute
Dr. H. van der Weijde ⟷ Tata Steel
Dr. C. Wesdorp ⟷ Philips

7.3 Group pages →

BIOPHYSICS

⟷ Sander Tans

We aim to understand autonomous self-organization in biology focusing on the single protein and single cell level. Key techniques are optical tweezers and single-molecule fluorescence for the former, and 3D microscopy and deep learning driven cell tracking and analysis for the latter. These methods can uniquely reveal the conformational dynamics of amino-acid chains during protein biogenesis, and the growth, differentiation, and spatial organization of cells in developing organoid systems. The approaches we develop and the organizational principles we aim to elucidate are relevant to a wide range of questions regarding protein homeostasis and tissue maintenance.

Highlights

- We showed that cellular motility can explain the coexistence of different bacterial populations, which also opens up direct study of spatial ecology questions.
- We found that proteins are disaggregated by the processive translocation of amino acid chains.
- We developed novel approaches to quantify the dynamics of cells within organoids.
- We developed methods to reveal co-translational protein assembly at the single-molecule level.

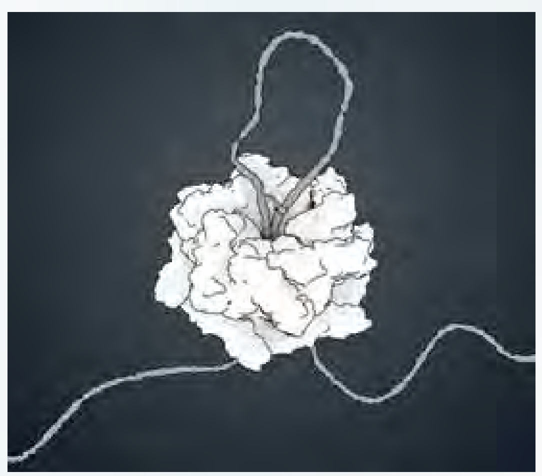
Plans

In our single cell organoid research, we will extend to rare cell types in the intestine, as they are poorly understood yet key to several conditions, and will start exploring cancer models and immune cell interactions. To do so, we will continue to expand our collaborative network with various biology groups, also driven by our cell tracking methods. Technically, we will continue to expand deep-learning enabled methods. Our molecular research will be focused on co-translational assembly and ubiquitin mediated protein processing, which both are unaddressed at the single-molecule level. In the latter we will integrate with partner groups that focus on ribosome profiling, which provides genome-wide data, and cryo-EM, which provides insight at the atomic level.

Key research items

1. M.M. Naqvi, M.J. Avellaneda, A. Roth, E.J. Koers, A. Roland, V. Sunderlikova, G. Kramer, H.S. Rye, S.J. Tans, *Protein chain collapse modulation and folding stimulation by GroEL-ES*, Sci. Adv., 8 (9), eabl6293 (2022)
2. F. Büke, J. Grilli, M. Cosentino Lagomarsino, G. Bokinsky, S.J. Tans, *ppGpp is a bacterial cell size regulator*, Current Biol., 32 (4), 870 (2022)
3. S. Gude, E. Pince, K.M. Taute, A.B. Seinen, T.S. Shimizu , S.J. Tans: *Bacterial coexistence driven by motility and spatial competition*, Nature 578 (7796), 588 (2020)
4. M.J. Avellaneda, K.B. Franke, V. Sunderlikova, B. Bukau, A. Mogk, S.J. Tans: *Processive extrusion of polypeptide loops by a Hsp100 disaggregase*, Nature 74, 212 (2020)
5. G. Huelsz-Prince, R.N.U. Kok, Y. Goos, L. Bruens, X. Zheng, S.I. Ellenbroek, J. van Rheenen, S.J. Tans, J.S. van Zon, *Mother cells control daughter cell proliferation in intestinal organoids to minimize proliferation fluctuations*, Elife 11, e80682 (2022)

ClpB disaggregase protein (white) translocates an amino-acid loop, as we revealed for the first time using single-molecule methods.



AUTONOMOUS MATTER

QUANTITATIVE DEVELOPMENTAL BIOLOGY

⟷ Jeroen van Zon

Our central question is how cells in developing organisms make decisions and self-organize into intricate patterns, despite strong variability on the molecular and cellular level. We use two simple biological model systems, the nematode worm *C. elegans* and intestinal organoids, the latter in collaboration with the group of Sander Tans. We study these by custom microscopy, quantitative image and data analysis and predictive mathematical modeling, often in collaboration with biologists studying similar questions by genetic approaches.

Highlights

- Combining biophysics measurements and stochastic simulations, we identified a novel mechanism that prevents spontaneous reversals of a cell fate switch in *C. elegans*, explaining why neuronal fate is never lost during the animal's life.
- Using our unique ability to follow cell dynamics throughout development in moving worms, we demonstrated that cell division and gene expression timing adjusts precisely to environmentally-induced slowdown of development.
- We development a cutting-edge image analysis pipeline, based on deep learning neural networks, that enables fully automated tracking of all cells in intestinal organoids, and used this pipeline to study control of proliferation and differentiation.

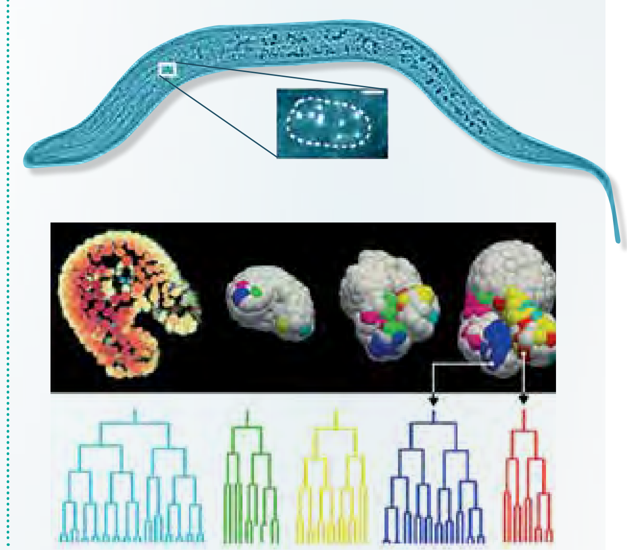
Plans

For worms, an emerging direction is control of body growth and developmental timing, and how this depends on external stresses that slowdown or arrest development. Here, we build on our exciting discovery that insulin signaling controls growth and arrest through pulses that are stochastic, yet synchronized throughout the body. For organoids, we will expand to systems such as lung and liver, and address medically-relevant questions, including proliferation patterns in cancer and interactions between organoids and immune cells. We will further push our neural network approaches, to predict organoid cell types or features such as cell volume in a label-free manner.

Key research items

1. J.J.H. Traets, S.N. van der Burght, G. Jansen and J.S. van Zon, *Mechanism of life-long maintenance of neuron identity despite molecular fluctuations*, Elife, 10:e66955 (2021)
2. O. Filina, B. Demirbas, R. Haagmans and J.S. van Zon, *Temporal scaling in C. elegans larval development*. PNAS 119:e2123110119 (2022)
3. https://github.com/jvzonlab/OrganoidTracker. *Software for our organoid cell tracking approach*, described in Kok et al, PLoS One (2020)
4. G. Huelsz-Prince, R.N.U. Kok, Y.J. Goos, L. Bruens, X. Zheng, S.I. Ellenbroek, J. van Rheenen, S.J. Tans and J.S. van Zon, *Mother cells control daughter cell proliferation in intestinal organoids to minimize proliferation fluctuations*, Elife, 11:e80682 (2022)
5. M. Betje, X. Zheng, R.N.U. Kok, J.S. van Zon and S.J. Tans, Cell Tracking for Organoids: *Lessons From Developmental Biology*, Front. Cell. Dev. Biol., 9:675013 (2021) [Invited review]

Single molecule imaging in a *C. elegans* worm to quantify gene expression (top) and cell tracking in organoids to measure cell lineages (bottom).



PHYSICS OF CELLULAR INTERACTIONS

⟷ Kristina Ganzinger

We study how immune cells communicate with each other, both in natural and immunotherapy contexts: how do immune cells use molecular signaling pathways to process and respond to information, both precisely and unambiguously? Our approach is based on microscopy that pushes technical boundaries and on synthetic biology. Combining signaling pathway reconstitution with single-molecule biophysics, our work provides a unique mechanistic and quantitative perspective on cell signaling. We work closely with theoreticians to develop predictive models and with immunologists to apply physical insights to problems in immunology.

Highlights

- Signaling in synthetic cells. We developed methods for the in vitro reconstitution of signaling molecules in lipid vesicles, the groundwork for our goal to develop communicating synthetic cells [1-3].
- Engineering signaling pathways. We pioneered the application of a hybrid in vitro-in vivo approach, interfacing cell surface models with immune cells, to understand chimeric antigen receptors (CARs), funded by a Vidi grant and in collaboration with Majzner (Stanford, US) and Fernandes (U Oxford, UK).
- Technique development. My group developed a new approach (DNA-PAINT SPT) that allows us to follow single molecules for minutes rather than seconds [4,5].

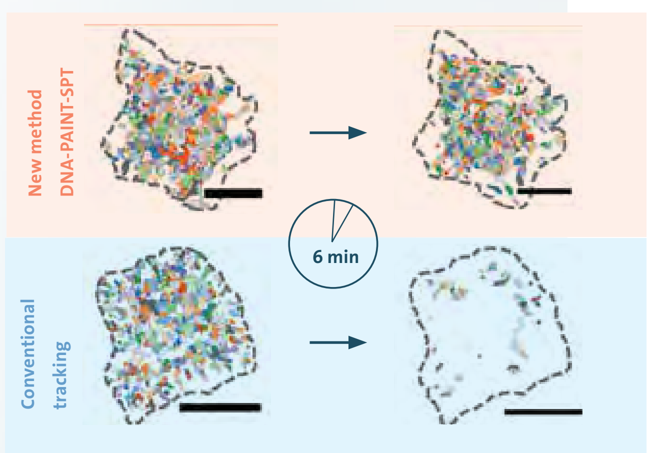
Plans

The central aim will remain to understand how cell function – information exchange between cells – emerges from its molecular constituents. We will continue to push the boundaries of in vitro reconstitution to build communicating synthetic cells, and further expand our research on signaling pathways relevant to cancer therapies. Even once molecules are known to play a pivotal role in cell function, many open questions remain at the molecular level – a gap we can often address with our biophysics approach. Using model membrane systems and single-molecule microscopy, we ultimately aim to generate findings of therapeutic value.

