Annual Report CogniGron

university of groningen

Annual Report CogniGron 2021

Table of Contents

Foreword

Beatriz Noheda
CogniGron Director

Each month, Google searches generate an amount of CO_2 equivalent to that of a car driving around the earth 25 times[1]; a single data centre consumes the same energy as needed to power 80,000 homes[2]. It is our responsibility as scientists to search for solutions and the research community is responding loud and clear to this challenge: developing novel materials and devices for neuromorphic/cognitive computing has emerged as a key area of research worldwide.

Increasing numbers of researchers from different fields in materials science and condensed matter physics (from photovoltaics to ferroelectrics and spintronics) are joining forces in multidisciplinary teams that include experts in AI, computer science and neuromorphic circuit engineering, to reach that goal. These communities are also dedicating increasing resources towards neuromorphic architectures and systems, and they are learning to communicate with device scientists. Mathematicians are also getting increasingly interested. Initiatives are ongoing in several countries to put neuromorphic computing high on national research agendas. CogniGron is proud to have been featured in a recent article in *Nature* as a "pioneering example" in these efforts [*Nature* 604, 255–260 (2022)].

Since its inception in 2018, CogniGron, the Groningen Cognitive Systems and Materials Centre, has become a dream environment. As an insider, I witness interactions and exchanges between research groups on a weekly basis. I see the young researchers in the driving seats, owning their projects, supported by the strong knowledge base of the older generations, motivated by the opportunity to impact the world we live in. I see the senior scientists learning from the youth and getting out of their comfort zone to contribute to achieving this big challenge. It is a new way of doing science that we are forging.

This way of working has led already to some substantial results of which I would like to highlight two: i) the paper by Herbert Jaeger on a generalized theory of computing [*Neuromorph. Comput. Eng.* 1, 012002 (2021)], published as the first paper in the first issue of the new journal *Neuromorphic Computing and Engineering*, which was downloaded a record number of times and was trending on Altmetrics[3], and ii) the development of intelligent gloves that use piezo-resistive sensors coupled with neuromorphic systems to interpret hand gestures and tactile information without using an external computer [*ACS Appl. Electron. Mater.* 4, 308 (2022)]. This is a collaboration between the groups of Ajay Kottapalli and Elisabetta Chicca at the Engineering and Technology institute Groningen (ENTEG) and CogniGron, respectively, that shows the potential we have in front of us.

I invite you to read further to learn more about CogniGron's adventures in 2021. We hope to inspire you and to hear from you in the near future!

Beatriz Noheda
CogniGron Director

[1]https://visual.ly/community/Infographics/science/surprising-energy-used-google-search
[2]https://energyinnovation.org/2020/03/17/how-much-energy-do-data-centers-really-use/
[3]https://twitter.com/IOPneuromorphic/status/1424654191784566785

CogniGron: Founded to Make a Difference

Need for a Paradigm Change

Our modern society is shaped by technological advances and thrives on developments in information and communication technology (ICT). The emergence of the internet in the mid-1990s has ultimately shaped a new era. Digitized or digital information can easily be shared worldwide at the touch of a button, with the internet providing automated access to huge collections of data. The rapid increase in the use of sensors and the rise of the Internet of Things have triggered an explosion in streaming data volumes, opening a wealth of new application perspectives. When properly processed, this amount of data can generate an unprecedented level of knowledge. Thus, large-scale data processing has an enormous transformative potential, enabling for instance rapid disease diagnosis, personalized medical treatments, increased national security and forecasting of natural disasters. To realize this potential, we need computers that can classify, prioritize, combine and analyse data, as well as generate new suggestions – systems that can learn and become better by doing. Deep learning offers a solution by detecting, classifying and predicting patterns in data, for example for facial recognition in video surveillance, recognition of traffic patterns by self-driving cars or predicting epidemics based on Google search requests.

Currently, successful methods from the field of artificial intelligence rely on neural networks or other brain-inspired algorithms and software. These are then implemented on traditional hardware (a computer) that is not optimized for neural functionality and also lacks plasticity, that is, the ability to learn. This results in a very high energy demand for the efficient handling of data and has led to the ICT field consuming 10% of the world's electricity consumption. This is expected to exceed 20% by 2030 [*Nature* 561, 163 (2018)].

In contrast, our brain has the ability to learn at a fraction of the energy consumption required by a supercomputer: with around 9x1010 neurons and 1.5x1014 connections (synapses), it consumes only 20 W, which is less energy than a light bulb. A man-made system that can approach the cognitive functioning of the human brain consumes ~80 kW, both for computing and communication functions.

This means that the energy usage of information processing can be reduced by several orders of magnitude if we embrace the principles of neuromorphic computing. A paradigm change in how we process information is all the more urgent as the era of Moore's law, which describes that the processing power of 'conventional' computers doubles every two years, has come to an end. In other words, we are reaching the physical limits of what can be achieved with the current technology. It is obvious that significant investments in science and technology are needed to address the future demands of cognitive computing.

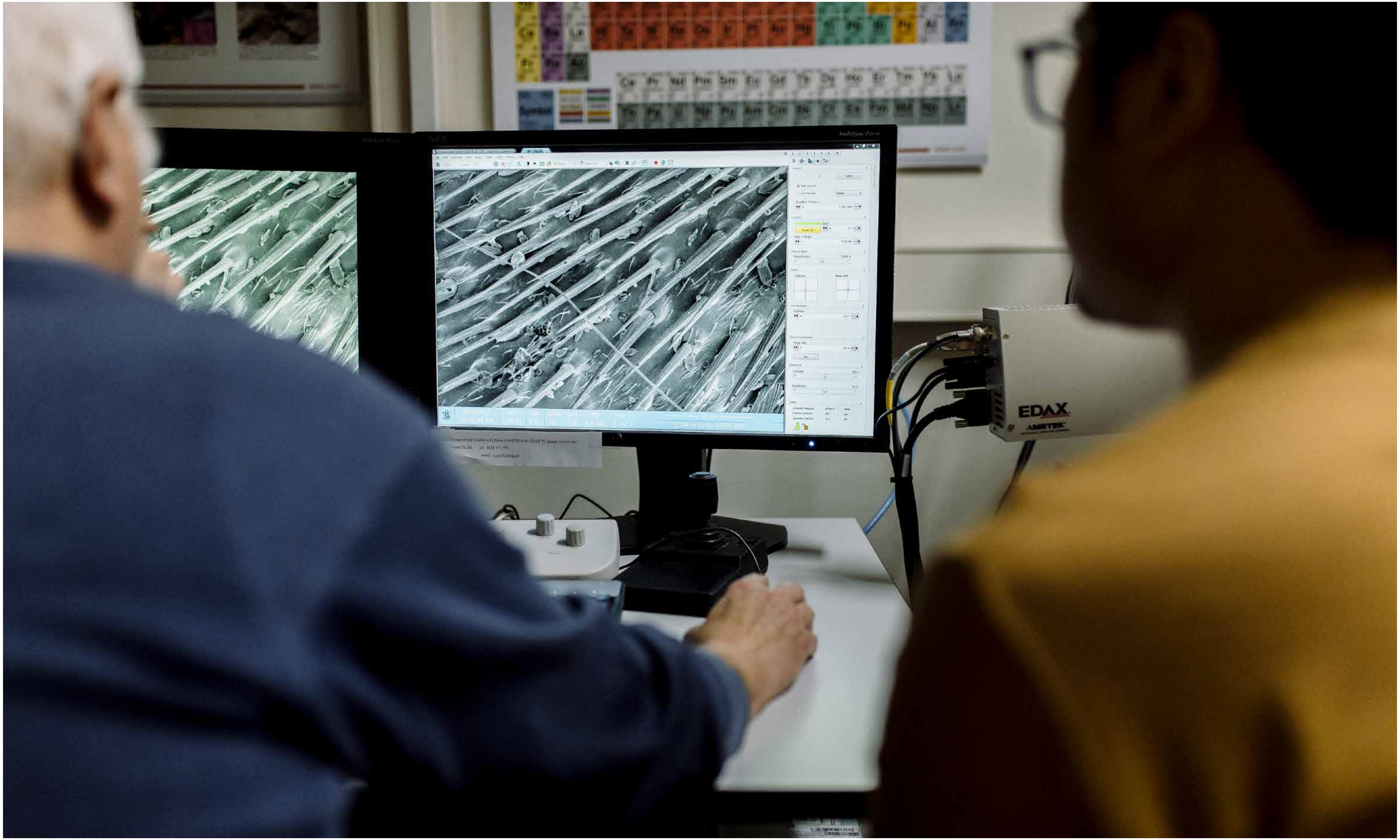
CogniGron is working on the necessary fundamental breakthroughs and technological advances to develop novel architectures for neuromorphic or cognitive computing that promise energy efficiencies orders of magnitude better than current computers. Creating such architectures requires a holistic approach that joins efforts in materials science, physics, mathematics, computer science and artificial intelligence.

Ambition and Mission

CogniGron was founded in 2018 to create the fundamental building blocks for a new type of computing, that is cognitive computing or computing inspired by the brain. These building blocks consist of self-learning materials that can perform the tasks that are currently assigned to thousands of transistors and complex algorithms in a more efficient and straightforward manner. Hence, these building blocks form the basis for a new generation of computer platforms for cognitive applications, such as pattern recognition and analysis of complex data.

Towards this ambition, CogniGron aims to create the conditions for researchers from materials science (physics and chemistry), computer science, artificial intelligence and mathematics to work closely together with a common mission: *to develop cognitive computing at all levels: from materials that can learn to devices, circuits and algorithms.*

To the best of our knowledge, CogniGron is the first collaborative initiative of its kind.


EDAX
AMETEK

Elisabetta Chicca

How does the brain work? And more specific, how do organisms process sensory information? Those are the big questions that Elisabetta Chicca wants to answer. As a specialist in Neurmorphic Engineering, she creates models of biological systems that can be translated into novel devices, for brain-inspired computation, bio-inspired sensing (vision, olfaction, touch, active electrolocation, audition), and motor control.

'My main drive is that I want to understand biological systems', she explains. Human brains are much more energy-efficient than computers. 'And bees can fly around obstacles with only a tiny brain. That needs to be very optimized. Therefore, I want to extract the principles of computation they and other organisms use, and implement these principles in devices.'

Chicca studied Physics in Rome, and before she joined CogniGron in 2020, she worked at the University of Bielefeld (Germany) on these questions. 'There were lots of biologists there, but not many materials scientists, and they were not focusing on neuromorphic applications. I already knew Beatriz Noheda, the Scientific Director of CogniGron, and when she contacted me about a position there, I was very interested.' In Groningen, she can combine her knowledge of physics and neuroscience with that of specialists in materials science and computer science. 'The collection of competencies present here is really amazing.'

She had experienced a similar interdisciplinary ecosystem during her PhD and a postdoc at the ETH Zürich. 'And I know how rare this kind of environment is. That is why I found CogniGron so exciting.' As she arrived early in the coronavirus pandemic, getting to know all her colleagues was a bit complicated. 'Fortunately, I already knew quite a few people here.' Sometimes, meetings happened by chance: Chicca noticed a poster on bio-inspired sensors from the group of Ajay Kottapalli in a corridor of the Physics and Chemistry building. She got in touch with Kottapalli, and they already have published a paper together.

Another way to get to know each other are the Monday afternoon meetings 'CogniGron at Work', in which a CogniGron scientist gives a short presentation which is then open for discussion. Chicca was part of a group who started this weekly get together.

'Communication can be difficult between scientists from disciplines, as we all use different scientific languages. These meetings are ideal to build a common language, and bring people from different fields together.'

She has recently started an interdisciplinary project with CogniGron scientists Maria Antonietta Loi (Professor of Photophysics and Optoelectronics) and Alden Waters (assistant professor in mathematics). They each supervise one PhD student, to create a new type of gas sensor. 'Maria's group builds the sensor, my group creates models for computation of what is being sensed, and Alden's group is responsible for the mathematical modelling.'

And apart from creating new devices like this, Chicca also hopes that a her increased understanding of the workings of insect brains will eventually be of use to neuroscientist. 'My models can generate hypotheses that biologist can turn into new experiments, that lead to a better understanding of the neural substrate of insect behaviour.'

But the real long term outcome should be the creation of low-power neuromorphic systems that will overcome the limitations of traditional digital architectures. 'We want to create biologically inspired learning, sensing and acting systems, which allow us to test current theories of neural computation.'

'The collection of competencies present here is really amazing.'

The Minds of CogniGron

In-house Expertise

The strength and uniqueness of CogniGron lie in the physical systems that are investigated (with scalability potential beyond current solutions) and in the multidisciplinary character of the approach. Therefore, collaborations beyond disciplinary boundaries are a main priority. CogniGron brings together expertise from two prominent institutes within the Faculty of Science and Engineering, the *Zernike Institute for Advanced Materials* and the *Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence,* building on their strengths in various disciplines: materials science, physics, mathematics, computer science and artificial intelligence. To help these disciplines answer scientific questions, CogniGron creates an environment that encourages creativity and open communication.

Figure 1 presents the existing expertise related to CogniGron and the relevant disciplines, highlighting the excellent position of CogniGron to make progress in the field of cognitive computing. Over the last two years, CogniGron has attracted new expertise on the borders of various disciplines, aiming to increase synergy and collaboration and providing a bridge between existing expertise in materials science, AI, mathematics and computer science.