Key research items

1. KA Ganzinger and P. Schwille, *More from less—bottom-up reconstitution of cell biology*, Cell Sci., 132, jcs227488 (2019)
2. L. Van de Cauter et al, *Optimized cDICE for efficient reconstitution of biological systems in giant unilamellar vesicles*, ACS Synth. Biol., 10, 1690 (2021)
3. L. Van de Cauter and K.A. Ganzinger, *Design plan, parts list and protocols for our cDICE setup (lipid vesicles fabrication)*, https://github.com/Ganzinger-Lab/cDICE-plans
4. C. Niederauer, et al., *The K2: Open-source simultaneous triple-color TIRF microscope for live-cell and single-molecule imaging*, Non-research article in HardwareX, 2023 (https://doi.org/10.1016/j.ohx.2023.e00404). See also https://ganzingerlab.github.io/K2TIRF/K2TIRF/index.html
5. C. Niederauer et al., *Dual-color DNA-PAINT single-particle tracking enables extended studies of membrane protein interactions*, Nature Commun. 19;14(1):4345 (2023)

Longer visualization of single proteins (colored trajectories) in cell membranes (cell outline shown with dotted line) with DNA-PAINT-SPT technique. Scale bars 5 um.



THEORY OF BIOMOLECULAR MATTER

⟷ Bela Mulder

Our group uses the tools of statistical mechanics to study molecular structures and processes in the living cell. Whenever feasible we use analytical theory to develop minimal models that provide basic insight and subsequently perform computer simulations adding relevant biological detail and complexity, whenever required. Most of the work is performed in collaborations with experimental partners. In the past few years our main focus was on understanding the dynamics of populations of the cytoskeletal filamentous polymers actin and microtubules, and the mechanism of entropy-driven chromosome segregation and its implementation in the context of a synthetic cell.

Highlights

- A simple conceptual explanation supported by extensive computer simulations how depletion induced confinement sets the size of the bacterial nucleoid [1].
- A microtubule-based mechanism explaining the choice of cell division planes in the early plant embryo, shedding light on a long-standing problem in developmental biology [2].
- An in-depth study of how the subtle mechanisms by which the microtubule severing complex katanin modulates the structure of the plant cortical array [3].

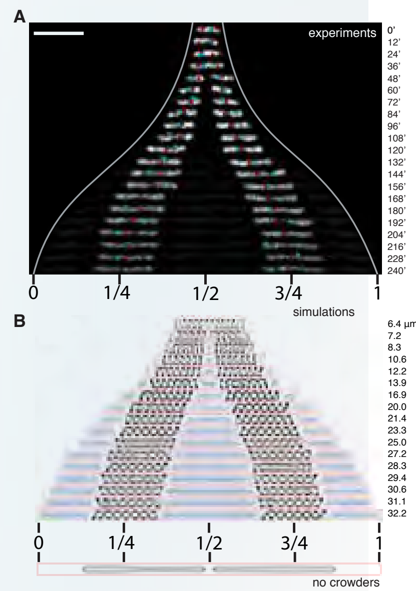
Plans

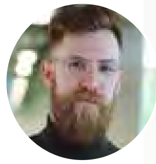
Although the group leader is formally retiring in 2023, the scientific activities of the group are continued. The work on DNA segregation will be wrapped up, and the focus of the cytoskeletal work will shift in the direction of neuronal systems. In addition, several new research lines are being developed ranging from the impact of the spatial distribution of importer channels on the uptake of nutrients by non-spherical organs/organisms, the design of multi-component colloidal using bespoke interactions mediated by engineered DNA strands, and the fundamental question of the relation between the shape of non-spherical colloidal particles and the lyotropic liquid phases they can form.

Key research items

1. E.E. Deinum, B.M. Mulder, Y. Benitez-Alfonso, *From plasmodesma geometry to effective symplasmic permeability through biophysical modelling*, Elife 8, e49000 (2019)
2. F. Wu, P. Swain, L. Kuijpers, X.Zheng, K. Felter, M. Guurink, J. Solari, S. Jun, T. S. Shimizu, D. Chaudhuri, B.M. Mulder, C. Dekker, *Cell boundary confinement sets the size and position of the E. coli chromosome*, Current Biol., 29(13): 2131-2144 (2019) [1]
3. M. Nakamura, J.J. Lindeboom, M. Saltini, B.M. Mulder, D.W. Ehrhardt, *SPR2 protects minus ends to promote severing and reorientation of plant cortical microtubule arrays*, J. Cell Biol., 217 (3), 915-927 (2018)
4. B. Chakrabortty, V. Willemsen, T. de Zeeuw, C.-Y. Liao, D. Weijers, B.M. Mulder, B. Scheres, *A Plausible Microtubule-Based Mechanism for Cell Division Orientation in Plant Embryogenesis*, Current Biol., 28(19):3031-3043 (2018) [2]
5. E.E. Deinum, S.H. Tindemans, J.J. Lindeboom, B.M. Mulder, *How selective severing by katanin promotes order in the plant cortical microtubule array*, PNAS, 114 (27), 6942-6947 (2017) [3]

A simple mechanical model of a spring loaded double piston in contact with two ideal gas reservoirs elucidates the dynamics of the depletion-mediated compaction of the bacterial chromosome in elongating cells.





SOFT ROBOTIC MATTER

⟷ Bas Overvelde

The Soft Robotic Matter group focuses on research at the crossroads of soft robotics and mechanical metamaterials. Combining computational, experimental and analytical tools, the group explores how shape, nonlinearities and feedback can be harnessed to embody intelligent behavior in mechanical systems. In particular, the group works on the design, fabrication and fundamental understanding of robotic materials that are capable of autonomously adapting to – and even harnessing – variations in their environment. Along these lines, the group aims to uncover principles that help us understand how such nonlinearities and feedback can bring about complex – but useful – behavior in soft actuated systems.

Highlights

- We developed a soft hysteretic valve that can be integrated in soft fluidic circuits to achieve pulsatile and sequential activation of soft robots and devices [1].
- We built robotic matter, a physical platform to study distributed algorithms to implement learning in (material) systems with limited computational power [3].
- We mapped the occurrence of elastic multistability in prismatic metamaterials by exploring the complex energy landscape through local actuation [4].
- We worked with artists and designers to showcase our research on prismatic metamaterials to the general public [5].

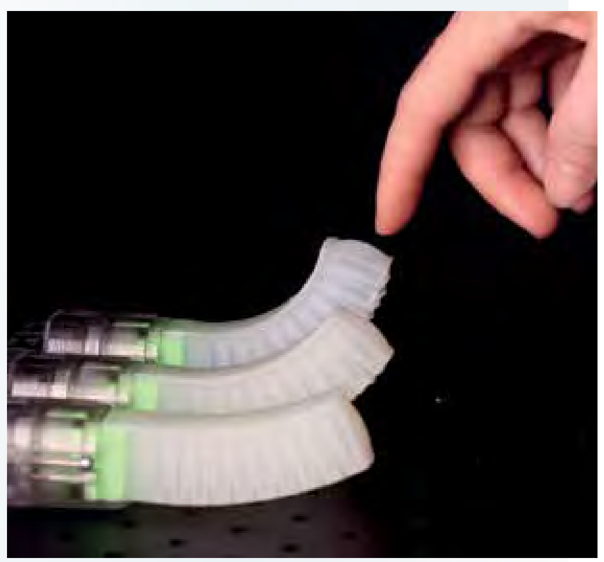
Plans

We will explore new ways in which intelligence can be embodied in soft robotic devices, with the goal of making soft robots and materials that operate autonomously. We aim to not only demonstrate such principles at the macroscale, but also explore the fact that many of the proposed underlying principles are scale-independent, such that they can be applied in micro- and nanoscale (robotic) systems.
Moreover, we aim to connect this fundamental scientific research with application-driven research, specifically in medical and agri-food applications, in order to have direct societal impact.

Key research items

1. L.C. van Laake, J. De Vries, S. Malek Kani and J.T.B. Overvelde, *A Fluidic Relaxation Oscillator for Reprogrammable Sequential Actuation in Soft Robots*, Matter, 5(9), 2898-2917 (2022)
2. A. Vis, M. Arfaee, H. Khambati, M.S. Slaughter, J.F. Gummert, J.T.B. Overvelde and J. Kluin, *The Ongoing Quest for the First Total Artificial Heart as Destination Therapy*, Nat. Rev. Cardiol. 19, 813-828 (2022)
3. G. Oliveri, L.C. van Laake, C. Carissimo, C. Miette and J.T.B. Overvelde, *Decentralized Reinforced Learning in Soft Robotic Matter,* PNAS, 118(21), e2017015118: 1-6 (2021)
4. A. Iniguez-Rabago, Y. Li and J.T.B. Overvelde, *Exploring Multistability in Prismatic Metamaterials through Local Actuation*, Nature Commun., 10 5577:1-10 (2019)
5. "*Edge of Chaos*", Art exhibition on world tour at WoeLab in Lomé TG, La Gaîté Lyrique in Paris FR; Cinekid in Amsterdam NL; KIKK Festival in Namur BE (Dec 2017 - Jan 2019)

Sequential activation of soft actuators using hysteretic valves (credits: Alberto Comoretto).



SELF-ORGANIZING MATTER

⟷ Wim Noorduin

The Self-Organizing Matter group focuses on the dynamic interplay between chemical reactions and crystallization phenomena to control the emergence of complexity in the solid state. In particular, we aim to design physical/chemical schemes to self-organize complex materials and develop new chiral amplification methods for the synthesis of enantiomerically pure building blocks. Current research includes the development of new routes to control crystallization, material composition, shape and hierarchical organization of mineralized structures and the design of physical/chemical feedback mechanisms to self-correct and amplify the emergence of complexity.

Highlights

- We demonstrated new chiral amplification mechanisms and developed practical synthesis routes towards a wide range of molecules including block buster pharmaceuticals.
- We introduced light-controlled steering of self-assembly following user-defined light-patterns.
- We developed shape-preserving ion exchange reactions to more than 50 chemical compounds including catalysts and semiconductors, in addition resulting in the founding of the startup company LumetalliX.
- We combined reaction/diffusion processes with mechanically mediated transport phenomena to achieve simple and scalable pattern formation of complex motifs that can serve for instance as for optomechanical sensors and tunable diffraction grating.

Plans

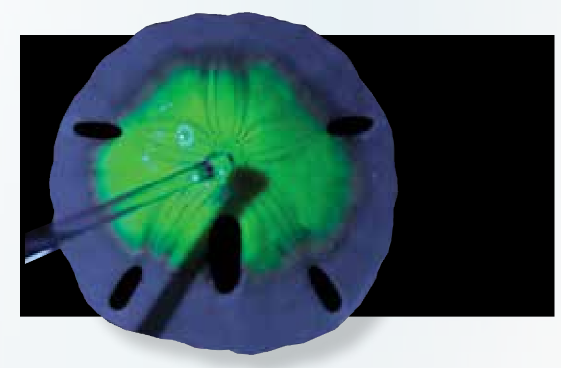
Future research will be aimed at the following two directions:

1. We aim to develop new chiral amplification mechanisms: in particular by exploiting non-equilibrium conditions. A breakthrough in this field would open new routes to important molecular building blocks and reveal unexplored mechanism for manipulating crystallizing materials.
2. We will pursue the development of new light-controlled reactions to steer self-assembly processes with spatiotemporal control and develop new mechanochemical feedback mechanisms to create complexity according to exact designs. Ultimately, these results may be exploited for developing new materials with advanced next generation functionalities.

Key research items

1. S.W. van Dongen, I. Ahlal, M. Leeman, B. Kaptein, R.M. Kellogg, I. Baglai and W.L. Noorduin, *Chiral Amplification through the Interplay of Racemizing Conditions and Asymmetric Crystal Growth*, J. Am. Chem. Soc., 145, 436 (2023)
2. C. van Campenhout, D. ten Napel, M. van Hecke and W.L. Noorduin, *Rapid formation of uniformly layered materials by coupling reaction–diffusion processes with mechanical responsiveness*, PNAS, 119, e2123156119 (2022)
3. M.H. Bistervels, M. Kamp, H. Schoenmaker, A.M. Brouwer and W.L. Noorduin, *Light-controlled nucleation and shaping of self-assembling nanocomposites*, Adv. Mater., 34, 210784 (2022)
4. L. Helmbrecht and W.L. Noorduin, *Method for detecting lead*, EP Patent Application EP21166957, filed April 6 (2021)
5. H.C. Hendrikse, A. van der Weijden, M. Ronda-Lloret, T. Yang, R. Bliem, N. Raveendran Shiju, M. van Hecke, L. Li and W.L. Noorduin, *Shape-Preserving Chemical Conversion of Architected Nanocomposites*, Adv. Mater., 32, 2003999 (2020)

Conversion of a sand dollar skeleton into a green light-emitting perovskite.



NANOSCALE SOLAR CELLS

⟷ Erik Garnett

We specialize in the synthesis, characterization and integration of nanomaterials into solar cells, LEDs and light-driven chemical reactors. We also develop advanced instrumentation with unique capabilities worldwide to interrogate the properties, efficiency limits and losses of our novel energy conversion materials and device architectures. Our group members have very diverse backgrounds – from synthetic chemistry to optics and materials engineering – and we also actively scout women and underrepresented minorities (so far 38% of those hired have been women and 48% foreigners with 20 different nationalities represented). Our driving mission is to accelerate the clean energy transition to help mitigate the effects of climate change.

Highlights

- Co-development with EDAX and Amsterdam Scientific Instruments of a direct electron detector for electron backscatter diffraction (EBSD) with a 6000x improvement in signal compared to state-of-the-art [1], which allowed for nanoscale crystallographic mapping of beam-sensitive halide perovskite films [2].
- Demonstrated that tuning the excitation wavelength can lead to completely different reaction mechanisms and products in plasmonic nanoreactors [3]
- Simulated that antennas made from a non-standard plasmonic metals with high electron-phonon coupling and low thermal conductivity can provide unprecedented thermal gradients in space and time (>10K/nm and >500K/ps) [4]
- Demonstrated material learning in mixed halide perovskite films for self-optimized directional emission [5]

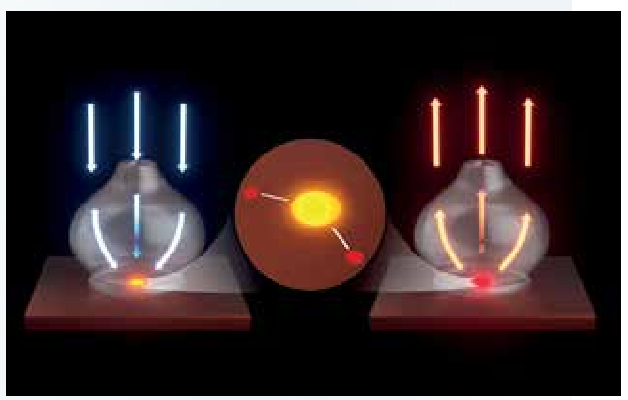
Plans

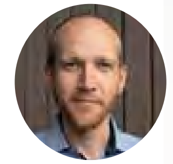
We will develop in operando EBSD to study degradation of halide perovskite films under light and electrical bias. We will use the extreme thermal gradients and wavelength programmable reactions offered by light-driven chemistry to improve CO_2 reduction. Finally, we will expand our efforts on material learning to make a device that can efficiently collimate and focus diffuse light to very high intensity.

Key research items

1. *World's first commercial direct electron detector for EBSD* (EDAX Clarity, https://www.edax.com/news-events/amolf)
2. G.W.P Adhyaksa, S Brittman, H Abolins, A Lof, X Li, J.D Keelor, Y Luo, T Duevski, R.M.A Heeren, S.R Ellis, D.P Fenning and E.C Garnett, *Understanding detrimental and beneficial grain boundary effects in halide perovskites*, Adv. Mater. 30, 1804792 (2018)
3. E. Oksenberg, I. Shlesinger, A. Xomalis, A. Baldi, J.J. Baumberg, A.F. Koenderink and E.C. Garnett, *Energy-resolved plasmonic chemistry in individual nanoreactors*, Nature Nanotechnology 16, 1378 (2021)
4. S.H.C. Askes and E.C. Garnett, *Ultrafast Thermal Imprinting of Plasmonic Hotspots*, Adv. Mater. 33, 2105192 (2021)
5. J.S. van der Burgt, F. Scalerandi, J.J. de Boer, S.A. Rigter and E.C. Garnett, *Perovskite Plasticity: Exploiting Instability for Self-Optimized Performance*, Adv. Funct. Mater. 32, 2203771 (2022)

Material learning in mixed halide perovskite thin films demonstrated by a nanophotonic lens focusing a training stimulus (collimated excitation) to a point where the high intensity nucleates local emitters, which are self-aligned to the focal point and therefore direct emission back to (mimic) the source.





HYBRID SOLAR CELLS

⟷ Bruno Ehrler

The Hybrid Solar Cell group develops the next generation of solar cells using hybrid materials like metal halide perovskites. We develop a deep understanding of material properties and their impact on device performance.
Our focus is on improving the stability of perovskite solar cells, addressing ion migration as a key challenge. We have developed unique techniques to study and suppress ion migration, and explore new applications for ion migration. By combining the excellent semiconducting properties of perovskites with mobile ions, we develop devices for memory applications like artificial synapses.

Highlights

- We demonstrated the transfer of triplet excitons from tetracene into silicon, a technique that could double the photocurrent from high-energy photons in a solar cell.
- We developed a new technique to study ion migration, the main factor making perovskite solar cells unstable and used it to develop strategies that reduce ion migration in perovskite solar cells.
- We invented a direct patterning method for semiconductor quantum dots using photolithography and electron-beam lithography.
- We developed an artificial synapse from halide perovskite with the lowest energy consumption reported to date.

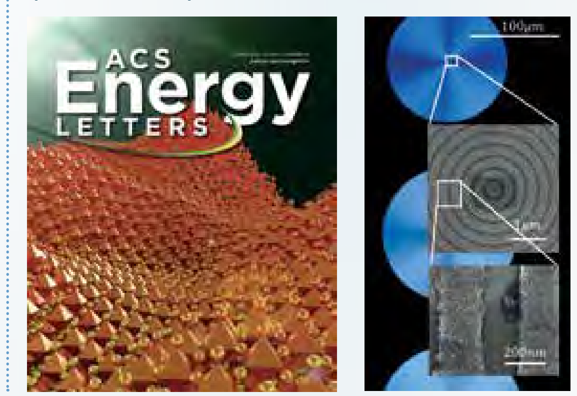
Plans

Ions are the key in determining perovskite device operation and stability. We will use simulations in combination with advanced impedance measurements to understand the role ions play for devices. With lateral devices and XRF measurements we quantitatively study which ions migrate, and how fast. The resulting structural change is measured using EBSD. With this comprehensive approach, we can determine ion characteristics and their effects on optical and structural properties of the material and devices. We use this knowledge to stabilize solar cells and expand our research to memristor devices for artificial neural networks.