Materials Science Expertise

The ambition of CogniGron is to develop and build the fundamental building blocks for cognitive computing, also called 'Cognitive Materials'. The researchers working on these topics are therefore central participants, with leading roles in current research. Materials scientists explore, study and further design electronic materials and devices. The CogniGron research programme encompasses the entire chain of materials research from modelling, synthesis, experiments and theory to device fabrication:

Prof. Tamalika Banerjee
Spintronics of Functional Materials

Prof. Elisabetta Chicca
Bio-Inspired Circuits and Systems

Prof. Maria Loi
Photophysics and Opto-Electronics

Prof. Bart Kooi
Nanostructured Materials and Interfaces

Prof. Beatriz Noheda
Nanostructures of Functional Oxides

Prof. George Palasantzas
Physics - Surface interactions and Nanostructures

Prof. Petra Rudolf
Experimental Solid-State Physics

Prof. Caspar van der Wal
Quantum Devices

Prof. Jianting Ye
Device Physics of Complex Materials

Artificial Intelligence Expertise

The availability of large data sets and computing power have led to a revolution in machine learning, notably in the area of deep learning with neural networks. This provides both opportunities and challenges. It should be noted that current neural-networking methods are implemented on Turing/Von Neumann machines, which is not sustainable for reasons such as a very high energy demand, both for computing and communication functions. In close cooperation with materials scientists, artificial intelligence experts develop models and methods facilitating the search for novel materials that are suitable for neural computing. In this way, CogniGron covers the full range from low-level modelling to cognitive principles:

Prof. Sander Bohté
Neural Computation

Dr. Jelmer Borst
Artificial Intelligence

Prof. Davide Grossi
Cognitive Multiagent Systems

Prof. Herbert Jaeger
Computation in Cognitive Materials

Prof. Lambert Schomaker
Artificial Intelligence

Prof. Niels Taatgen
Artificial Intelligence

Dr. Marieke van Vugt
Cognitive Modelling

Computer Science Expertise

Computer science is an essential component in the development of cognitive systems and materials. It addresses fundamental issues to understand basic principles of developing and building novel computer architectures. The computer science expertise within CogniGron is broad:

Dr. George Azzopardi
Information Systems

Prof. Michael Biehl
Intelligent Systems

Prof. Georgi Gaydadjiev
Innovative Computer Architecture

Prof. Boris Koldehofe
Computer Networks

Dr. Revantha Ramanayake
Theory of Computation

Prof. Jos Roerdink
Scientific Visualization and Computer Graphics

Dr. Michael Wilkinson
Digital image analysis and computer vision

Mathematics Expertise

A unique feature of CogniGron is the prominent involvement of mathematics. To understand the underlying principles of 'cognitive materials', mathematical principles and modelling are key. The mathematics expertise within CogniGron covers a broad spectrum:

Dr. Bart Besselink
Systems and Control Theory

Dr. Gilles Bonnet
Stochastic Studies and Statistics

Prof. Kanat Camlibel
Systems and Control Theory

Dr. Christian Hirsch
Topological Data Analysis and Data Science

Prof. Arjan van der Schaft
Applied Analysis

Dr. Alef Sterk
Dynamical Systems Theory

Prof. Holger Waalkens
Dynamical Systems Theory

Dr. Alden Waters
Systems Control and Applied Analysis

Prof. Fred Wubs
Numerical Mathematics

Technical Expertise

CogniGron would not be where it is today without the skills that the technicians bring. The technicians amongst others train the students in the various labs and make sure that all labs are running smoothly.

Ir. Jacob Baas
Solid State Materials for Electronics

Henk Bonder
Nanostructures of Functional Oxides

Gert ten Brink
Nanostructured Materials and Interfaces

Johan Holstein
Fysica van Nano Devices

Dr. Arjun Joshua
Nanostructures of Functional Oxides

The Next Generation

PhD Students and Postdoctoral Researchers

CogniGron-funded

Staff members are encouraged to submit joint PhD proposals with PIs from different disciplines. These proposals lead to CogniGron-funded PhD positions. Brainstorming and discussion sessions are organized to develop the research plans for these positions.

Dr. Shuyan Shao (2018-2019)
Organic memristors
Photophysics and Opto-Electronics

Dr. Oleksandr Zheliuk (2020-2021)
Enhanced learning efficiency of synaptic devices for neuromorphic computations
Device Physics of Complex Materials

Jhon Kevin Astoquillca Aquilar (2021-2025)
Nanoparticle based percolating networks towards neuromorphic computing
Stochastics and Statistics

Anouk Goossens (2018-2021)
Nanoscale memristors for new computing paradigms
Spintronics of Functional Materials

Ruben Hamming Green (2021-2024)
Combined volatile/non-volatile memristive ferroelectric arrays.
Nanostructures of Functional Oxides

Anne-Men Huijzer (2019-2023)
Memristor Networks
Systems and Control Theory Research Group

Fabian IJpelaar (2022-2026)
Qualitative modeling, simulation and exploration of multi-phenomenal materials dynamics
Computing in Cognitive Materials

Azminul Jaman (2020-2024)
Towards a cognitive computer architecture based on memristive devices: developing short- and long-term memory
Spintronics of Functional Materials

Jesse Luchtenveld (2021-2025)
Analogue phase-change memory cells for neuromorphic computing
Nanostructured Materials and Interfaces & IBM

Julien van der Ree (2020-2024)
Nanoparticle based percolating networks towards neuromorphic computing
Physics - Surface interactions and Nanostructures

Jan Rieck (2019-2019)
Memristor networks from self-assembled domain walls in oxides
Nanostructures of Functional Oxides

Saad Saleh (2020-2024)
New switching architectures with memristors for neuromorphic computing
Computer Networks

Thomas Tiotto (2020-2024)
Towards a cognitive computer architecture based on memristive devices: developing short- and long-term memory
Artificial Intelligence

Karolina Tran (2020-2024)
Carbon nanotube-based neuromorphic electronics
Photophysics and Optoelectronics

Daniel Willhalm (2020-2024)
Large deviations in stochastic geometry
Topological Data Analysis and Data Science

Associated PhD students and Postdocs

Below, the PhD students are listed that are funded by other means but whose work is closely related to CogniGron and who take part in CogniGron activities.

Dr. Celestine Lawrence (2020-2023)
Theory of neuromorphic computing – *This project has received funding from the EU Horizon 2020 Research and Innovation programme under grant agreement no. 871371*
Computing in Cognitive Materials

Dr. Cynthia Quinteros (2018-2020)
Exploration of ferroic domain walls assemblies in BiFeO3 for neuromorphic implementations
Nanostructures of Functional Oxides

Dr. Pavan Nukala (2018-2020)
Multiscale investigations on Si-integrable Ferroelectric Hafnia-Zirconia systems (FERHAZ) – *This project has received funding from the EU Horizon 2020 programme under Marie Skłodowska-Curie Actions Individual Fellowship grant agreement no. 794954*
Nanostructures of Functional Oxides

Bhavana Ballal (2021-2025)
Design and development of novel CMOS hybrid circuits for neuromorphic applications
Bio-inspired Circuits and Systems

Sanne Berg (2018-2021)
Self-assembled networks of functional metal oxides for neuromorphic materials
Nanostructures of Functional Oxides

Davide Cipollini (2021-2025)
Adaptive random non-linear mappings for neural computing in ferroelastic films – *This project has received funding from the EU Horizon 2020 programme under Marie Skłodowska-Curie grant agreement no. 861153*
Artificial Intelligence

Madison Cotteret (20XX-20XX)
Neuromorphic memristive VLSI architectures for cognition
Bio-inspired Circuits and Systems

Silvia Damerio (2018-2021)
Thin films of modulated multiferroic oxides as adaptable systems for cognitive computing
Nanostructures of Functional Oxides

Maxim Fabre (2021-2025)
On-chip training on analog circuits with memristive devices and bio-plausible learning algorithms
Bio-inspired Circuits and Systems

Hugh Greatorex (2021-2025)
Memristive time difference encoder
Bio-inspired Circuits and Systems

Philipp Klein (2018-2022)
Learning in neuromorphic systems
Bio-inspired Circuits and Systems - external PhD student (employed at Bielefeld University, Germany)

Alexander Kugele (2018-2022)
Event-based vision for automated driving
Bio-inspired Circuits and Systems - external PhD student (employed at Bielefeld University, Germany)

Mian Li (2020-2024)
Morphological image analysis of conduction maps – *This project has received funding from the EU Horizon 2020 programme under Marie Skłodowska-Curie grant agreement no. 861153*
Scientific Visualization and Computer Graphics

Michele Mastella (2020-2024)
Neuromorphic embedded processing for touch – *This project has received funding from the European Research Council (ERC) under grant agreement no. 813713*
Bio-inspired Circuits and Systems

Guillaume Pourcel (2020-2024)
Theory of neuromorphic computing – *This project has received funding from the EU Horizon 2020 Research and Innovation programme under grant agreement no. 871371*
Computing in Cognitive Materials

Ole Richter (2020-2024)
Neuromorphic integrated systems for network stability and homeostasis
Bio-inspired Circuits and Systems

Jan Rieck (2020-2024)
Memristor networks from self-assembled domain walls in oxides – *This project has received funding from the EU Horizon 2020 programme under Marie Skłodowska-Curie grant agreement no. 861153*
Nanostructures of Functional Oxides

Mart Salverda (2018-2019)
Neuromorphic phenomena in thin film perovskite oxides
Nanostructures of Functional Oxides

Thorben Schoepe (2018-2022)
Neuromorphic sensorimotor systems
Bio-inspired Circuits and Systems - external PhD student (employed at Bielefeld University, Germany)

Willian Soares Girão (2020-2023)
Neuromorphic circuits for novel devices – *This project has received funding from the EU Horizon 2020 programme under Marie Skłodowska-Curie grant agreement no. 861153*
Bio-inspired Circuits and Systems

Wytse Talsma (2018-2020)
Neuroplasticity in neural networks utilising semiconducting single-walled carbon nanotube inks
Photophysics and Opto-Electronics

Bachelor's & Master's Students

Bachelor's and Master's projects are designed to test CogniGron ideas and their suitability to become PhD projects. The Master's students involved in CogniGron in 2021 are listed below:

Ishitro Bhaduri (supervisor: Tamalika Banerjee)
Area-dependent resistive switching in memristive Co/Nb-doped SrTiO3 Schottky junctions
Spintronics of Functional Materials

Ton Juny Pina (supervisor: Elisabetta Chicca)
Keyword spotting with the time difference encoder
Bio-inspired Circuits and Systems

Julian Lopez Gordillo (supervisor: Elisabetta Chicca)
Local Unsupervised Learning of Multimodal Event-Based Data with Spiking Neural Networks
Bio-inspired Circuits and Systems

Lisa Oosterhof (supervisor: Bart Besselink)
Modeling and Analysis of Memristive Circuits
Systems and Control

Governance

Below we describe the governance of CogniGron, detailing the Scientific Director, Programme Board and Coordinating Office, who together form the daily management team, as well as the Supervisory Board and Scientific Advisory Panel.

Scientific Director

The Scientific Director is responsible for the scientific programme and chairs the Programme Board (see below). The director functions as the official representative of the centre. CogniGron's founding Scientific Director is Prof. Beatriz Noheda.

Beatriz Noheda received her PhD in Physics from the Universidad Autónoma de Madrid, Spain. In 2003, after holding various positions at Saarland University, the Clarendon Laboratory in Oxford, Brookhaven National Lab in New York and the Vrije Universiteit in Amsterdam, she was awarded a Rosalind Franklin Fellowship by the University of Groningen, where she is now Full Professor. Noheda is a Fellow of the American Physical Society and recipient of the IEEE Robert E. Newnham Ferroelectrics Award. She has served as member of numerous national and international committees and several editorial boards. She is the author of more than 150 publications and receives more than 10 invitations a year to speak at international conferences. Noheda's research focuses on understanding the relationship between the structure and functionality of thin films of ferroelectric, piezoelectric and multiferroic materials, often used as memory elements. Her research, although fundamental in nature, is inspired by two main application areas that she believes will enable the next technological revolution: piezoelectric energy harvesting for low-power electronics and the development of novel materials for adaptable electronics and neuromorphic computing.

Programme Board

The Programme Board is responsible for determining scientific strategy, for the daily running of the scientific programme, the allocation of the budget, as well as the recruitment of new staff. It is composed of the following members:

Prof. Beatriz Noheda (chair)
Professor Nanostructures of Functional Oxides

Prof. Tamalika Banerjee
Professor Physics of Nanodevices

Prof. Georgi Gaydadjiev
Professor Innovative Computer Architectures

Prof. Maria Antonietta Loi
Professor Photophysics and Optoelectronics

Prof. Lambert Schomaker
Professor Artificial Intelligence

Dr. Alef Sterk
Assistant Professor Mathematics

Prof. Niels Taatgen
Professor Artificial Intelligence and Chair of the Board of the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence

Prof. Caspar van der Wal
Professor Physics of Quantum Devices and Director of the Zernike Institute for Advanced Materials

Prof. Ton Engbersen
Advisor to the Programme Board
Professor Data Science Engineering

Changes to CogniGron Programme Board

In 2021, Prof. Kanat Camlibel (Associate Professor Systems and Control and vice-chair of the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, University of Groningen) has resigned from his position as member of the programme board of CogniGron as a result of other opportunities. CogniGron would like to thank Kanat for all his efforts to in working towards the goals and ambitions of CogniGron. Prof. dr. Kanat Camlibel is replaced in the programme board by Dr. Alef Sterk (Assistant Professor Mathematics) as the mathematics representative.

Supervisory Board

The Supervisory Board approves the budget and, in collaboration with the Programme Board, reviews the long-term strategy of the CogniGron programme on a yearly basis. It also supervises and discusses significant changes in focus and implementation with the Programme Board. It is composed of the following persons:

Drs. Hans Biemans
Member of the Board of the University of Groningen

Prof. Jasper Knoester
Dean of the Faculty of Science and Engineering, University of Groningen.

Dr. Esther Marije Klop
Managing director of the Faculty of Science and Engineering, University of Groningen.

Coordinating Office

The Coordinating Office assists the Scientific Director and the Programme Board in all aspects of management, outreach and communication activities. The office is led by Dr. Jasper van der Velde, Scientific Coordinator CogniGron.

Dr. Jasper van der Velde
Scientific Coordinator

Scientific Advisory Panel

CogniGron also has an international Scientific Advisory Panel, which is tasked with advising the Scientific Director and the Programme Board on the scientific merits of research plans and with assisting in delineating new scientific directions.