Key research items

1. M.H. Futscher, J.M. Lee, L. McGovern, L.A. Muscarella, T. Wang, M.I. Haider, A. Fakharuddin, L. Schmidt-Mende and B. Ehrler, *Quantification of ion migration in CH3NH3PbI3 perovskite solar cells by transient capacitance measurements*, Mater. Horiz. 6, 1497-1503 (2019)
2. L. McGovern, M.H. Futscher, L.A. Muscarella and B. Ehrler, *Understanding the Stability of MAPbBr3 versus MAPbI3: Suppression of Methylammonium Migration and Reduction of Halide Migration*, J. Phys. Chem. Lett. 11, 17, 7127–7132 (2020)
3. C.D. Dieleman, W. Ding, L. Wu, N. Thakur, I. Bespalov, B. Daiber, Y. Ekinci, S. Castellanos and B. Ehrler, *Universal direct patterning of colloidal quantum dots by (extreme) ultraviolet and electron beam lithography*, Nanoscale 12, 11306-11316 (2020)
4. L.A. Muscarella, E.M. Hutter, F. Wittmann, Y.W. Woo, Y.-K. Jung, L. McGovern, J. Versluis, A. Walsh, H.J. Bakker and B. Ehrler, *Lattice Compression Increases the Activation Barrier for Phase Segregation in Mixed-Halide Perovskites*, ACS Energy Lett. 5, 10, 3152–3158 (2020)
5. B. Daiber, S. Maiti, S.M. Ferro, J. Bodin, A.F.J. van den Boom, S.L. Luxembourg, S. Kinge, S.P. Pujari, H. Zuilhof, L.D.A. Siebbeles, and B. Ehrler, *Change in tetracene polymorphism facilitates triplet transfer in singlet fission-sensitized silicon solar cells*, J. Phys. Chem. Lett. 11, 20, 8703–8709 (2020)

(Left) Illustration of the effect of strain on perovskite semiconductors. (Right) Patterning of semiconductor quantum dots into photonic structures.



PHOTONIC MATERIALS

⟷ Albert Polman

The Photonic Materials group designs and fabricates optical metasurfaces for photovoltaic energy conversion to increase light absorption and photovoltaic energy conversion beyond current limits. In parallel, we develop optical metasurfaces for analog optical information processing. To characterize nanostructured surfaces we study electron-light-matter interaction using time-resolved cathodoluminescence spectroscopy. Our overarching goal is to develop fundamental insights that help speed up the energy transition, to realize novel concepts for low-power opto-electronics, and to demonstrate novel analysis and metrology tools for materials research.

Highlights

- **Photovoltaics:** Integrated near-field/far-field scattering matrix formalism creates (with Fraunhofer ISE) record Si-based multi-junction solar cell (36.1%).
- **Cathodoluminescence:** Ultrafast time-resolved photoemission electron microscope and first demonstration of electron-pump/optical-probe spectroscopy.
- **Metamaterials:** Silicon metasurfaces solve an integral equation using visible light.
- **Startup:** cathodoluminescence spectroscopy inventions created sales by Delmic (co-funded by us) that added 16 M€ to the Dutch economy.
- **SolarNL:** National research, innovation and industrial development program for PV industry in NL and EU (312 M€ grant).

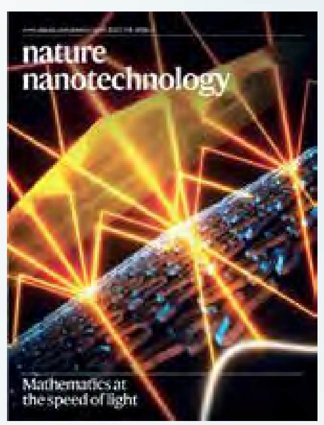
Plans

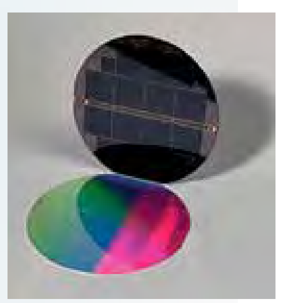
We will further develop ultrafast cathodoluminescence microscopy to study carrier dynamics and nanoscale optical phenomena in opto-electronic materials. We aim to develop the microscope into a quantum instrument in which electron wavepackets are tailored in space and time to enable novel materials spectroscopies. Using 2D materials, we will develop tunable optical metasurfaces for optical processing and exploit them in advanced geometries including optical neural networks. We will use our expertise in microscopy and optical metasurfaces to develop perovskite-silicon solar cells with ultrahigh efficiency. In parallel, we will carry out the SolarNL plan to grow the photovoltaics industry in NL and EU.

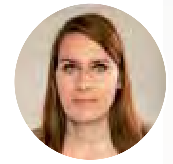
Key research items

1. A. Cordaro, V. Nikkhah, A. Alu, N. Engheta, and A. Polman, *Solving integral equations in free space with inverse-designed ultrathin optical metagratings*, Nature Nanotechn. 18, 365 (2023)
2. N. Schilder, H. Agrawal, E.C. Garnett, and A. Polman, *Phase-resolved surface plasmon scattering probed by cathodoluminescence holography*, ACS Photon. 7, 1476 (2020)
3. V. Neder, S.L. Luxembourg, and A. Polman, *Efficient colored silicon solar modules using integrated resonant dielectric nanoscatterers*, Appl. Phys. Lett. 111, 073902 (2017)
4. *National Agenda Materials: Accelerating materials technologies:* establishment of national Agenda for materials research. See: https://materialennl-platform.nl/.
5. SolarNL: *Circular integrated high-efficiency solar panels:* establishment of a national research, innovation and industrial plan to start a photovoltaics industry in the Netherlands and Europe (312 M€ grant). See: https://www.solarnl.eu.

Multiple light scattering from optical metasurfaces. (Left) Silicon metasurface that solves a Fredholm integral equation using light. (Right) light trapping metasurface backcontact results in record photovoltaic conversion efficiency for Si-based multi-junction solar cells of 36.1%.







HYBRID NANOSYSTEMS

⟷ Wiebke Albrecht (started in 2021)

We investigate the interaction between different components in complex hybrid nanostructures. For instance, we want to understand the interplay of morphology and underlying charge and energy transfer processes in metal-semiconductor hybrid nanosystems. We furthermore explore new concepts to create hybrid architectures and to locally modify interactions by external stimuli. We also analyze the stability of nanoobjects and explore routes to enhance it. In this way, we hope to make use of synergistic properties in a smart and reliable way, specifically tailored for applications in solar energy harvesting and quantum information processing. Our research combines advanced electron microscopy and single particle optical and time-resolved spectroscopy, for which we constantly develop new techniques and workflows.

Highlights

- Demonstrated that pulsed laser excitation is a powerful tool to engineer the morphology and structure of (plasmonic) nanomaterials [1]. We unravelled the ultrafast dynamics of atomic restructuring in gold nanorods after femtosecond laser excitation [4].
- We built a confocal setup that combines scattering and (time-resolved) luminescence and created a workflow for correlative measurements combining electron microscopy and optical spectroscopy (see Figure). We also highlighted the necessity of performing such correlative measurements [3] and demonstrated new insights into nano-chirality obtained in a correlative manner [2].
- By in situ electron tomography experiments we determined design principle for thermally stable plasmonic nanoheaters [5].

Plans

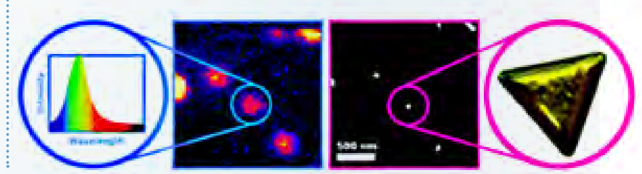
We want to use optical spectroscopy to determine the morphology of nanoobjects on the nanometer scale with the help of machine learning. We also want to combine optical excitation of nanomaterials and advanced electron microscopy in a new and unique infrastructure at AMOLF. In addition, we will use spectroscopic tools inside the electron microscope to measure the spatial and temporal temperature profiles of catalytically relevant nanoheaters. We will introduce external stimuli like heat and gases inside the transmission electron microscope and our home-built optical microscope to assess the stability of these nanoheaters *in situ*.

Key research items

1. G. González-Rubio, and W. Albrecht, *Engineering of plasmonic gold nanocrystals through pulsed laser irradiation*, Applied Physics Letters 121, 200502 (2022)
2. P. Spaeth, S. Adhikari, W. Heyvaert, X. Zhuo, I. García, L. M. Liz-Marzán, S. Bals, M. Orrit, and W. Albrecht, *Photothermal Circular Dichroism Measurements of Single Chiral Gold Nanoparticles Correlated with Electron Tomography*, ACS Photonics 9, 3995-4004 (2022)
3. M. Dieperink, F. Scalerandi, and W. Albrecht, *Correlating structure, morphology and properties of metal nanostructures by combining single-particle optical spectroscopy and electron microscopy*, Nanoscale 14, 7460-7472 (2022)
4. W. Albrecht, E. Arslan Irmak, T. Altantzis, A. Pedrazo-Tardajos, A. Skorikov, T.-S. Deng, J.E.S. van der Hoeven, A. van Blaaderen, S. Van Aert, and S. Bals, 3D *Atomic-Scale Dynamics of Laser-Light-Induced Restructuring of Nanoparticles Unraveled by Electron Tomography*, Advanced Materials 33, 2100972 (2021)*
5. W. Albrecht, E. Bladt, H. Vanrompay, J.D. Smith, S.E. Skrabalak, and S. Bals, *Thermal Stability of Gold/Palladium Octopods Studied in Situ in 3D: Understanding Design Rules for Thermally Stable Metal Nanoparticles*, ACS Nano 13, 6522-6530 (2019)*

*pre-AMOLF

Combining optical spectroscopy and electron tomography on the same nanoparticle.



3D PHOTOVOLTAICS

⟷ Esther Alarcón Lladó

The 3DPV group focuses on the manipulation of light and matter at the nanoscale with nanophotonic and nanoelectrochemistry concepts, and vice versa. With these, we develop new energy conversion concepts with higher efficiency with less quantity and more cost-effective materials. We generate strategies for the rational designing of photonic structures that maximize light absorption in ultra-thin PV architectures. In parallel, we exploit nanoelectrochemical methods to control where and when reactions take place. We exploit this control to introduce new synthesis pathways for PV materials (IIII-V, perovskites and metals) in line with circular chemistry, as well as to underpin the key physico-chemical properties of solid-liquid interfaces that rule charge transport, transfer and conversion from electrical to chemical energy.

Highlights

- Demonstrated the highest light absorption in ultra-thin Si films from rationally-designed nanopatterns with hyperuniform disorder [1]
- Developed a methodology for imaging and understanding light extinction in 3D along dielectric nanowires [2]
- Demonstrated the manipulation of charge transfer at liquid-electrode interface with controlled nanoscale resolution using scanning probes [3]
- Built new combinatorial scanning probe microscopy tools for in-situ photo-electro-chemical and photo-conductivity characterization [4]

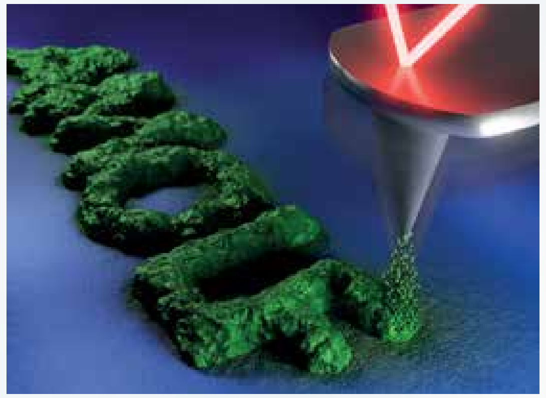
Plans

Building on our high degree of spatio-temporal control over light and ions in solution, we will now explore their synergistic interplay, enabling new types of light-controlled material growth and chemistry at the nanoscale, for more efficient PV and electro-catalysis. We will further develop distinctive in-situ/operando scanning probe microscopes and use them for the investigation of both light-driven (electro)chemical phenomena at photonic/plasmonic nanoparticles, as well as charge transport through interfaces in solar cell devices.

Key research items

1. N. Tavakoli, R. Spalding, A. Lambertz, P. Koppejan, G. Gkantzounis, C. Wan, R. Röhrich, E. Kontoleta, A. F. Koenderink, R. Sapienza, M. Florescu, E. Alarcon-Llado, *Over 65% sunlight absorption in a 1 µm Si slab with hyperuniform texture*, ACS Photonics 9, 1206 (2022)
2. R.S. Federiksen, F. Matteini, H. Potts, G. Tutuncuoglu, K. Martinez, A. Fontcuberta i Morral, E. Alarcon-Llado, *Visual understanding of light absorption and waveguiding in standing nanowires with 3D fluorescence confocal microscopy*, ACS Photonics 4, 2235 (2017)
3. M. Aarts thesis, *Interphase: On Nanofabrication and Electrical Double Layer Dynamics with Electrochemical Scanning Probes*, University of Amsterdam, January 2021
4. F. Podjaski, D. Weber, S. Zhang, L. Diehl, R. Eger, V. Duppel, E. Alarcon-Llado, G. Richter, F. Haase, A. Fontcuberta i Morral, C. Scheu, B.V. Lotsch, *Rational strain engineering in layered oxides for highly efficient hydrogen evolution catalysis in acidic media*, Nature Catalysis 3, 55 (2019)
5. L.S.D. Antony, G. Grimaldi, A. Van der Weijden, I. Schuringa, J. Borchert, B. Ehrler, W.L. Noorduin, E. Alarcon-Llado, *The role of Pb oxidation state of the precursor in the formation of 2D perovskite microplates*, Nanoscale 15, 6285 (2023)

Artist impression on probe-driven nanoscale electrochemical deposition (credits: Laura Canil).



ULTRAFAST SPECTROSCOPY

⟷ Huib Bakker

We aim to understand the structural and dynamical properties of dynamical complex aqueous systems, and how these properties are governed by the interactions on the molecular scale, in particular the interactions with water molecules. These systems include proteins in water, hydrogels and membranes, and reactive systems like electrochemical systems and water nanodroplets and water nanochannels containing protons. To this purpose we study the structural dynamics of water molecules and of molecules interacting with water with femtosecond (two-dimensional) vibrational spectroscopy, surface sum-frequency generation and GHz-THz dielectric relaxation spectroscopy.

Highlights

- Adding the neutral surfactant C12E6 to water enhances the hydrogen bond strength of water close to the surface, and creates a ~3 nm deep interface with a large electric field of ~1 V/nm.
- In water nanodroplets with a diameter of ~7 nm, proton hopping is 4 times slower than in bulk water, for droplets <4 nm, proton hopping is even more than 10 times slower.
- The hyperactive anti-freeze protein RmAFP retains its hydrating water molecules upon adsorption to the ice surface with a hydrogen-bond structure different from the ice surface, thereby inhibiting the insertion of water layers in between the protein and the ice surface.
- The surface of water ice is covered with a quasi-liquid water layer that persists down to 245 K, far below the melting point.

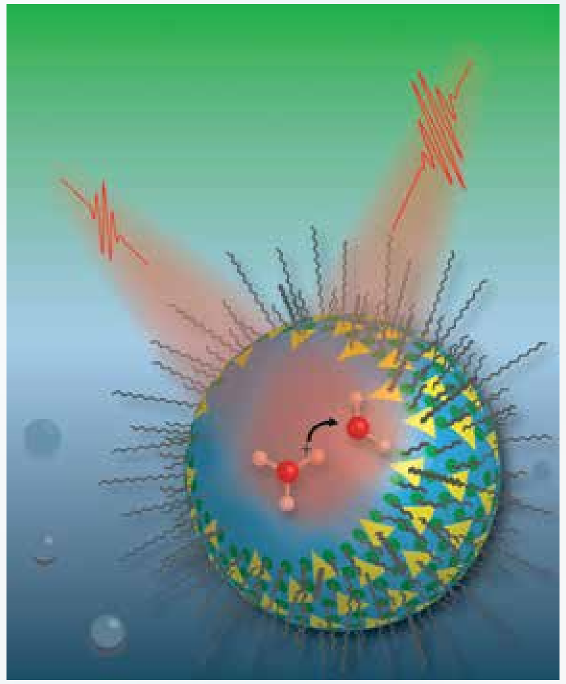
Plans

In the coming years we will study the molecular mechanism of proton transfer reactions at the surfaces of water and ice and in nanoconfined water. We will also study the role of water in the self-assembly and visco-elastic properties of supramolecular hydrogels, and the molecular-scale properties of electrolyte solutions near electrode surfaces in the electrochemical reduction of CO_2, and in the electrochemical generation of H_2. To probe the ultrafast structural dynamics at surfaces, we will develop time-resolved surface sum-frequency generation.

Key research items

1. B. Antalicz, J. Versluis and H.J. Bakker, *Observing Aqueous Proton-Uptake Reactions Triggered by Light*, J. Am. Chem. Soc. 145, (12), 6682-6690 (2023)
2. C.J. Moll, J. Versluis and H.J. Bakker, *Direct Evidence for a Surface and Bulk Specific Response in the Sum-Frequency Generation Spectrum of the Water Bend Vibration*, Phys.Rev.Lett. 127, (11), 116001: 1-6 (2021)
3. O.O. Sofronov and H.J. Bakker, *Slow Proton Transfer in Nanoconfined Water*, ACS Cent. Sci. 6, (7), 1150-1158 (2020)
4. G. Giubertoni, O.O. Sofronov and H.J. Bakker, *Observation of Distinct Carboxylic Acid Conformers in Aqueous Solution*, J. Phys. Chem. Lett. 10, (12), 3217-3222 (2019)
5. W.J. Smit and H.J. Bakker, *The surface of ice is like supercooled liquid water*, Angew. Chem. Int. Ed. 56, (49), 15540-15544 (2017)

Schematic picture of a femtosecond mid-infrared study of proton transfer of in water nanodroplets covered with surfactants and embedded in an apolar matrix.



RESONANT NANOPHOTONICS

⟷ Femius Koenderink

We develop resonant optical metasurface and nano-antenna motifs for controlling light-matter interaction, and for realizing new types of information processing and sensing schemes. Key concepts are precise spatial and spectral control of local density of optical states to manipulate emission, amplification, non-linear conversion and inelastic scattering (SERS/molecular optomechanics) of light, and also full control and measurement of far field information encoded in vector, amplitude and phase properties of light. Societal impact domains include solid-state lighting, wafer metrology, SERS/IR and chiral spectroscopy, and energy-efficient information processing.

Highlights

- We observed that optical bound states in the continuum that have no symmetry protection are nonetheless protected by far-field polarization topology [2].
- We developed plasmonic-photonic resonators with tunable high-Q resonances yet record confinement (Q/V ~ $(\lambda^3/10^6)$), and demonstrated their use for sideband-resolved molecular optomechanics [4].
- Our high-NA, fully polarimetrically and phase-resolved single nano-object radiation microscopy enables from foundational to applied research, including on singular light generated by plasmonic-photonic resonators, metasurface mathematical operations, and diffraction-based super-resolution [3].
- We disseminate know-how as Open Source code, e.g., for unbiased Bayesian-inference based photon-by-photon analysis of single-emitter intermittency photophysics [5], and for light-matter engineering design relevant for LEDs, PV, and enantioselective microscopy.