Prof. Giacomo Indiveri
Professor Neuromorphic Cognitive Systems and Director of the Institute of Neuroinformatics
UZH / ETH Zurich, Switzerland

Prof. Julie Grollier
Professor Nanodevices for Bio-Inspired Computing and Chair of the interdisciplinary research network GDR BioComp
CNRS/Thales, France

Dr. Heike Riel
IBM Fellow, Department Head Science & Technology
IBM Zurich, Switzerland

Prof. Ivan Schuller
Professor Nanoscience and Director of QMEENC (Quantum Materials for Energy Efficient Neuromorphic Computing)
Department of Physics and Centre for Advanced Nanoscience, University of California, San Diego, USA

Prof. Rainer Waser
Professor of Electrical Engineering and Information Technology at RWTH Aachen University, Germany, and Director of the Peter Grünberg Institute, Julich, Germany

Prof. Yoeri van de Burgt
Assistant Professor in Microsystems group
Institute of Complex Molecular Studies (ICMS), TU Eindhoven, Netherlands

Prof. Wilfred van der Wiel
Professor of Nano Electronics and Director of the Centre for Brain-Inspired Electronics (BRAINS)
University of Twente, Netherlands

Prof. Chris Eliasmith
Professor Philosophy and Systems Design Engineering, and cross-appointed to Computer Science and Director of the Centre for Theoretical Neuroscience
University of Waterloo, Canada

Prof. Susan Stepney
Professor of Computer Science
University of York, United Kingdom

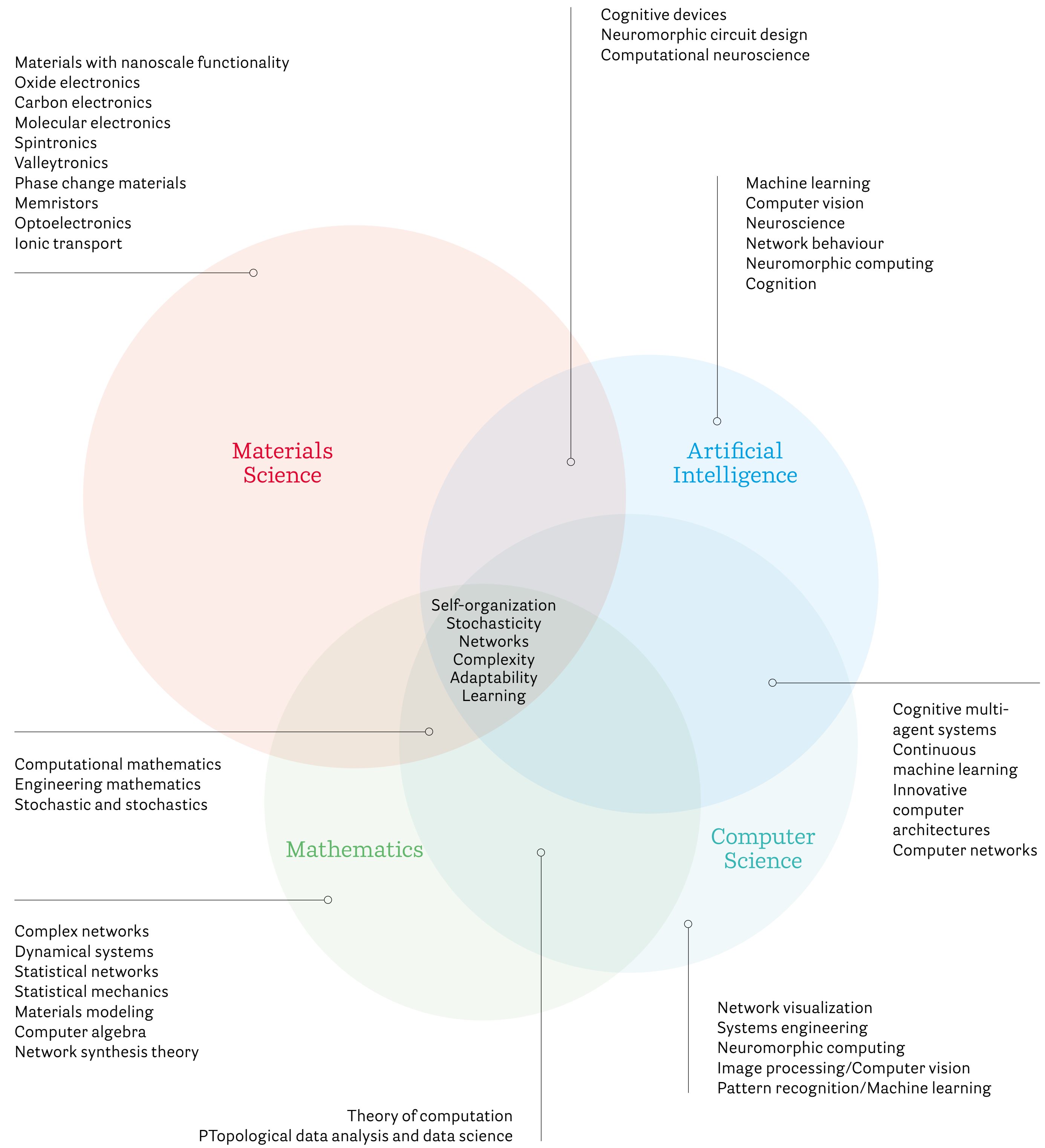


Figure 1. Sketch of the originally existing expertise within the four disciplines involved in CogniGron (four circles and black font topics), as well as of the new interdisciplinary professor positions (P1-P12, in red font), The new profiles are located in between the disciplines whose interaction they aim to strengthen (represented by the overlapping areas). The themes that are of common interest to the whole of CogniGron are displayed in the centre of the figure.

Hans Biemans

‘CogniGron originated from an idea, a vision and a very generous donation. These came together to create an institute that carries a huge potential for society’, says Hans Biemans, Vice President of the Board of the University of Groningen and Member of the CogniGron Supervisory Board. As the trend for miniaturization of microchip technology reaches its limits, scientists everywhere work on new computer systems. Quantum computers are a promising path. ‘But what CogniGron is working on is the generation beyond quantum computing.’

Some five years ago, CogniGron was born. Its vision for interdisciplinary research fits well with the ambitions of the University Board. ‘We are a broad University, the ideal place for interdisciplinary work. This is part of our Strategic Plan.’ The long term vision of CogniGron is risky, Biemans acknowledges. ‘Yet I am reminded of what Simon Kuipers once said, a past President of the University Board. His conviction was that a university should host projects that might fail, but could also produce important results. Just put some good people together, and give them space and time.’

This vision of Kuipers is realized in a project like CogniGron. The ambition to develop a totally novel way of computing, inspired by the brain, brings together scientists from mathematics, materials science, computer science and artificial intelligence, from three different Faculties: Science and Engineering, Arts, and Behavioural Science. A large donation kick started the project and allowed the new research institute to attract a number of new professors. ‘Nearly all positions are now filled’, says Biemans. ‘Most PhD students for the first period have also started. The institute is now really established, and moving into a new phase, producing the first scientific results and attracting external funding.’

Inside the scientific community, the buzz about CogniGron has spread. Now, according to Biemans, it is time to reach out to companies and the general public: ‘Some of the rather abstract work has produced concrete examples, like a smart glove that could support the wearer without any external computers. Or a microchip which controls the transponder on a migratory bird in such a way that it only transmits when required, making the batteries last much longer.’ The Supervisory Board discusses the need for outreach with the scientists. ‘They are really eager to learn how to do this, I am pleased with how quick they respond to our suggestions.’

Over the next five years, Biemans expects that CogniGron will produce enough concrete results to interest industrial partners. ‘And my hope is that this institute will be guiding in research towards the next generation of computing.’ The early signs are hopeful, he adds. ‘CogingRon is attracting funding, both nationally and from EU programs. I find this project really exciting. This is what universities are all about: doing research that might fail, but could have a huge impact on society.’

‘My hope is that this institute will be guiding in research towards the next generation of computing.’


BERNOULLIBORG

New Staff

CogniGron has been an interdisciplinary programme from the outset, as summarized in Figure 1. In the past years, twelve new professor positions were created to increase the synergy between disciplines. These new staff members will further bolster interaction between our experts in materials science, AI, mathematics and computer science. Selecting these new colleagues has been one of the main focuses of CogniGron since its official start.

Visionary academics were invited to apply for one of the following positions:

1. Cognitive Devices
2. Neuromorphic Circuit Design
3. Computational Neuroscience
4. Cognitive Multi-Agent Systems
5. Continuous Machine Learning
6. Innovative Computer Architectures
7. Computer Networks
8. Theory of Computation
9. Topological Data Analysis and Data Science
10. Computational Mathematics
11. Engineering Mathematics
12. Stochastics

We are delighted to report that highly talented staff have already been appointed for nine of these twelve positions. They are introduced below (in reverse chronological order of their appointments).

Dr. Gilles Bonnet

Stochastics research group

Gilles Bonnet has been appointed as Assistant Professor in Stochastics at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence within CogniGron. Performing research at the crossroads of probability theory and convex geometry, his position has been designed to bridge the gap between mathematics, material science, computer science and artificial intelligence. Bonnet investigates properties of random geometric structures, such as random convex hulls, cells of random tessellations (Voronoi, Delaunay and hyperplane tessellations) and Poisson Delaunay graphs. Within the context of CogniGron his research on tessellations can be used as good models for materials, and random geometric graphs can be the basis for studying (random) electrical networks for example.

Bonnet obtained his Bachelor's (2007) and Master's (2009) degrees in Mathematics at the University of Bordeaux (France). During the first year of his Master's he was an Erasmus student at the University of Manchester (UK). In Bordeaux he also passed the Capes and Agrégation examinations, which are French competitive examinations to become a teacher. It led him to teach mathematics in Paris for two years (2010-2012). Afterwards he studied for one year at the University of Barcelona (Spain), where he obtained a second Master's degree (2013) with a thesis in the field of tropical geometry. Then he decided to do a PhD at the University of Osnabrück (Germany) under the supervision of Professor Matthias Reitzner. His doctoral thesis (2016) was about the Poisson hyperplane tessellation. After that, Bonnet was a postdoc at the University of Bochum (Germany) in the group of Prof. Christoph Thäle. In 2021 he was appointed at the University of Groningen.

Dr. Revantha Ramanayake

Theory of Computation research group

Revantha Ramanayake has been appointed as Assistant Professor in Theory of Computation at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, within CogniGron. His position has been designed to bridge the gap between mathematics, computer science and artificial intelligence. Ramanayake's area of expertise is proof theory and logics in computer science. He investigates various families of reasoning such as substructural, modal and fuzzy logics, their (meta)logical and proof-theoretic properties, and their application in computer science and mathematics. He is also interested in the use of proof assistants for the formal verification of proofs. As part of CogniGron, he will investigate the computational properties of neuromorphic computing systems, as well as the use of formal logical methods to study such systems.

Ramanayake studied Mathematics at the Australian National University, where he obtained his PhD in theoretical computer science/logic in 2011. From 2011-2012 he was a postdoctoral researcher at the Laboratoire d'Informatique of the École Polytechnique (France). Subsequently, he was a (senior) postdoctoral researcher at the TU Wien (2012-2020) and at the Wolfgang Pauli Institute (Austria). Within this period, he headed an Austrian Science Fund grant on unifying logical frameworks in proof theory. He commenced at Groningen in March 2021.

Prof. Elisabetta Chicca

Bio-inspired Circuits and Systems research group

Elisabetta Chicca has been appointed as Professor Bio-inspired Circuits and Systems at the Zernike Institute for Advanced Materials within CogniGron. Her position has been designed to bridge the gap between material science, computer science and artificial intelligence. She aims to identify the principles of neural computation and implement them in fully parallel and low-power neuromorphic systems that offer the opportunity to overcome the limitations of traditional digital architectures. Hereby she develops biologically inspired learning, sensing and acting systems, which allow to test current theories of neural computation. The physical substrate of these implementations consists of CMOS technology and novel materials.

Chicca obtained a "Laurea" degree (MSc) in Physics from the University of Rome 1 "La Sapienza", Italy in 1999, a PhD in Natural Science from the Swiss Federal Institute of Technology Zurich (ETHZ, Physics department) and in Neuroscience from the Neuroscience Centre Zurich, in 2006. Chicca has carried out her research as a Postdoctoral fellow (2006-2010) and as a Group Leader (2010-2011) at the Institute of Neuroinformatics (University of Zurich and ETH Zurich) working on development of neuromorphic signal processing and sensory systems. From 2011 to 2020 she led the Neuromorphic Behaving Systems research group at Bielefeld University (Faculty of Technology and Cognitive Interaction Technology Centre of Excellence, CITEC). Since 2020 she leads the Bio-inspired Circuits and Systems research group in Groningen. Her current interests are in the development of VLSI models of cortical circuits for brain-inspired computation, learning in spiking VLSI neural networks and systems based on memristive devices, bio-inspired sensing (olfaction, active electrolocation, audition, visually guided navigation) and motor control.

Prof. Boris Koldehofe

Computer Networks

Boris Koldehofe has been appointed as Professor in Computer Networks at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, within CogniGron. His position has been designed to bridge the expertise gap between mathematics, computer science and Physics. His research contributes to mechanisms and methods for distributed and self-adaptive intelligent systems. This comprises methods and mechanisms that i) account for today's tremendous data volumes, ii) help utilize resources like the network infrastructure and processing resources efficiently, iii) provide information in a consistent and reliable way, and iv) account for several constraints such as privacy of information and quality of data/service.

Koldehofe obtained a Diplom in Informatik at the Universität des Saarlandes, Saarbrücken, Germany in 1999. In 2003, he obtained a Licentiate of Philosophy degree at Chalmers University of Technology, Göteborg, Sweden, where he also received his PhD degree in 2005. Koldehofe carried out his postdoctoral research (2005-2006) at the Swiss Federal Institute of Technology in Lausanne (EPFL), Switzerland. Afterwards he became a senior researcher and lecturer at the Institute for Parallel and Distributed Systems (IPVS) at Universität Stuttgart, Germany, where he headed the Adaptive Communication Systems research group until 2014. From 2014 to 2020 he was appointed as senior researcher and lecturer in the Multimedia Communications Lab (KOM) at the Technische Universität

Darmstadt, Germany. Since 2017 he was also the Principal Investigator of the DFG Collaborative Research Centre 1053 MAKI. In 2020, Koldehofe was appointed in Groningen to lead the computer networks research group. His current interests are networked and distributed systems, middleware and event-based systems.