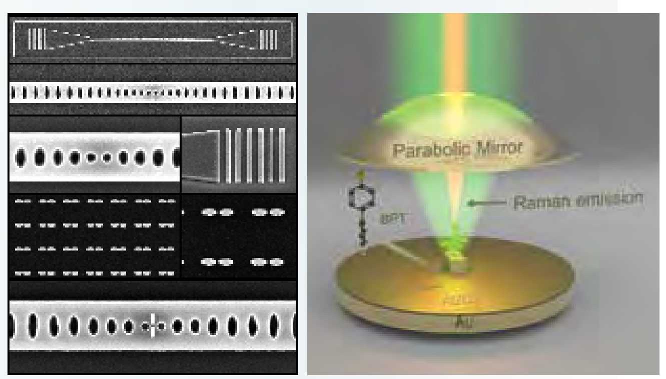
Plans

On the crossroads of metasurfaces, wavefront-shaping, and computational imaging we will impact two main research arenas: metrology and imaging in complex systems (e.g. wafer metrology) with linear and nonlinear nanophotonics, and metaphotonics for information processing. Here we envision stacks of reconfigurable, nonlinear and trainable metaphotonics to process and classify analog data encoded in 2D wavefronts, and that can ultimately interface 2D to in-plane optoelectronics. Regarding light-matter interaction, we will develop photonic reservoir engineering (generalized spatial, spectral and vector LDOS control) for coherent molecular optomechanics, nonlinear light generation, and chiral nanophotonics.

Key research items

1. A.F. Koenderink, *Single-Photon Nano-Antennas (Perspective)*, ACS Photonics 4, 710–722, (2017) [most read ACS Photonics paper in 2017]
2. H.M. Doeleman, F. Monticone, W. den Hollander, A. Alù and A.F. Koenderink, Experimental Observation of a Polarization Vortex at an Optical Bound State in the Continuum, Nature Photonics 12, 397–401, (2018) [winner 2019 thesis award]
3. R. Röhrich, C. Hoekmeijer, C.I. Osorio and A.F. Koenderink, *Quantitative Single Nano-Antenna Far Fields through Interferometric and Polarimetric k-Space Microscopy*, Light: Science and Applications 7, 65, (2018) [nucleus of ARCNL-ASML collaboration]
4. I. Shlesinger, I.M. Palstra and A.F. Koenderink, *Integrated Sideband-Resolved SERS with a Dimer on a Nanobeam Hybrid*, Phys. Rev. Lett. 130, 016901 (2022/2023)
5. I.M. Palstra and A.F. Koenderink, *A Python Toolbox for Unbiased Statistical Analysis of Fluorescence Intermittency of Multi-Level Emitters*, J. Phys. Chem. C 125, 12050–12060, (2021) - Open Code project (DOI: 10.5281/zenodo.4557226).

Two concepts for hybrid plasmonic-photonic resonators – lithographic (left), and based on the nanocube-on-mirror geometry, in a Fabry-Perot microcavity (right).



PHOTONIC FORCES

⟷ Ewold Verhagen

The Photonic Forces group studies light-matter interactions at the nanoscale, in particular the coupling between light and nanomechanical motion in optomechanical systems. We seek to understand how the behavior of light and sound in nanoscale devices is governed by fundamental principles such as spatiotemporal symmetries and quantum mechanics. We explore how suitable system design and control over light-matter interactions can induce unusual phenomena for photons and phonons such as nonreciprocity and topological states of sound and light. Using such insights, we challenge the conventional limits to nanophotonic and nanomechanical functionality, in application domains from quantum sensing and metrology to communication.

Highlights 2017-2022

- Demonstrated optical nonreciprocity in optomechanical systems, including magnet-free circulation and optomechanical birefringence [5].
- Demonstrated that strong pulsed, projective optical measurements of a mechanical resonator can be brought to the quantum regime [4].
- Observed topologically protected flow of light in silicon photonic crystals [3].
- Proposed and demonstrated effective magnetic fields for phonon transport in nanomechanical networks through radiation pressure control, and discovered gauge fields that control non-Hermitian dynamics [1,2].

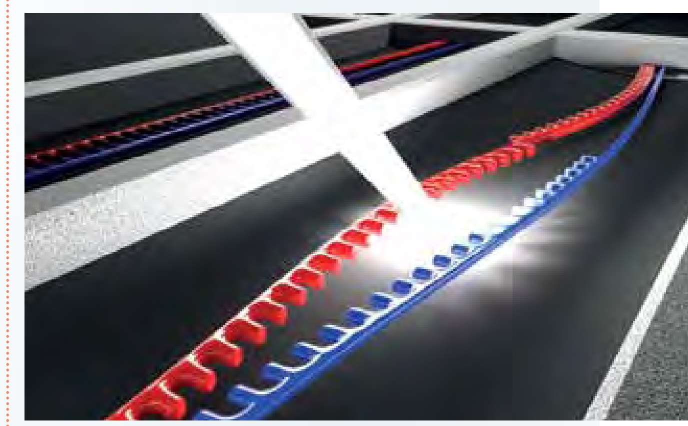
Plans

The group's research in the next years comprises two synergetic main thrusts: On the one hand, we challenge the conventional limits of mechanical quantum metrology through strong, projective optomechanical measurements. We study how quantum squeezing and entanglement can be used to boost sensing performance, and develop high-resolution chip-based optomechanical sensors. On the other hand, we explore exotic states of light and sound that in metamaterials where temporal and spatial symmetries can be controlled through nanophotonic design and active radiation pressure control. This includes nonreciprocal behavior as well as non-Hermitian and nonlinear topological bosonic phases, with applications from sensing to communication.

Key research items

1. J. del Pino, J.J. Slim and E. Verhagen, *Non-Hermitian chiral phononics through optomechanically-induced squeezing*, Nature 606, 82 (2022)
2. J.P. Mathew, J. del Pino and E. Verhagen, *Synthetic gauge fields for phonon transport in a nano-optomechanical system*, Nature Nanotechnology 15, 198 (2020)
3. N. Parappurath, F. Alpeggiani, L. Kuipers and E. Verhagen, *Direct observation of topological edge states in silicon photonic crystals: Spin, dispersion, and chiral routing*, Science Advances 6, eaaw4137 (2020)
4. J.T. Muhonen, G.R. La Gala, R. Leijssen and E. Verhagen, *State preparation and tomography of a nanomechanical resonator with fast light pulses*, Physical Review Letters 123, 113601 (2019)
5. F. Ruesink, J.P. Mathew, M.-A. Miri, A. Alù and E. Verhagen, *Optical circulation in a multimode optomechanical resonator*, Nature Communications 9, 1798 (2018)

Nanoscale optomechanical system, where radiation pressure control fields induce nonreciprocal and topological states states of sound.



INTERACTING PHOTONS

⟷ Said Rahimzadeh Kalaleh Rodriguez

We investigate optical systems where nonlinearity, noise, memory effects, and dissipation can synergistically enhance the transport of energy and information in light. We are mainly interested in fundamental physics questions with technological relevance, such as: What is the optimal strategy for detecting a weak optical signal in a noisy environment? What are the fundamental limits to the energy efficiency, speed, and precision of optical devices? To address these and related questions, we develop and test new ideas that draw inspiration from recent trends in photonics, nonlinear & statistical physics, quantum science, condensed matter physics, thermodynamics, materials science, information theory, and complexity science.

Highlights

- We discovered a universal scaling law for the dynamic hysteresis of systems with memory.
- We demonstrated how memory effects can make stochastic resonance (noise-assisted signal amplification) extremely broadband.
- We introduced nonlinear optical sensing strategies with surprising advantages over linear strategies. Examples of such advantages include noise-enhanced sensitivity, and overcoming the trade-off between measurement speed and precision.
- The first PhD student of the group, Dr. Zhoumuyan Geng, obtained his PhD from the University of Amsterdam in 2022.

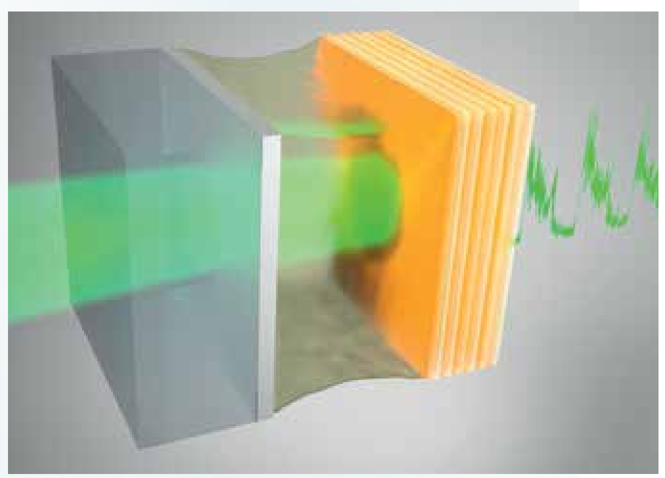
Plans

Consider an optical device processing information, like a switch or a sensor. What are the fundamental limits to its energy efficiency, speed, and precision, in the inevitable presence of noise? Surprisingly, there is currently no way to answer that question which is vital to the future of many optical technologies. One of our main goals for the coming years is to develop the methods necessary to answer that question. To achieve that, we will combine ideas from information theory, thermodynamics, and optics, in order treat optical devices as information processing machines subject to thermodynamic constraints. We envision optical experiments that will test our ability to treat laser-driven resonators as optical engines, and to use the framework of information thermodynamics to optimize their performance in information-processing operations.

Key research items

1. K.J.H. Peters, J. Busink, P. Ackermans, K.G. Cognée and S.R.K. Rodriguez, *Scalar potentials for light in a cavity*, Phys. Rev. Res. 5, 013154 (2023)
2. K.J.H. Peters and S.R.K. Rodriguez, *Exceptional precision of a nonlinear optical sensor at a square-root singularity*, Phys. Rev. Lett. 129, 013901 (2022)
3. B. Garbin, A. Giraldo, K.J.H. Peters, N.G.R. Broderick, A. Spakman, F. Raineri, A. Levenson, S.R.K. Rodriguez, B. Krauskopf and A. Yacomotti, *Spontaneous symmetry breaking in a coherently driven nanophotonic Bose-Hubbard dimer*, Phys. Rev. Lett. 128, 053901 (2022)
4. K.J.H. Peters, Z. Geng, A.A.P. Trichet, K. Malmir, J.M. Smith and S.R.K. Rodriguez, *Extremely broadband stochastic resonance of light and enhanced energy harvesting enabled by memory effects in the nonlinear response*, Phys. Rev. Lett. 126, 213901 (2021)
5. Z. Geng, K.J.H. Peters, A.A.P. Trichet, K. Malmir, R. Kolkowski, J.M. Smith and S.R.K. Rodriguez, *Universal scaling in the dynamic hysteresis, and Non-Markovian dynamics, of a tunable optical cavity*, Phys. Rev. Lett. 124, 153603 (2020)

A laser-driven oil-filled cavity has memory in its nonlinear optical response. The future state of the system depends not only on the present, but on its entire past. Using this system, we discovered a universal scaling law [5], and an extremely enhanced bandwidth for noise-assisted signal amplification [4].



PHYSICS OF BEHAVIOR

⟷ Tom Shimizu

Research in the Physics of Behavior group aims to achieve a physical understanding of biological behavior by connecting dynamics across scales. Our experiments quantify dynamics at multiple levels of organization, from molecules to whole organisms. We develop theoretical and computational frameworks to link phenomena at different scales. Understanding is achieved when we succeed in reducing higher dimensional data to interpretable lower-dimensional descriptions. When those descriptions have predictive value over higher-dimensional dynamics, we call the understanding mechanistic. Ultimately, we seek design principles that explain nature and inspire applications by studying those mechanisms in terms of functional causes and consequences.

Highlights

- A random-walk model of nematode motility [1]: By imaging and analyzing C. elegans motility at high throughput, we extracted a statistical model of whole-animal behavior with just seven parameters.
- Motility and spatial competition as a mechanism for coexistence [2]: Combining experiments with theory, we revealed the fundamental role of physical space in competitive outcomes in microbial ecology.
- Near-critical tuning of a protein signaling array [3]: Using single-cell FRET technology developed in our group, we revealed how bacteria tune the strength of signaling protein interactions close to a critical point.

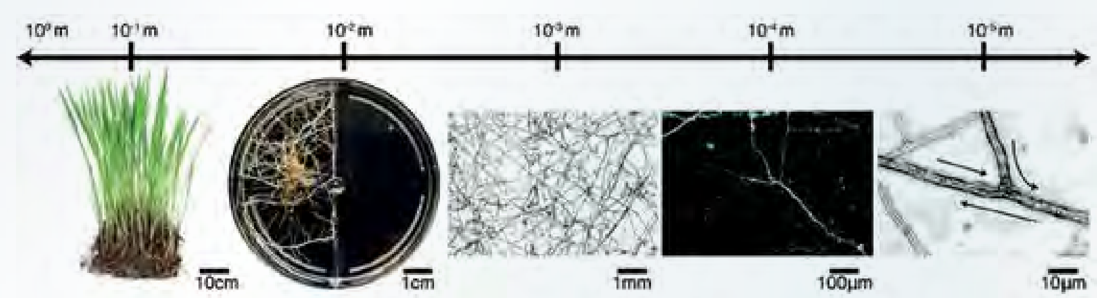
Plans

In recent years, we have begun extending our multiscale approach beyond whole organisms, to the level of collective population-scale behavior [3] and even ecological / community-level dynamics such as symbiosis [5]. In the coming years, our ambition is to establish the biophysics of soil – a functional complex matter of fundamental importance – as a new interface between physics, mechanistic biology and ecology. It is an exciting frontier that brings together all three experimental model systems (bacteria [2,3], nematodes [1,5], and fungi [4]) we have established in our group over the years, with substantial real-world implications for biodiversity and sustainability.

Key research items

1. S.J. Helms, M.W. Rozemuller, A.C. Costa, L. Avery, G.J. Stephens and T.S. Shimizu, *Modelling the ballistic-to-diffusive transition in nematode motility reveals variation in exploratory behaviour across species*, J. R. Soc. Interface 16, (157) (2019)
2. S. Gude, E. Pince, K.M. Taute, A.B. Seinen, T.S. Shimizu and S.J. Tans, *Bacterial coexistence driven by motility and spatial competition*, Nature 578, 588-592 (2020)
3. J.M. Keegstra, F. Avgidis, Y. Mullah, J.S. Parkinson, T.S. Shimizu, *Near-critical tuning of cooperativity revealed by spontaneous switching in a protein signalling array*, bioRxiv doi:10.1101/2022.12.04.518992 (2022)
4. M.D. Whiteside, G.D.A. Werner, V.E.A. Caldas, A. van't Padje, S.E. Dupin, B. Elbers, M. Bakker, M. Klein, G.A.K. Wyatt, M.A. Hink, M. Postma, B. Vaitla, R. Noë, T.S. Shimizu, S.A. West and E.T. Kiers, *Mycorrhizal Fungi Respond to Resource Inequalityby Moving Phosphorus from Rich to PoorPatches across Networks*, Current Biol. 29, (12), 1-8 (2019)
5. W.M. Rozemuller, *C. elegans behaviour and brain dynamics; a physical exploration*, PhD Thesis, VU University Amsterdam, 2023-04-26

Multiscale investigations of arbuscular mycorrhizal fungi (AMF) [5] (pictured), as well as bacteria [2,3] and nematodes [1,5] will form a foundation for our future work on the biophysics of soil – a functional complex matter of fundamental importance for biodiversity and sustainability.



BIOCHEMICAL NETWORKS

⟷ Pieter Rein ten Wolde

Biochemical networks are the information processing devices of life. We use concepts from information theory and recent advances from non-equilibrium thermodynamics to quantify what the resource requirements are for cellular information transmission, in terms of protein copy numbers, time, and energy. In addition, we aim to elucidate the design principles that govern cellular rhythms, ranging from the bacterial cell cycle to circadian clocks. Lastly, we use techniques from statistical mechanics to describe cellular force generation.

Highlights

- We have shown that biochemical networks can come surprisingly close to the Landauer bound on the thermodynamic cost of computational copying ([1,2].
- We have demonstrated that the combination of active forces, dimensionality, and membrane bending free energy creates a plethora of novel shape transitions in active vesicles [3].
- We have developed a theory for the optimal cellular sensing of time-varying signals [4].
- We have developed the first mechanistic model of how the bacterium E. coli controls the initiation of DNA replication [5].

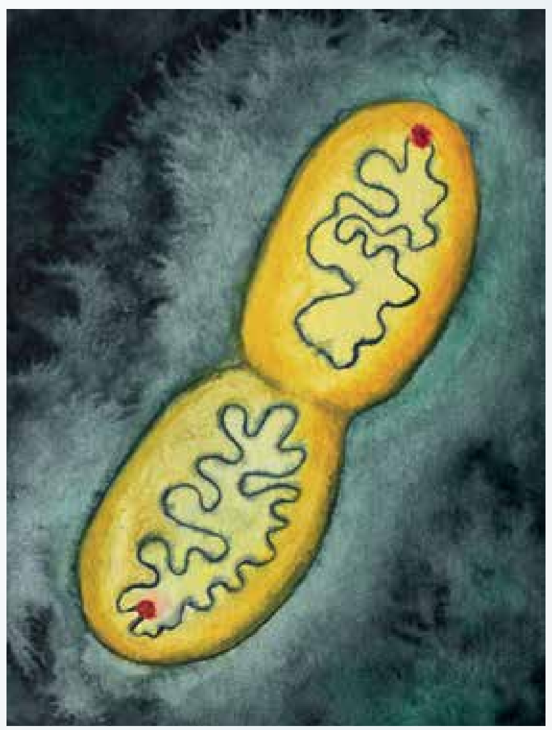
Plans

Living cells can enhance their fitness by anticipating environmental change. In the coming years, we aim to extend our work on cellular information transmission to address not only the question how reliably living cells can predict future signals, but also how the accuracy of prediction limits behavioral tasks like navigation. Moreover, we plan to investigate how cells can learn, and hence adapt to changes in, the statistics of time-varying signals. Lastly, we aim to elucidate the role of mechanics, and its interplay with chemistry, in organoid development.

Key research items

1. T.E. Ouldridge, C.C. Govern and P.R. ten Wolde, *Thermodynamics of Computational Copying in Biochemical Systems*, Physical Review X 7, 021004 (2017)
2. T.E. Ouldridge and P.R. ten Wolde, *Fundamental Costs in the Production and Destruction of Persistent Polymer Copies,* Physical Review Letters 118, 158103 (2017)
3. Y. Li and P.R. ten Wolde, *Shape Transformations of Vesicles Induced by Swim Pressure,* Physical Review Letters 123, 148003 (2019)
4. G. Malaguti and P.R. ten Wolde, *Theory for the Optimal Detection of Time-Varying Signals in Cellular Sensing Systems,* eLife 10, e62574 (2021)
5. M. Berger and P.R. ten Wolde, *Robust Replication from Coupled Homeostatic Mechanisms,* Nature Communications 13, 6556 (2022)

Artist impression of a dividing bacterial cell with its circular chromosome.



Credits: Mareike Berger

INFORMATION IN MATTER

MECHANICAL METAMATERIALS

⟷ Martin van Hecke

The Mechanical Metamaterials group designs, creates and studies flexible mechanical metamaterials. We use a condensed-matter perspective, using concepts from spin-ices, frustration and glasses, holography and topology, to venture into unexplored design spaces of geometrically complex, rationally designed materials. In particular we are spearheading the evolution of mechanical metamaterials towards 'machine materials' with unprecedented properties that far exceed those of ordinary materials, including programmability, shape-morphing, and information processing. Our research, carried out both at AMOLF and at Leiden University, combines experimental, theoretical, and numerical approaches.