Dr. Christian Hirsch

Topological Data Analysis and Data Science

Christian Hirsch has been appointed as an Assistant Professor in Topological Data Analysis and Data Science at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, within CogniGron. His position has been designed to bridge the expertise gap between mathematics and computer science. Hirsch is especially interested in applying mathematical principles in seemingly unrelated contexts, in collaboration with engineers and physicists. His research interests lie in the domain of spatial random structures, i.e., random structures that come with an embedding into a Euclidean space. These structures give rise to fascinating research questions within mathematics as well as in application domains ranging from materials science to neuroscience. For example, Hirsch is working on random network models to explain phenomena related to synaptic plasticity. Understanding such mechanisms holds the promise of yielding insights not only into the inner workings of learning in the brain, but also into artificial neural networks. In recent years, topological data analysis has emerged as one of Hirsch's methods to analyse randomly organized structures in materials science. One of his research goals is to build up a firm statistical underpinning by proving central limit theorems for persistent Betti numbers and related quantities. Hirsch studied mathematics at LMU Munich, Germany, before pursuing a PhD at Ulm University, Germany, which he obtained *summa cum laude* on the connectivity and percolation properties of stochastic networks. Next, he was postdoctoral researcher at the WIAS Berlin, Germany, where he applied techniques of stochastic geometry, large deviations and statistical physics in the analysis of next-generation wireless networks. Subsequently, he was a postdoctoral researcher at Aalborg and Munich, Germany, working on more interdisciplinary topics, before he was appointed as an Assistant Professor at the University of Mannheim, Germany. On 1 January 2020, Hirsch was appointed in Groningen.

Prof. Georgi Gaydadjiev

Computer Architectures

Georgi Gaydadjiev has been appointed as a Full Professor in Innovative Computer Architectures at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence within CogniGron. His position has been designed to bridge the expertise gap between artificial intelligence and computer science. Gaydadjiev is a Computer Engineer with over 30 years of industrial and academic experience. He has worked on various designs of embedded systems (even before such systems were given this name). He also performed research on computer architectures and microarchitectures for reconfigurable, highly customized and safety-critical computing systems. His current research focus is on advanced (digital and non-digital), highly customized computing systems, based on cognitive materials and devices.

Gaydadjiev obtained his degree in control systems engineering at Voenmeh (currently the Baltic State Technical University) in Leningrad, Soviet Union, and subsequently worked designing personal computer I/O peripherals at System Engineering Ltd in Pravetz (Bulgaria). He later joined Pijnenburg Microelectronics and Software in Vught, the Netherlands, working on various designs of embedded systems. While working at Pijnenburg M&S, he also enrolled at TU Delft and successfully completed a Master's in Electrical Engineering.

In 2002, Georgi joined the Computer Engineering laboratory at the Faculty of Electrical Engineering, Mathematics and Computer Science of TU Delft. His research was funded by STW, the European Commission, point.one, CenterNovem/BSIK and Google Inc. In 2011, he received a personal grant from the Swedish Research Council (VR) and joined Chalmers University of Technology, holding the professorial chair in Computer Systems Engineering. In 2014, he joined Maxeler Technologies Ltd in London, an appointment that led to the creation of Maxeler IoT-Labs BV in Delft. At Maxeler, Gaydadjiev led the Dataflow Software Engineering division as one of the company's vice presidents and focused on the research and development of highly customized high-performance computing (HPC) systems. Some of these systems were able to outperform TOP-500 supercomputers in very specific tasks while using only a fraction of the electrical energy required. In August 2019, Gaydadjiev moved to Groningen.

Prof. Herbert Jaeger

Computation in Cognitive Materials

Herbert Jaeger has been appointed as a Full Professor in Computation in Cognitive Materials at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence within CogniGron. His position has been designed to bridge the expertise gap between artificial intelligence, computer science and materials science. Jaeger is internationally recognized for pioneering the field of 'reservoir computing' (RC). In this non-standard approach to computer chip design, computing can be non-digital and does not necessarily use transistors as basic computing elements. Instead, a randomly structured lump of nonlinear material (possibly nanoscale) is used as a 'reservoir' of dynamic phenomena. The input data are fed into this material reservoir and 'excite' high-dimensional response dynamics within it, from which the desired output is distilled with machine learning methods. This can be done not only with electrical forms of input signals, but also with optical, chemical, mechanical or magnetic signals, or mixtures thereof. Due to this universality, and also because there are fascinating similarities with how biological brains work, RC has become an important approach to making computing more 'cognitive' and also more energy-efficient than is possible with standard digital hardware. Jaeger's quest to model 'cognitive' information processing systems has led him to classical AI, robotics, signal processing, computational neuroscience, machine learning and neuromorphic computing. In all of these fields, he aims to find mathematically beautiful descriptions and efficient modelling/learning algorithms. Within CogniGron, he helps create mathematical/algorithmic bridges between AI, machine learning, computer science, mathematics, materials science and neuroscience. This means developing new 'cross-cultural' formalisms and models, a wonderful challenge both for the most abstract theoretical/conceptual process of thinking, as well as for the most concretely useful algorithm design.

Jaeger studied Mathematics and Psychology at the University of Freiburg and obtained his PhD in Computer Science (Artificial Intelligence) at the University of Bielefeld in 1994. After a five-year postdoctoral fellowship at the German National Research Centre for Computer Science (Sankt Augustin, Germany) he headed the Intelligent Dynamical Systems group at the Fraunhofer Institute for Autonomous Intelligent Systems AIS (Sankt Augustin, Germany). In 2003, he was appointed Associate Professor for Computational Science at Jacobs University Bremen, where he led the Modelling Intelligent Dynamical Systems (MINDS) group until his CogniGron appointment as Professor of Computing in Cognitive Materials on 1 August 2019.

Prof. Bart Besselink

Engineering Mathematics

Bart Besselink has been appointed as an Assistant Professor in Engineering Mathematics at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, within CogniGron. His position has been designed to bridge the expertise gap between mathematics and materials science. Besselink's research interests are in the analysis and control of large-scale dynamic systems with emphasis on nonlinear systems and model reduction problems. Currently, he focuses on the development of modular techniques for the analysis and control of such systems, including the analysis of large-scale electrical circuits with nonlinear elements such as memristors. Memristive devices are regarded as promising elements for cognitive computing as, first, they have dynamics that make them suitable for acting as synapses in artificial neural networks and, second, they have natural nanoscale implementations in specific materials. Within CogniGron, this research line targets the analysis of large-scale electrical circuits with memristive elements as models of neuromorphic materials, with the aim of understanding material behaviour as well as guiding the design of material network structures. Such analysis requires the development of novel mathematical tools to analyse the robustness of electrical circuit behaviour with respect to non-uniformity in the electrical components, then to synthesize the desired behaviour, and finally, study the scalability of such networks. Besselink received his MSc and PhD degrees in Mechanical Engineering from Eindhoven University of Technology, the Netherlands, in 2008 and 2012, respectively, both with a focus on systems and control theory. He was a short-term visiting researcher at Tokyo Institute of Technology, Japan, before becoming a postdoctoral researcher at the ACCESS Linnaeus Centre and Department of Automatic Control at KTH Royal Institute of Technology, Stockholm, Sweden, between 2012 and 2016.

Prof. Davide Grossi

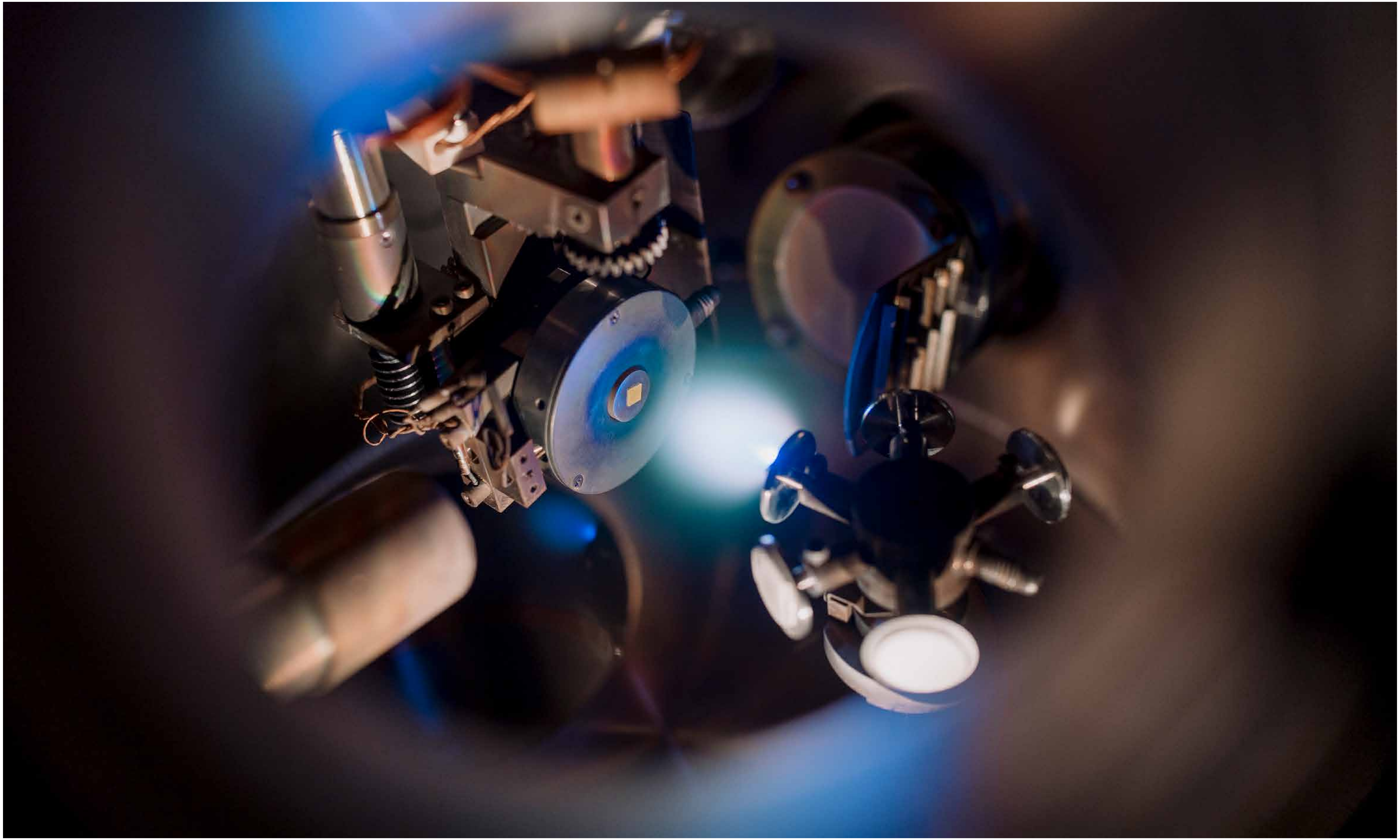
Cognitive Multi-Agent Systems

Davide Grossi has been appointed as an Associate Professor in Multi-Agent Decision-making at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence within CogniGron. His position has been designed to bridge the expertise gap between artificial intelligence and computer science. He works on foundational topics in artificial intelligence and multi-agent systems. His main research focus concerns the question: How do different autonomous (human or artificial) entities make good decisions as groups? Examples of processes of this type are elections, referenda, deliberative committees and assemblies, information markets and consensus protocols. Grossi currently explores whether tools from computational economics (e.g., game and social choice theory, network theory) can be used to gain insights into how groups of relatively simple entities (e.g., neurons) can (self-)organize to support computational processes.

Grossi obtained his degree in Philosophy (with distinction) at the University of Pisa and obtained his PhD in Computer Science at the University of Utrecht in 2007. After undertaking postdoctoral research at the University of Luxembourg and the University of Amsterdam, he became a lecturer (Assistant Professor) in the Department of Computer Science at the University of Liverpool, where he was promoted to senior lecturer (Associate Professor) in 2015. In 2017, he was appointed Associate Professor at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, within CogniGron. Grossi has authored over 60 peer-reviewed articles published in international journals and presented at international conferences, including top-tier journals and conferences in artificial intelligence. He has been the recipient of grants from research agencies in the UK (EPSRC) and the Netherlands (NWO), among other countries.

Outlook to 2022

In 2022, Julian Koellermeier will start as an Assistant Professor in Computational Mathematics at the Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence within CogniGron. We are looking forward to welcoming him in Groningen and working together.



‘We must find a theory for these material-based phenomena, that will help us to create a totally novel neuromorphic computer.’

Herbert Jaeger

Modern computers are very powerful, but they also consume a lot of energy. An AI language model that uses deep learning to produce texts that read as if they were written by humans, GPT-3, had to be trained using an enormous amount of text at the cost of some $10 million for electricity. ‘This is the down side of using digital systems with transistors that can only switch between 0 and 1’, explains Herbert Jaeger, Professor of Computing in Cognitive Materials at the Bernoulli Institute.

Jaeger joined CogniGron in 2019. ‘I was very lucky to get this position, as this institute is the ideal place for my niche in computer science. Everyone I would want to discuss my work with is here.’ Jaeger has a background in both computer science and mathematics. Later in his career, materials science came into the mix as well. He worked on robotics, signal processing and machine learning through neural networks. ‘But I am also the co-inventor of a method to use materials science to build simple demonstrator systems.’ As a senior scientist, an important part of his job is to build bridges between the different disciplines within CogniGron. ‘I give tutorials to the staff, organize meetings and generally bring the different communities together.’ This takes about half of his scientific working time. The other half is to work on a theoretical underpinning of new, materials-based computing methods.

The digital computers are a far cry from our brains. We can learn a new language with a brain using around 20 Watts, which is nothing to the energy use of GPT-3. ‘Evolution has found a way to exploit every possibility that physics and physiology can deliver. The neurons in our brain use more than two hundred different chemicals for transmitting signals to each other, and an unknown number of “computational” tricks. A computer only uses one type of switch: transistor on, transistor off, the famous 0 and 1 of digital computing. Neuromorphic computing will be totally different’, says Jaeger.