Highlights

- We designed and created the first metamaterial that autonomously executes self-folding via a mechanical pathway with embedded error correction [1].
- We uncovered a characteristic length scale in mechanical metamaterials and showed how to manipulate and leverage it for enhanced functionalities [2].
- We developed a combinatorial design method for pluripotent origami metamaterials [3].
- We realized non-trivial sequential pathways, memory effects and elementary counting in experiments on frustrated sheets [5]

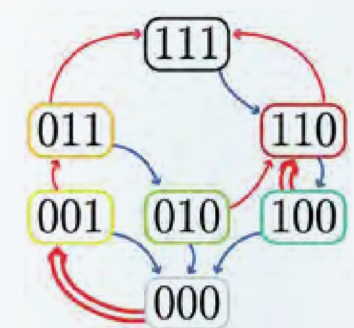
Plans

Our current work, partly supported by an ERC-Advanced grant, investigates the emergent information processing capabilities of frustrated media, and develops metamaterials for targeted computations. A key concept are interacting material bits called hysterons, which generically occur in materials with local bistable elements. Driving such a material – such as a frustrated crumple or a carefully designed metamaterial – leads to complex deformation pathways. These encode finite state machines, the paradigm of sequential computing. We are now developing design, training and learning strategies to firmly establish a new class of matter which we term *finite state materials.*

Key research items

1. C. Coulais, A. Sabbadini, F. Vink and M. van Hecke, *Multi-step self-guided pathways for shape-changing metamaterials*, Nature 561, 512 (2018)
2. C. Coulais, C. Kettenis and M. van Hecke, *A characteristic length scale causes anomalous size effects and boundary programmability in mechanical metamaterials*, Nat. Phys. 14, 40 (2018)
3. P. Dieleman N. Vasmel S. Waitukaitis and M. van Hecke, *Jigsaw puzzle design of pluripotent origami*, Nat. Phys. 16, 63 (2020)
4. A. Meeussen, *Imperfections: using defects to program designer matter*, PhD thesis (2021). In 2020, Anne was awarded the Young Speaker Award at the annual 'FYSICA' meeting; in 2021, Anne received her PhD cum laude, and her thesis received the 2021 Ehrenfest-Afanassjewa award of the Dutch Physics Council.
5. H. Bense and M. van Hecke, *Complex pathways and memory in compressed corrugated sheets*, PNAS 118, 1 (2021)

The complex pathways of a 'crumpled metasheet' (inset) encode elementary computations.



The rubber computer

HYPERSMART MATTER

⟷ Marc Serra Garcia (started in 2021)

We aim at using mechanical degrees of freedom to store and process information, with the goal of building zero or ultra-low power processors, embodying intelligence in robotic structures and understanding the ultimate energy limits of computation. We pursue this goal through a combination of experimental and theoretical efforts. On the experimental front, we invent algorithms to simulate and design large-scale nonlinear and stochastic elastic systems, while on the experimental front we fabricate elastic structures, with scales ranging from centimeters to nanometers, with precisely controlled nonlinearity and dissipation. ques from statistical mechanics to describe cellular force generation.

Highlights

- We demonstrated that elastic systems could perform machine learning tasks such as distinguishing between pairs of words; all while consuming zero power.
- We developed a methodology to design information-processing mechanical systems by combining a large number of elementary nonlinear interactions on a first step followed by a second step that consists of mapping them to geometric features of the structure.
- We demonstrated a variety of topological wave phenomena in mechanical systems by applying our design method to topological models.

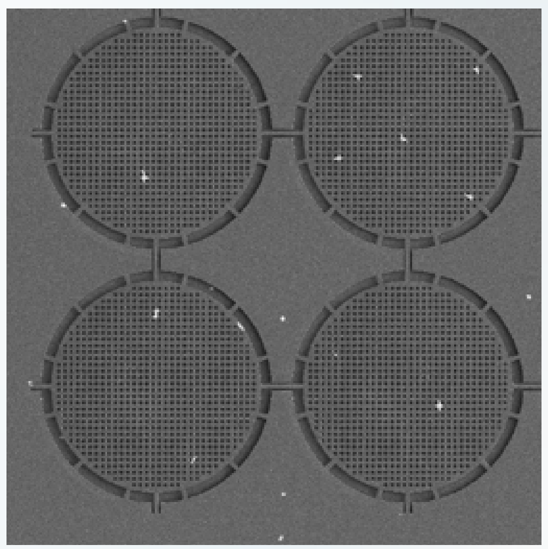
Plans

In the coming years, we aim to take advantage of the ultralow dissipation and high nonlinearity of mechanical systems to answer both fundamental and applied questions. On the fundamental side, we aim to demonstrate mechanical logic gates that operate near the ultimate thermodynamic limits of computing. On the applied side, we aim to build zero-power sparse event detection systems that use mechanical neural networks to recognize events while consuming zero standby power – enabling novel battery-less edge computing systems. We will demonstrate this by building a passive voice activated switch.

Key research items

1. T. Dubček, D. Moreno-Garcia, T. Haag, H.R. Thomsen, T.S. Becker, C. Bärlocher, F. Andersson, S.D. Huber, D.-J. van Manen, L. Guillermo Villanueva, J.O.A. Robertsson and M. Serra-Garcia, *Binary classification of spoken words with passive elastic metastructures*, arXiv:2111.08503 (2021) *
2. M. Serra-Garcia, *Turing complete mechanical processor via automated nonlinear system design*, Phys. Rev, E. 100, 042202 (2019) *
3. M. Serra-Garcia, V. Peri, R. Süsstrunk, O.R. Bilal, T. Larsen, L. Guillermo Villanueva and S.D. Huber, *Observation of a phononic quadrupole topological insulator*, Nature 555, 342-345 (2018). *
4. K.H. Matlack, M. Serra-Garcia, A. Palermo, S.D. Huber and C. Daraio, *Designing perturbative metamaterials from discrete models*, Nat. Mater. 17, 323-328 (2018) *
5. J. Robertsson, M. Serra-Garcia, T. Dubček and D.-J. van Manen, *Zero-power operable classification device and switching device and voice-operated powerless wake-up switch*, European Patent Application EP4181163A1 (2021) *

*Work from before joining AMOLF



Fragment of a mechanical neural network for zero-power speech processing.

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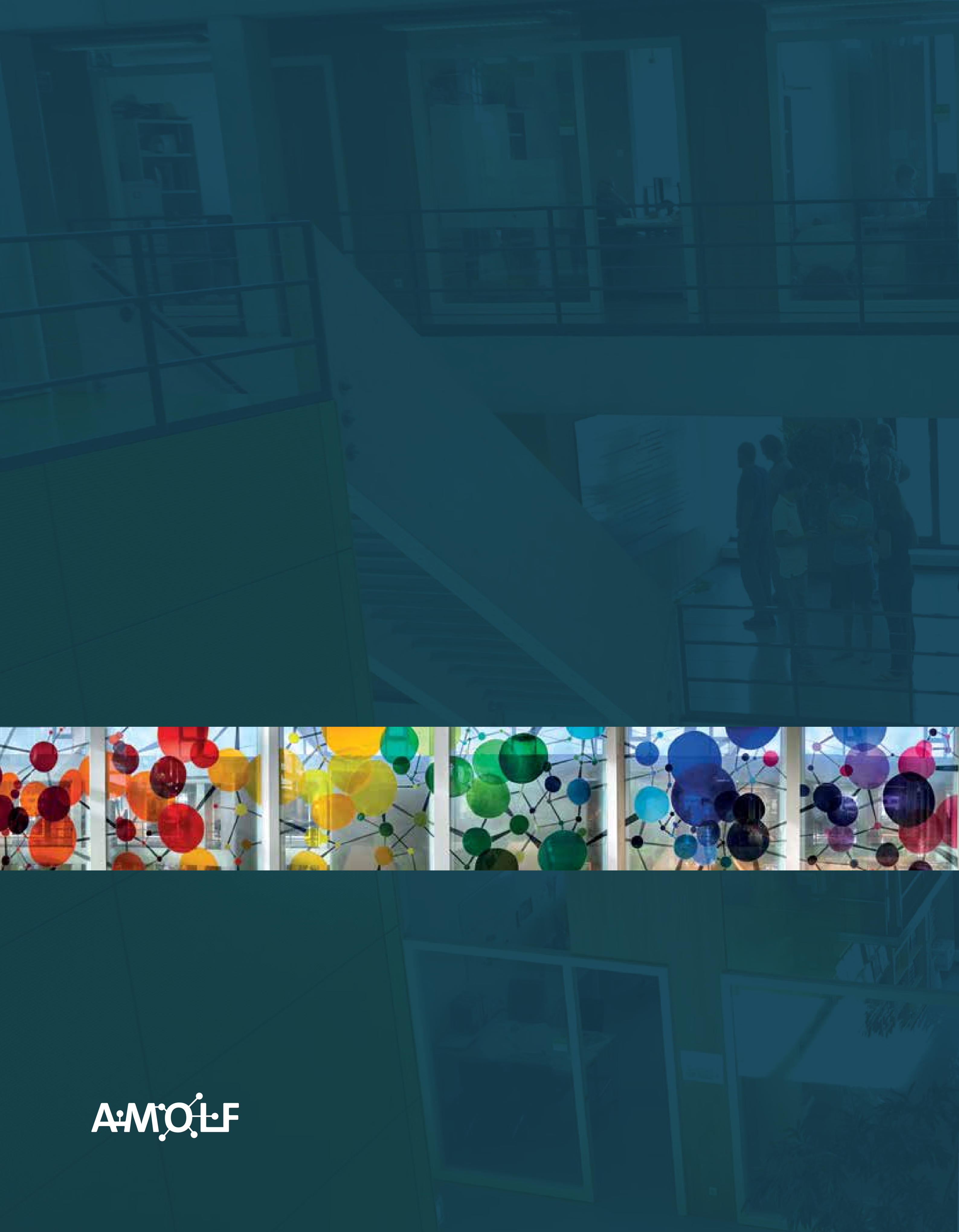

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