New materials, often at the nanoscale, promise to create new physical phenomena. ‘But the materials scientists don’t know yet exactly what to look for, which phenomena could contribute to this new way of computing.’ A theoretical foundation is needed on which to build the architecture and networks. ‘This should be created by theoretical computer scientists and AI specialists.’

As mentioned before, the new neuromorphic computer will not be a more complex variation of the digital computer. ‘So we need new metaphors’, Jaeger explains. ‘Like the ripple patterns you get when you throw a stone in a pond. You get a different interaction pattern with each throw. The new computer chips will be plastic, unformed. The training process will shape them for the right purpose. But no two chips will be the same, you can’t clone a successful one.’
There are no mathematical methods or models on the shelf to describe such systems. ‘You need something like chaos theory to describe them. Or the models biologists use to describe pattern formation in organisms. But no one knows which direction will be the right one. This field has no textbooks, just some volumes with collections of ideas. It will take many more years to turn this into a solid discipline.’

He has a research project together with CogniGron director Beatriz Noheda. Their two PhDs work on percolation in thin films, one from physics, the other from computer science. ‘We create slices of new materials and characterize them, and work out specific aspects of the phenomena that occur. This should give us some inspiration to move on, and some constraints on where we can go.’ The journey will take some time, but the reward can be great. ‘We must find a theory for these material-based phenomena, that will help us to create a totally novel neuromorphic computer.’

Research Projects

Cross-Disciplinary PhD Projects

Staff can participate and contribute to the CogniGron research programme by having a PhD student funded via this programme. A requirement is that staff and team members fully commit to the scientific goals and work plan of CogniGron. In addition, projects that strengthen the collaboration between different disciplines are prioritized. A 4-page proposal is submitted for each PhD. The proposal should clarify how the research directly addresses the main goals of CogniGron and how it will contribute solutions beyond the state of the art. In addition, the proposal should explain how it will make use or enhance the collaboration between different disciplines/institutes. The proposals are reviewed by the CogniGron Supervisory Board and, if needed, by the Scientific Advisory Panel composed of external experts.

Running projects awarded in 2021:

Smart Electronic Olfactory System (awarded in 2021)
The use of so-called electronic noses has spread widely in many industrial sectors thanks to their ability to detect chemicals in very small concentrations. In the health-care sector, this technology is starting to play a key role as a rapid and low-cost diagnostic tool for many diseases. In this project we are specifically interested in the development of an electronic noses for lung cancer detection.

Project leaders: Elisabetta Chicca, Maria Loi and Alden Waters.

Qualitative modelling, simulation and exploration of multi-phenomenal materials dynamics (awarded in 2021)
Current approaches to computing based on digital hardware have limitations and call for novel alternatives. The aim of this project is to pioneer a new qualitative physics formalism, together with a qualitative physics engine that is able to simulate a wide range of phenomena while being fast to run, replacing numerical accuracy by qualitative validity.

Project leaders: Herbert Jaeger and Beatriz Noheda

Running projects awarded before 2021:

Nanoparticle based percolating networks towards neuromorphic computing (awarded in 2020)
Nanoparticle percolating networks exhibit interesting switching behaviour and potentiation, which are characteristics of the brain with neurons and synapses. In this project, phase change material nanoparticles are designed, synthesised and mathematically modelled. These materials are expected to have a richer network activity and therefore excellent materials used for neuromorphic computing.

Project leaders: George Palasantzas, Bart Kooi, Holger Waalkens and Daniel Valesin

Nb-doped SrTiO3 memristive interfaces for bio-inspired computing (awarded in 2019)
This project studies the physics of interface-based memristive devices on semiconducting SrTiO3 substrates and develops phenomenological models to predict the performance of such devices.

Project leaders: Tamalika Banerjee and Lambert Schomaker

Towards a cognitive computer architecture based on memristive devices: developing short- and long-term memory (awarded in 2019)
The goal of this project is to build a pattern-completion memory, which we believe is a critical component in developing novel cognitive computing architectures. We will accomplish this by building a neural network in which memristive devices act as synapses, and potentially also as soma. One of the two sub-projects focuses on the development of networks, while the other focuses on the materials.

Project leaders: Niels Taatgen, Tamalika Banerjee and Jelmer Borst

WALLNET: Memristor networks from self-assembled domain walls in oxides (awarded in 2019)
This project investigates materials that self-organize in conducting networks that can transmit signals and host memory elements in a similar way to biological neurons and synapses.

Project leaders: Bart Besselink, Beatriz Noheda and Arjan van der Schaft

CogniGron Fellowships

Staff can also participate and contribute to the CogniGron research programme through a PhD student who works in close collaboration with external partners, preferably industry partners with a strong track record or interest in cognitive systems and materials. The goal of these CogniGron Fellowships is to strengthen interaction with industry. Additionally, it will give the PhD student the opportunity to take an inside view and collaborate with a world-leading industrial partner on cognitive computing. The primary supervisor will hold a position at the Faculty of Science and Engineering and the PhD degree will be awarded by the University of Groningen.

CogniGron-IBM Fellowships

We are very proud to announce the first CogniGron-IBM fellowships. CogniGron will partner with IBM in these projects to work on novel materials for neuromorphic computing.

COFERRAY: Combined volatile/non-volatile memristive ferroelectric arrays

The project aims to develop synaptic devices, like in the brain, based on ferroelectric materials. In particular, the goal is to build arrays of these (memristive) devices that can show both short-term and long-term potentiation and depression, which is important for the implementation of neural networks.

Project leaders: Beatriz Noheda, Bert Offrein (IBM-Research Zurich) and Jean Fompeyrine (Lumiphase AG)

Analogue phase-change memory cells for neuromorphic computing

Phase-change memories are, to date, arguably the most advanced resistive memory technologies. Phase-change memories are also being explored for in-memory computing applications, such as performing logical operations as well as realizing hardware substrates for neuromorphic computing. It has been shown that phase-change memory devices can emulate some of the key synaptic and neuronal functionalities, thus facilitating the realization of ultra-low power and dense neuromorphic hardware. In this project, we propose a relatively new concept of phase-change memory.

Project leaders: Bart Kooi and Abu Sebastian (IBM-Research Zurich)

First CogniGron PhD Thesis

On 5 November 2021, Wytse Talsma successfully defended his dissertation entitled “Low-dimensional solution-processable electronics: From field-effect transistor to artificial synapse” – the first PhD thesis with CogniGron research. We congratulate Dr. Talsma and his supervisor Prof. Maria Antonietta Loi. CogniGron is proud to have this as our first PhD thesis.

Thesis abstract

“Low-dimensional solution-processable electronics provide a potential solution to the need for novel computing hardware. Modern-day computing has irreversibly impacted our way of living. Nowadays, we are surrounded by computers that become smarter and more connected every day. The demand for more powerful hardware increases, while physical limitations already come into play. Pushing the boundaries of hardware development requires a new strategy, especially for (visual) pattern recognition. For this, novel candidate materials are semiconducting single-walled carbon nanotubes (s-SWCNTs). They promise inexpensive and scalable production methods for electronics. This thesis describes experimental research for the preparation and utilisation of these s-SWCNTs. We optimised s-SWCNT ink preparation by substituting the applicator-solvent in a colloidal dispersion of polymer-wrapped s-SWCNT. This resulted in improved shelf-life, field-effect transistor (FET) performances and device reproducibility. Also, we successfully demonstrated three newly designed low-bandgap polymers that wrap and select s-SWCNT. This resulted in FETs with improved energy-band alignment, potentially lowering energy consumption. More insight is provided into the relationship between the polymer structure and the dispersion capability for s-SWCNT, subsequently, the final inks’ physical properties. Finally, we demonstrated that sufficient plasticity arises to obtain a functional artificial synapse using simple pulse-shapes by utilising the hysteresis commonly found in bottom-gate structure SWCNT FETs. As synapses are the functional connection between neurons and are believed to be the units enabling learning and computing, our finding enables usage in more energy-efficient computing architecture. We conclude that our improved inks can be easily industrially applied. The artificial synapse can potentially be used by neuromorphic computing for everyday pattern recognition tasks, enabling more powerful hardware.”

The full dissertation can be found on the University Groningen webpage.

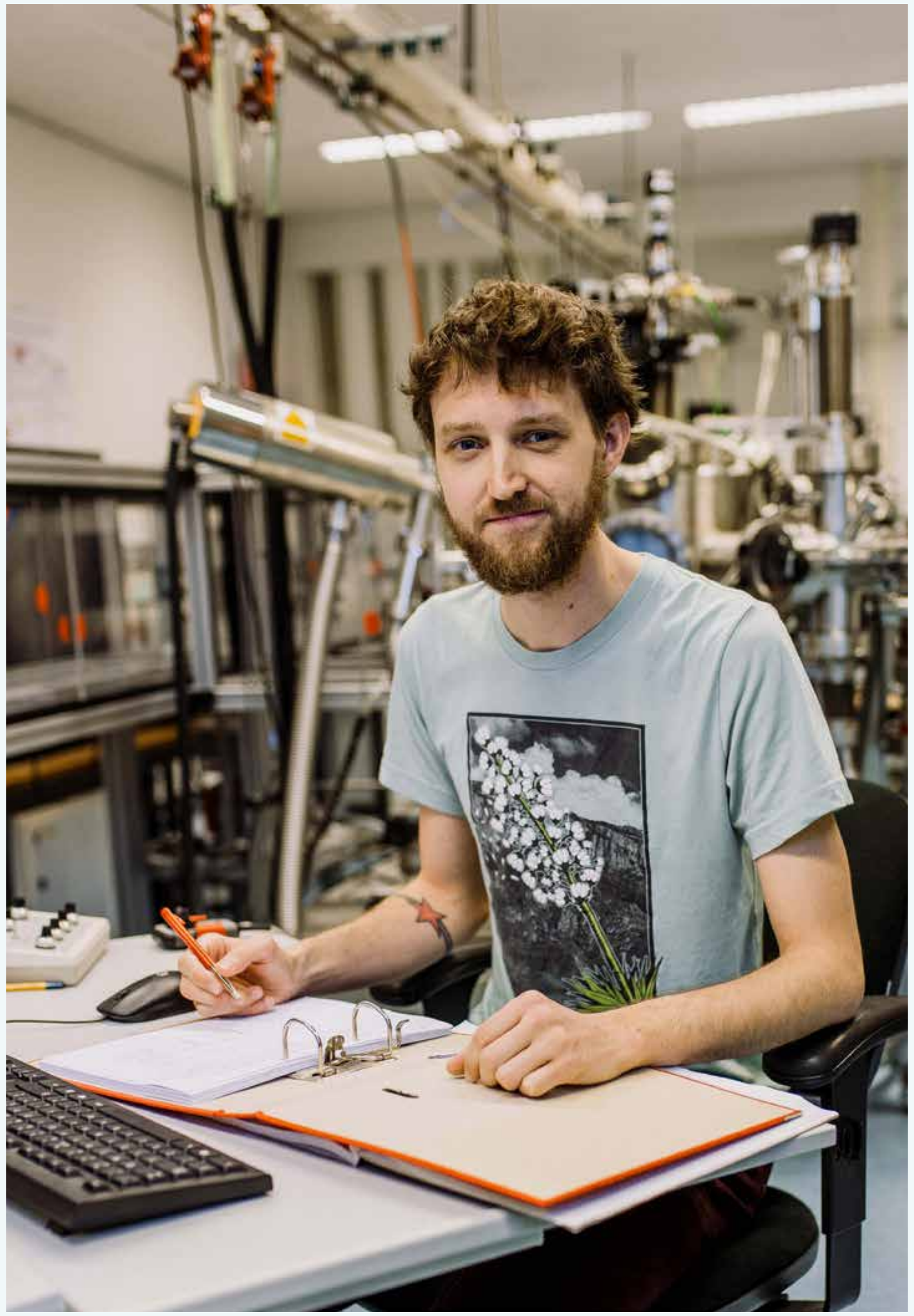
Collaboration with the International Centre for Neuromorphic Systems (WSU, Australia)

In 2021, CogniGron started a collaboration with the International Centre for Neuromorphic Systems at Western Sydney University, Australia. The vision and scientific ambition of the centre align perfectly with those of CogniGron. It is therefore more than natural to work together and to advance the field of neuromorphic computing and apply it to outstanding challenges in society.

The International Centre for Neuromorphic Systems aims to perform world-leading research to develop neuromorphic sensors, algorithms and processing hardware, and apply these to solve existing problems in modern society. The research of the centre focusses primarily on real-world applications of neuro-inspired perception and processing, where biological systems have natural advantages over conventional solutions because robust, low-power, high-speed processors must respond autonomously to noisy, unpredictable environments. The Centre is led by Prof. André van Schaik.

The best of both Worlds

The University of Groningen research centre CogniGron aims to develop a novel type of computer that is inspired by the brain. A lot of fundamental research on new materials and new technologies for this 'neuromorphic computing' is being conducted. Yet CogniGron won't be producing any computer chips. That is why the centre is collaborating with companies such as IBM. The IBM PhD Fellowship is a clear example of such a collaboration: two students enrolled in this programme, which provides them with the opportunity to work in Groningen and at the IBM Research Institute in Zürich, Switzerland.



Ruben Hamming-Green was the first IBM Fellow, he started in November 2019 at the University of Groningen and spent four months in Switzerland during the summer of 2020. He is looking forward to another few months at IBM Zürich later this year. 'I am making thin films of novel materials that could be used in neuromorphic computers. The production and initial assessment both take place in Groningen. I then take the thin films to Zürich, where I can use them in real devices.'

Materials science

Ruben applied for the IBM Fellowship programme because he wanted to do a PhD with his Master's thesis supervisor Beatriz Noheda, the scientific director of CogniGron. 'I was also looking for a position that would bring me into contact with research outside academia. I didn't fancy a university career.' Ruben, who grew up in New Mexico, USA, studied physics at the University of Groningen and took the Top Master's programme in Nanoscience there as well. 'My mother is Dutch,' he explains his choice for the Netherlands. 'And I came to Groningen specifically because of the Zernike Institute, as I was primarily interested in materials science.'

Jesse Luchtenveld, the second IBM Fellow, also completed his Bachelor's degrees in Applied Physics and Computing Science at the University of Groningen, where he joined the Honours Programme. 'I wasn't looking for a PhD position just yet but my supervisor, Professor Bart Kooi, offered me a place and I took it.' He is fascinated by physics. 'I really like how you can use fundamental knowledge to create something that has never existed before.' He is also producing thin films—in his case, of a phase change material. 'This can be switched between two phases that have different properties. In that way, it is possible to encode information.'

Equipment

He started in March 2021 and after a year in Groningen making his films, he is now in Zürich to further characterize their potential. This is one advantage of working in two different institutes. At the University of Groningen, there is advanced equipment to make thin films using pulsed laser deposition. But the devices that they can build here are relatively large, whereas IBM Zürich has equipment for miniaturization. Therefore, Jesse and Ruben can make devices there that are more like real computer parts.

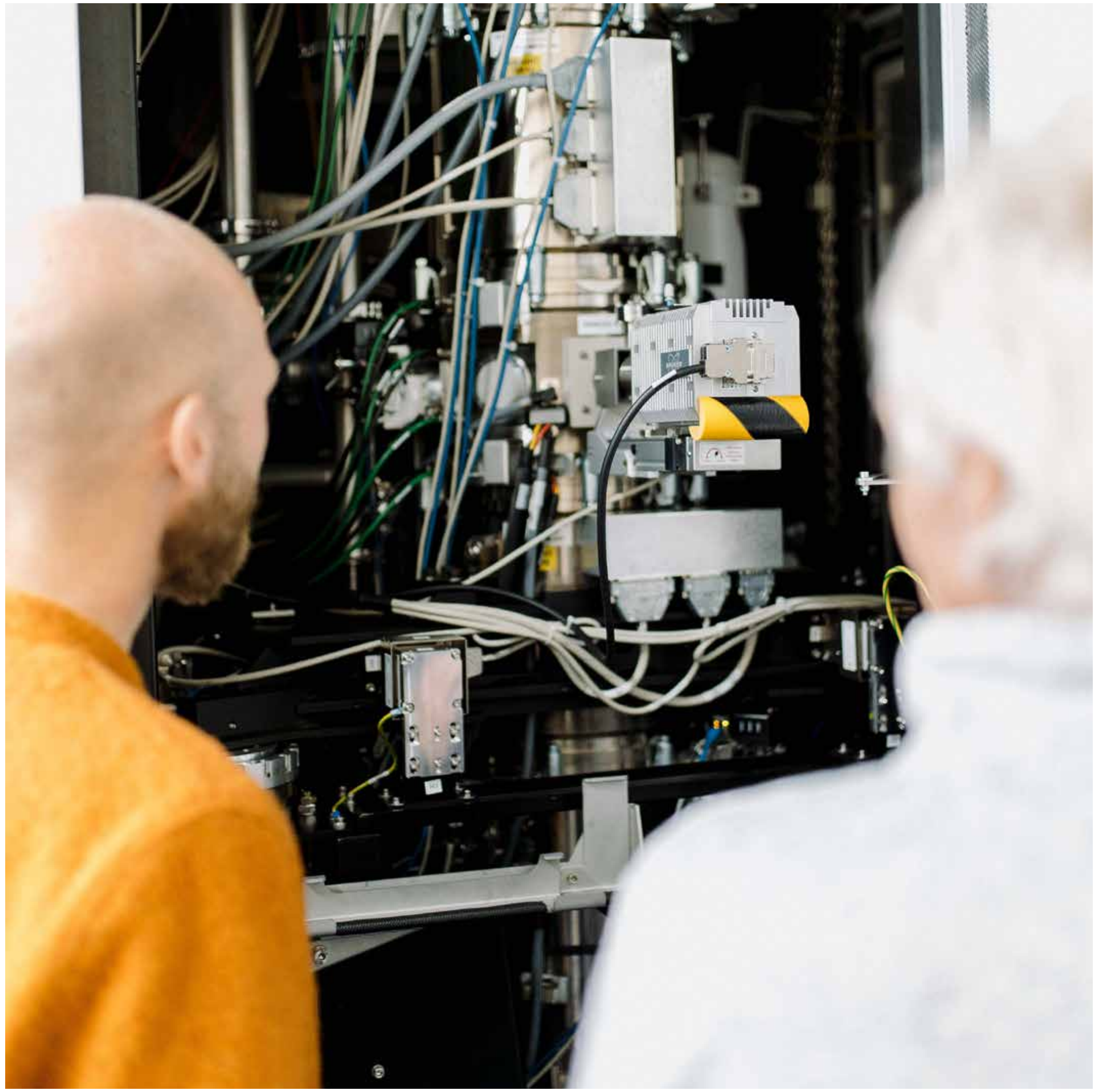
And it is not just the hardware that is complimentary. Working in an industrial environment is a bit different as well. 'In Groningen, I would see my supervisor perhaps once every two weeks,' says Jesse. 'Here, we meet twice a week.' Ruben finds the work more focused in Zürich: 'And faster paced. In Groningen, there is more individual work, whereas at IBM people work more in small teams.' Part of this difference can be explained by the nature of the projects: purely fundamental in Groningen and more applied in Zürich. Ruben: 'We basically already understand the stuff that we work on at IBM.' However, both also agree that IBM Zürich is a true research institute and as such, there are more similarities than differences compared to CogniGron. Jesse: 'I think that there are a couple of dozen PhD students here at any given time.'

Lunch

Of course, working in a different country highlights cultural differences beyond science. Having lived in Groningen for a long time, both Ruben and Jesse miss their bikes when in Zürich. Cycling is not common there and, as a result, not as safe as in the Netherlands. This is made up for by the much better hiking opportunities offered by the Swiss Alps. Another difference that Jesse noted is in the approach to eating lunch. His first impression is that it is more of a group activity in Switzerland, whereas in Groningen many will just grab a sandwich behind their desk. But Ruben sees less of a difference: 'My group in Groningen also always went out to lunch together.'

So, how do they see their futures? Both are keeping their options open. Ruben already mentioned that he doesn't aspire to an academic career. 'And in general, careers in neuromorphic computing are rare.' But the skills that they are learning are more general, such as the experimental techniques, as are the creative challenges and the dedication that is needed to obtain results. Doing all this in two different settings makes their work very rewarding. Jesse: 'And to me, physics is everything.'

Enabling Technologies



CogniGron aims to make fundamental advances towards a disruptive technology, and the efforts in this direction require sophisticated research facilities to synthesize and characterize materials and build devices. These facilities are in large part present at the University of Groningen. However, CogniGron has seen the opportunity to excel by supporting new developments in the form of two advanced research facilities: the electron microscopy centre and NanoLabNL.

Electron Microscopy Centre

The electron microscopy centre of the Zernike Institute for Advanced Materials was founded in 2019 to maintain and provide a coherent and accessible infrastructure for electron microscopy at the University of Groningen. The microscopy centre is made possible by and will primarily be used by the Zernike Institute for Advanced Materials and CogniGron. Electron microscopy is of key importance for the research of CogniGron as it facilitates studying the ultimate origin of memristive behaviour in the materials that will function as artificial (electronic) synapses or neurons. To this end, CogniGron invested (together with the Zernike Institute for Advanced Materials) in the purchase of a new transmission electron microscope (TEM) that allows the study of the structure of materials in unprecedented detail. One of its unique abilities is to produce images of both heavy and very light atoms simultaneously. The purchase also included a second system: a scanning electron microscope, combined with a focused ion beam, which allows scientists to study the general structure of materials (using an electron beam) and extract interesting sections using the ion beam for detailed study in the new TEM. Professor Bart Kooi is primarily responsible for running the new microscope.

NanoLabNL: nanofabrication facilities

NanoLabNL is a national consortium that was created to build, maintain and provide a coherent and accessible infrastructure for nanotechnology research and innovation in the Netherlands. However, with recent funding developments, maintaining the NanoLabNL facility through necessary updates – especially to keep up with developments in other countries in our region – is becoming a challenge.

The long-term stability of NanoLabNL is vital for CogniGron and we believe there is a need for CogniGron and NanolabNL to work together and make sure the facilities are up-to-date with the newest technological advances. Since the goal of CogniGron is closely related to developing novel electronic devices, for which the nanolithography and fabrication facilities provided by NanoLabNL are crucial, CogniGron has reserved funds to support NanoLabNL in the form of a new electron beam evaporator as well as a technician to support the new PhD students and staff who will be using the NanoLabNL facilities in Groningen. We are aware that more support is needed to maintain the NanoLabNL facilities in Groningen at international standards, and we are constantly working with the NanoLabNL management team to find solutions. Therefore, CogniGron has reserved 100 k€ per year for the running costs of NanolabNL Groningen from 2021 until 2025.

CogniGron Activities

Discussion Sessions

One of the keys to a successful research programme is to create sustainable synergy in a unique environment where everyone – from materials scientists to the computer scientists and from artificial intelligence scientists to mathematicians – speaks the same language and understands each other's motivations with respect to the common goal. Only then will partnerships arise naturally.

Therefore, we dedicate considerable effort to organizing brainstorming and discussion sessions of half-day duration, to which all the researchers at the Zernike and Bernoulli Institutes with interests close to CogniGron are invited. In these sessions, which have had various formats, the staff learn about each other's expertise and the first concrete ideas are developed for joint collaborations.

During the COVID-19 pandemic, when meetings had to be organized via various online platforms, we noticed that half-day meetings or meetings with larger groups did not have the desired effect. Therefore, we encouraged researchers to organize (online) meetings or discussion sessions with smaller numbers of people. These sessions have already produced several working teams and collaborative research projects.

Student Discussion Sessions

Working together with a multidisciplinary team means stepping out of your comfort zone. This is a challenging and time-consuming activity. To facilitate interactions and cross-disciplinary communication, all newly appointed professors work in more than one field and feel comfortable in two or more different worlds. In this respect, we have high expectations of the PhD students working at CogniGron, where they grow up in an inter- and multi-disciplinary environment. The PhD students will also form the solid foundation upon which the future of CogniGron will be built. CogniGron is, therefore, very happy to see that the students themselves organize weekly meetings with an informal character to discuss their scientific results and scientific challenges they face at the moment, and to keep up to date by discussing literature. Occasionally, they also invite researchers to give a presentation in these meetings.

CogniGron@Work Sessions

Being a very new and different initiative, we are aware that we need to make an extra effort to convey our goals and working philosophy to others, including those in our close neighbourhood, as well as to promote the exchange of research progress and ideas. It is with that purpose in mind that from January 2021 weekly CogniGron@Work (CogniGron at work) sessions have been initiated. In these sessions, two or more researchers from CogniGron explain their collaborative work, with a focus on the cross-disciplinary character of the research.

CogniGron Seminars for Invited Speakers

We consider the opportunity to invite experts from around the world to visit Groningen as one of the most important assets of CogniGron. This has been highly advantageous, not only to gain a better understanding of the latest developments in this diverse and emerging field of Cognitive Systems and Materials, but also to create a sense of community and, most importantly, to make CogniGron known to the international and national communities. We are proud of the list of internationally recognized experts who have kindly accepted our invitation and have spent days with us sharing their research ideas and also learning first-hand about the CogniGron vision. In the CogniGron webpages a complete list of speakers is provided, including the titles and dates of their presentations. Unfortunately, due to COVID-19, the list of speakers in the CogniGron seminar series of 2021 is quite short:

Gert Cauwenberghs (UCSD, USA)
Towards Efficient Neuromorphic Learning and Inference at Scale
January 13, 2021

James Smith (University of Wisconsin-Madison, USA)
A Temporal Neural Network Architecture for Online Learning
February 15, 2021

Martin Ziegler (Technische Universität Ilmenau, Germany)
Memristive systems for the emulation of biological learning
February 4, 2021

Alexander Ako Khajetoorians (Radboud University, Nijmegen)
What can we 'learn' from atoms? Going beyond neuromorphics
March 9, 2021

Stefano Fusi (Columbia University, NY, USA)
Memory compression leads to spatial tuning in the hippocampus
March 23, 2021

Matteo Mirigliano (University of Milan, Italy)
The RECEPTRON: a Boolean classifier based on multi-electrode cluster-assembled Au films with non-local and non-linear electrical conduction properties
May 17, 2021

Marcelo Rozenberg (CNRS - Université Paris Saclay, France)
Solid State Neuroscience
June 22, 2021

Nynke Vellinga (University of Groningen, the Netherlands)
Automated driving: legal hurdles on the road ahead
November 17, 2021

Federico Corradi (Holst Centre – IMEC, the Netherlands)
Spike-based neuromorphic computing for the extreme edge
November 19, 2021

CogniGron Goes Out

Due to COVID-19, most conferences, symposia and workshops that were scheduled for 2021 were cancelled or postponed. However, CogniGron researches did have some opportunities to present their recent work to colleagues around the globe and to be involved on the organization of workshops and conferences.

Conferences, Symposia and Workshops

NEUROTECH Education Programme: "What is neuromorphic engineering?"
Workshop series organized by partner organizations as part of the EU Horizon 2020 FETPROACT CSA project on Community Building in Neuromorphic Computing Technologies (NCT) under grant agreement no. 824103
Monthly

MANIC-ETN Network Wide Event
Conference organized as part of the EU Horizon 2020 programme under Marie Skłodowska-Curie grant agreement no. 861153
April 12-16, 2021

Professor Francken Symposium "Cognitive Matters"
Organized by Professor Francken, the study association for engineering physics in Groningen, and CogniGron.
Groningen, the Netherlands.
May 12, 2021

Workshop Randomness Unleashed Geometry, Topology and Data
Organized by CogniGron.
Groningen, the Netherlands.
June 22, 2021

Conference Contributions Featuring CogniGron

Lyes Khacef – Contributed Talk
Intel Neuromorphic Research Community (INRC) Winter Workshop 2021, Online
February 8-12, 2021

Tamalika Banerjee – Invited Talk
VIT Colloquium
March 10, 2021

Tamalika Banerjee – Invited Talk
Institute of Neural Computation, University of California San Diego
June 17, 2021

Hebert Jaeger – Keynote Talk
Second International Workshop on Theoretical and Experimental Material Computing (TEMC 2020; postponed), York, UK
July 19-23, 2021

Tamalika Banerjee – Invited Talk
ALife, Second International Workshop on Theoretical and Experimental Material Computing
July 21, 2021

Jan Rieck – Poster Presentation
International School of Oxide Electronics, Cargèse, France
August 24 – September 3, 2021

Lyes Khacef – Contributed Talk
Neural Interfaces and Artificial Senses (NIAS) Conference, Online
September 22 – 23, 2021

Gilles Bonnet – Contributed Talk
German Probability & Statistics Days, Mannheim (online), Germany,
September 27, 2021

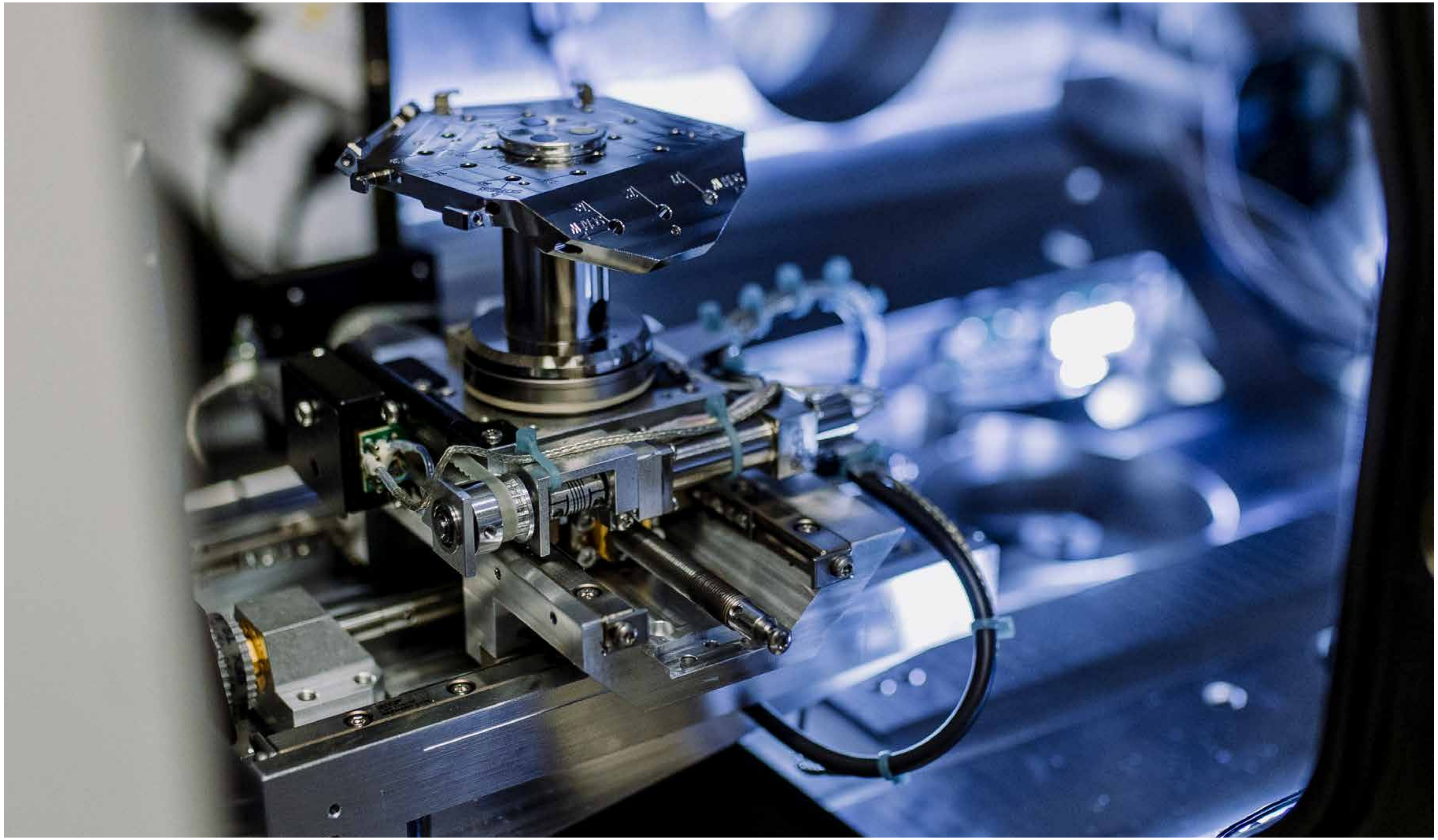
Herbert Jaeger – Contributed Talk
Annual Meeting of DPG and DPG-Tagung (DPG Meeting) of the Condensed Matter Section (SKM)
September 27 – October 1, 2021

Herbert Jaeger – Guest Lecture
Oslo AI Lab / NordStar research center, AI Lab seminar
November 2021

Anne-Men Huijzer – Contributed Talk
60th IEEE Conference on Decision and Control, Austin, Texas, USA
December 13-17, 2021

Industry Relations

Below we alphabetically list the industrial partners who in 2021 worked directly with CogniGron or collaborated via projects involving CogniGron researchers.



aixACCT Systems GmbH
Aachen, Germany

Building Between Bridges
Kortemark, Belgium

CrysTec GmbH
Berlin, Germany

DENSsolutions BV
Delft, the Netherlands

IBM Research Zurich
Zurich, Switzerland

IMEC - Holst
Eindhoven, the Netherlands

Océ Technologies BV
Venlo, the Netherlands

SmartTip BV
Enschede, the Netherlands

Solmates BV
Enschede, the Netherlands

Twente Solid State Technology BV
Enschede, the Netherlands

News Highlights

Pedestrians in Zuidhorn test the computer of the future

Researchers from CogniGron and the Engineering institute ENTEG, in collaboration with the Municipality of Westerkwartier near Groningen, laid a 'Piezo tile' connected to a data processor in the pavement next to Zuidhorn train station. The tile registers passengers passing by and the computer analyses the data. The computer is designed to be a plug-and-play system, in which the different items can easily be replaced. The goal is to develop a neuromorphic chip that demonstrates orders of magnitude gains in energy efficiency, eventually leading to an autonomous/self-powered system. The Zuidhorn setup can be used to test, and further develop, the different neuromorphic chips and computer architectures that are developed by CogniGron.

Neuromorphic Computing and Engineering Journal

There is finally a journal exactly fitting the scope of CogniGron: *Neuromorphic Computing and Engineering*. The journal aims to be the reference journal in the field, and truly multidisciplinary.

With Giacomo Indiveri (Member of the CogniGron Advisory Board) as the Editor-in-Chief, the quality of the papers is warrantied. Elisabetta Chicca (CogniGron) is in the Senior Advisory Board. Yoeri van de Burgt (Member of the CogniGron Advisory Board) and Beatriz Noheda (CogniGron director) are members of the Editorial Board.

Review article from Herbert Jaeger reaches >5K downloads

The first accepted manuscript in the new journal *Neuromorphic Computing and Engineering* is by Herbert Jaeger. The review article is titled "Toward a generalized theory comprising digital, neuromorphic, and unconventional computing" in which he investigates coordinates and conditions for a generalized concept of "computing" which comprises digital, neuromorphic, unconventional and possible future paradigms. By now the review article has reached over 5K downloads and is trending on Altmetrics.

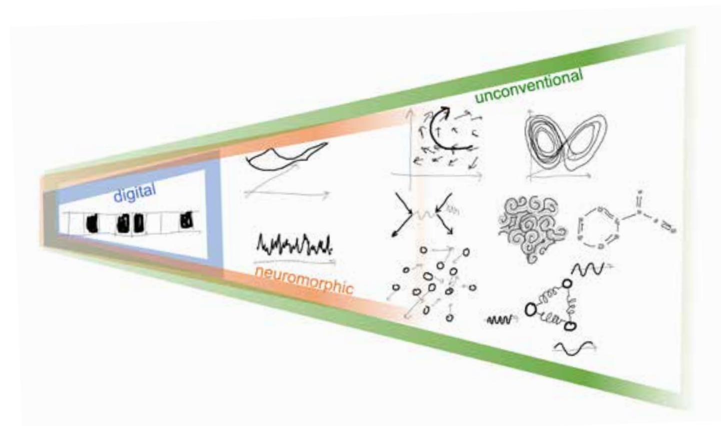


Figure 2. Image taken from "Neuromorph. Comput. Eng. 1 (2021) 012002"

Awards and Prizes in 2021

Jan Rieck (PhD student at CogniGron) received an APL Materials Excellence in Research Award for his publication on SrTiO3-based memristive devices. The publication is titled "Trade-off between variability and retention of memristive epitaxial SrTiO3 devices" and presents a study on SrTiO3 -based memristive devices. The research was performed during Rieck's Master's research project at the Peter Grünberg Institute (Forschungszentrum Juelich, Germany) under the supervision of Prof. Regina Dittmann. The publication provides valuable insights for applying memristive SrTiO3 devices as non-volatile memories or in neural networks - a study that is very relevant for CogniGron.

Dr. Julie Grollier (CogniGron Scientific Advisory Panel) received the Irène Joliot Curie Prize for Woman Scientist of the Year. The prize highlights that Grollier is a great inspiration to many scientists. Since 2001, the French Ministry of Higher Education, Research and Innovation has been committed to promoting the place of women in research and technology in France with this prize, supported by the French Academy of Sciences and the French Academy of Technologies.

Dr. Lyes Khacef (postdoctoral researcher at CogniGron) received the first thesis prize from the Sciences and Technologies of Information and Communication (STIC) doctoral school at the Université Côte d'Azur. The thesis discusses the modeled self-organized artificial neural networks utilizing a mechanism of structural plasticity to create or cut connections, as well as a mechanism of synaptic plasticity which allows to modify the strength of these connections.

Publications

Highlighted Publications

After the first years of CogniGron, and with new staff hired and postdoctoral researchers and PhD students starting their projects, an increasing number of scientific results are being published. From the publications submitted in 2021, we highlight the following:

Towards a generalized theory comprising digital, neuromorphic and unconventional computing

By Herbert Jaeger in *Neuromorph. Comput. Eng.* 1, 012002 (15 July 2021)
"The accelerating race of digital computing technologies seems to be steering towards impasses—technological, economical and environmental—a condition that has spurred research efforts in alternative, 'neuromorphic' (brain-like) computing technologies. Furthermore, for decades, the idea of exploiting nonlinear physical phenomena 'directly' for non-digital computing has been explored under names like 'unconventional computing', 'natural computing', 'physical computing', or 'in-materio computing'. In this article I investigate coordinates and conditions for a generalized concept of 'computing' which comprises digital, neuromorphic, unconventional and possible future 'computing' paradigms. The main contribution of this paper is an in-depth inspection of existing formal conceptualizations of 'computing' in discrete-symbolic, probabilistic and dynamical-systems oriented views. It turns out that different choices of background mathematics lead to decisively different understandings of what 'computing' is. However, across this diversity a unifying coordinate system for theorizing about 'computing' can be distilled."

Skin-Inspired Flexible and Stretchable Electrospun Carbon Nanofiber Sensors for Neuromorphic Sensing

By Debarun Sengupta, Michele Mastella, Elisabetta Chicca and Ajay Giri Prakash Kottapalli in *ACS Appl. Electron. Mater.* 4, 1, 308–315 (January 2, 2022)
"During the past few decades, a significant amount of research effort has been dedicated toward developing skin-inspired sensors for real-time human motion monitoring and next-generation robotic devices. Although several flexible and wearable sensors have been developed in the past, the need of the hour is developing accurate, reliable, sophisticated, facile yet inexpensive flexible sensors coupled with neuromorphic systems or spiking neural networks to encode tactile information without the need for complex digital architectures, thus achieving true skin-like sensing with limited resources. In this work, we propose an approach entailing carbon nanofiber–polydimethylsiloxane composite-based piezoresistive sensors, coupled with spiking neural networks, to mimic skin-like sensing. The strain and pressure sensors have been combined with appropriately designed neural networks to encode analog voltages to spikes to recreate bioinspired tactile sensing and proprioception. To further validate the proprioceptive capability of the system, a gesture tracking smart glove, combined with a spiking neural network, was demonstrated. Wearable and flexible sensors with accompanying neural networks such as the ones proposed in this work will pave the way for a future generation of skin-mimetic sensors for advanced prosthetic devices, apparel integrable smart sensors for human motion monitoring, and human-machine interfaces."

Peer-Reviewed Publications 2021

A. Balasubramanian, T. Lang, R. Ramanayake, in *2021 36th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS).* (IEEE, 2021), pp. 1-13.

S. A. Bethuelsen, C. Hirsch, C. Mönch, Quenched invariance principle for random walks on dynamically averaging random conductances. *Electronic Communications in Probability* 26, 1-13 (2021).

A. Ciabattoni, T. Lang, R. Ramanayake, Bounded-analytic sequent calculi and embeddings for hypersequent logics. *The Journal of Symbolic Logic* 86, 635-668 (2021).

A. Ciabattoni, T. S. Lyon, R. Ramanayake, A. Tiu, Display to Labeled Proofs and Back Again for Tense Logics. *ACM Transactions on Computational Logic (TOCL)* 22, 1-31 (2021).

Y. Couzinié, C. Hirsch, Weakly reinforced Pólya urns on countable networks. *Electronic Communications in Probability* 26, 1-10 (2021).

E. Covi *et al.*, in *2021 IEEE International Symposium on Circuits and Systems (ISCAS).* (IEEE, 2021), pp. 1-5.

S. Damerio *et al.*, Antiferromagnetic Ordering and Uncoupled Spins in CaFe2O4 Thin Films Probed by Spin Hall Magnetoresistance. *Advanced Electronic Materials*, 2100963 (2021).

A. S. Goossens, M. Leiviskä, T. Banerjee, Anisotropy and Current Control of Magnetization in SrRuO3/SrTiO3 Heterostructures for Spin-Memristors. *Frontiers in Nanotechnology* 3, 37 (2021).

R. Goré, R. Ramanayake, I. Shillito, in *International Conference on Automated Reasoning with Analytic Tableaux and Related Methods.* (Springer, 2021), pp. 299-313.

Q. Guo, B. Noheda, From hidden metal-insulator transition to Planckian-like dissipation by tuning the oxygen content in a nickelate. *npj Quantum Materials* 6, 1-7 (2021).

D. Gutierrez-Galan *et al.*, An event-based digital time difference encoder model implementation for neuromorphic systems. *IEEE Transactions on Neural Networks and Learning Systems,* (2021).

M. Heydenreich, C. Hirsch, Extremal linkage networks. *Extremes,* 1-27 (2021).

C. Hirsch, M. Holmes, V. Kleptsyn, Absence of WARM percolation in the very strong reinforcement regime. *The Annals of Applied Probability* 31, 199-217 (2021).

C. Hirsch, S. B. Moka, T. Taimre, D. P. Kroese, Rare events in random geometric graphs. *Methodology and Computing in Applied Probability*, 1-17 (2021).

A.-M. Huijzer, A. van der Schaft, B. Besselink, in *2021 60th IEEE Conference on Decision and Control (CDC).* (IEEE, 2021), pp. 6264-6269.

H. Jaeger, Towards a generalized theory comprising digital, neuromorphic and unconventional computing. *Neuromorphic Computing and Engineering* 1, 012002 (2021).

B. Jahnel, C. Hirsch, E. Cali, Percolation and connection times in multi-scale dynamic networks. (2021).

A.-M. Jürgensen, A. Khalili, E. Chicca, G. Indiveri, M. P. Nawrot, A neuromorphic model of olfactory processing and sparse coding in the Drosophila larva brain. *Neuromorphic Computing and Engineering* 1, 024008 (2021).

A. Kugele, T. Pfeil, M. Pfeiffer, E. Chicca, in *DAGM German Conference on Pattern Recognition.* (Springer, 2021), pp. 297-312.

M. Mastella, E. Chicca, in *2021 IEEE International Symposium on Circuits and Systems (ISCAS).* (IEEE, 2021), pp. 1-5.

M. Mastella, E. Chicca, in *2021 IEEE International Symposium on Circuits and Systems (ISCAS).* (IEEE, 2021), pp. 1-5.

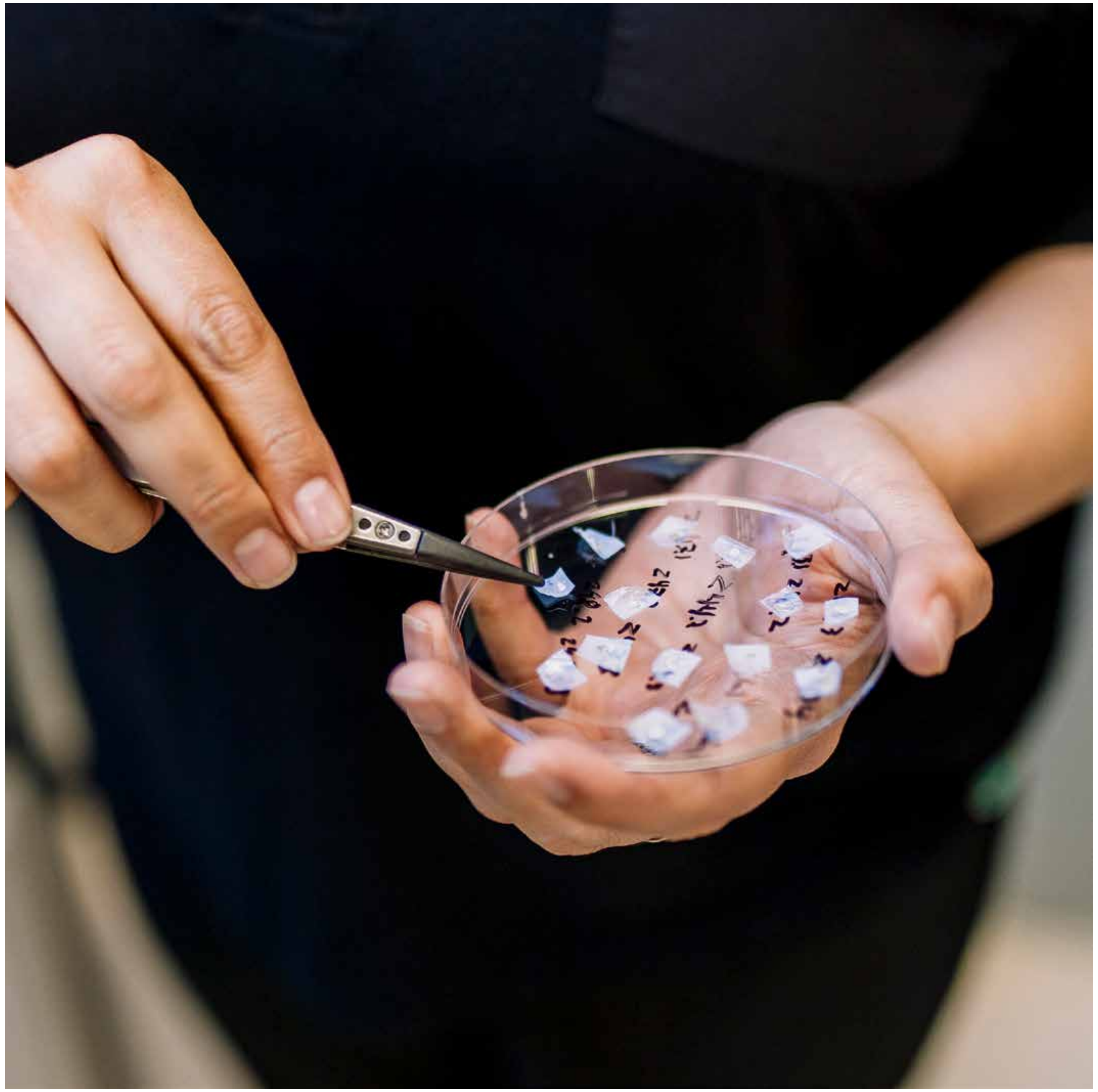
P. Nukala *et al.*, Reversible oxygen migration and phase transitions in hafnia-based ferroelectric devices. *Science* 372, 630-635 (2021).

C. P. Quinteros, J. Antoja-Lleonart, B. Noheda, Plausible physical mechanisms for unusual volatile/non-volatile resistive switching in HfO2-based stacks. *Condensed Matter* 6, 7 (2021).

S. Shao *et al.*, Field-effect transistors based on formamidinium tin triiodide perovskite. *Advanced Functional Materials* 31, 2008478 (2021).

T. F. Tiotto, A. S. Goossens, J. P. Borst, T. Banerjee, N. A. Taatgen, Learning to Approximate Functions Using Nb-Doped SrTiO3 Memristors. *Frontiers in neuroscience*, 1456 (2021).

External Funding



We are aware of the unique position that we have and are committed to obtaining the maximum benefits by developing strategic partnerships by means of national or international consortia and taking advantage of the available matching schemes, as long as the partnerships do not compromise our focus. CogniGron is actively participating in or coordinating externally funded projects. Details are provided below:

EU Funding

BeFerroSynaptic – BEOL technology platform based on ferroelectric synaptic devices for advanced neuromorphic processors
This project has received funding from the EU Horizon 2020 research and innovation programme under grant agreement no, 871737
Coordinator: Stefan Slesazeck (NaMLab gGmbH, Germany)
CogniGron participant: Elisabetta Chicca

MANIC – Materials for Neuromorphic Circuits
This project has received funding from the EU Horizon 2020 programme under Marie Skłodowska-Curie grant agreement no. 861153
Coordinators: Beatriz Noheda (Groningen) and Bernd Gotsmann (IBM-Research Zurich, Switzerland)
CogniGron participants: Beatriz Noheda and Elisabetta Chicca

MeM-Scales – Memory technologies with multi-scale time constants for neuromorphic architectures
This project has received funding from the EU Horizon 2020 programme under grant agreement no. 871371
Coordinator: Elisa Vianello (CEA-Leti, Grenoble, France)
CogniGron participant: Herbert Jaeger

MELON – Memristive and multiferroic materials for emergent logic units in nanoelectronics
This project has received funding from the EU Horizon 2020 Research and Innovation Staff Exchange programme under grant agreement no. 872631
Coordinator: Igor Lukyanchuk (University of Picardie Jules Verne, France)
CogniGron participant: Beatriz Noheda

NeuroTech – Neuromorphic Technology
This project has received funding from the EU Horizon 2020 FETPROACT CSA project on Community Building in Neuromorphic Computing Technologies (NCT) under grant agreement no. 824103
Coordinator: Giacomo Indiveri (The University of Zurich and ETH Zurich, Switzerland)
CogniGron participant: Elisabetta Chicca

NouTouch – Understanding neural coding of touch as enabling technology for prosthetics and robotics
This project has received funding from the European Research Council (ERC) under grant agreement no. 813713
Coordinator: Chiara Bartolozzi (Istituto Italiano di Tecnologia, Italy)
CogniGron participant: Elisabetta Chicca

National Funding

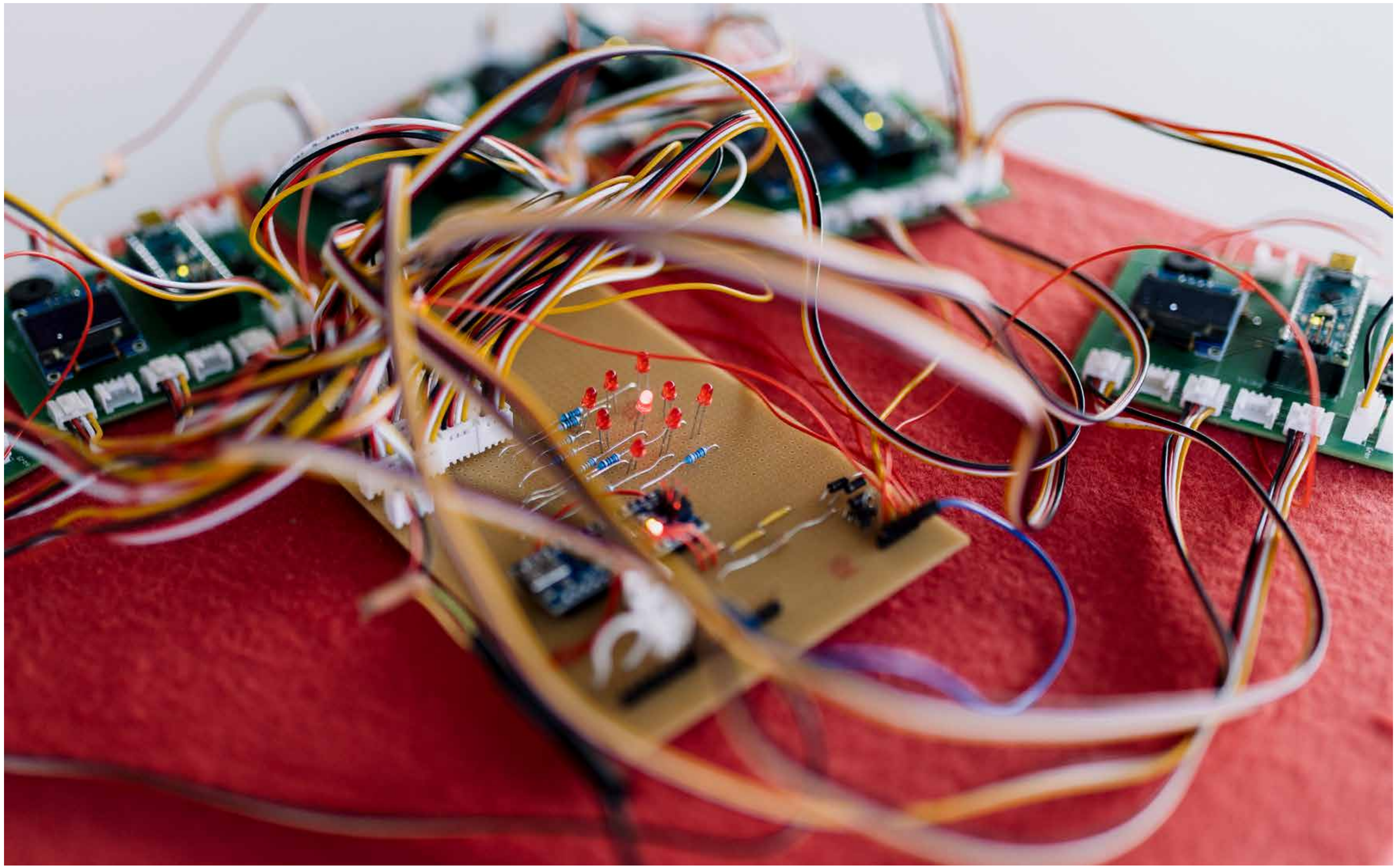
Materials for neuromorphic devices
This project has received funding from an NWO Visitor's Travel Grant under grant agreement no. 9047
Applicant: Beatriz Noheda
Visitor: Prof. Diego Rubi (University of Buenos Aires, Argentina)

International Funding

MemTDE – Memristive Time Difference Encoder
This project has received funding from the German Science Foundation (DFG) under individual research grant agreement no. 441959088
Applicant: Elisabetta Chicca
CogniGron participant: Elisabetta Chicca

MAKI - Multi-Mechanisms Adaptation
This project has received funding from the German Science Foundation (DFG) via the Collaborative Research Centre 1053
Applicant: Boris Koldehofe
CogniGron participant: Boris Koldehofe

Contact Information



CogniGron - Groningen Cognitive Systems and Materials Center

Website:	www.rug.nl/research/fse/cognitive-systems-and-materials/
Director:	**Prof. Beatriz Noheda**
Tel:	+31 50 363 4565
Email:	b.noheda@rug.nl
Scientific Coordinator:	**Dr. Jasper van der Velde**
Tel:	+31 (0)6 48 49 63 18
Email:	j.h.m.van.der.velde@rug.nl

Visiting address:

University of Groningen
Faculty of Science and Engineering
Nijenborgh 4
9747 AG
Groningen
The Netherlands

Office 5117.0016 (Prof. Beatriz Noheda)
Office 5117.0014 (Dr. Jasper van der Velde)

Annual Report **CogniGron** 2021

Annual Report CogniGron 2021