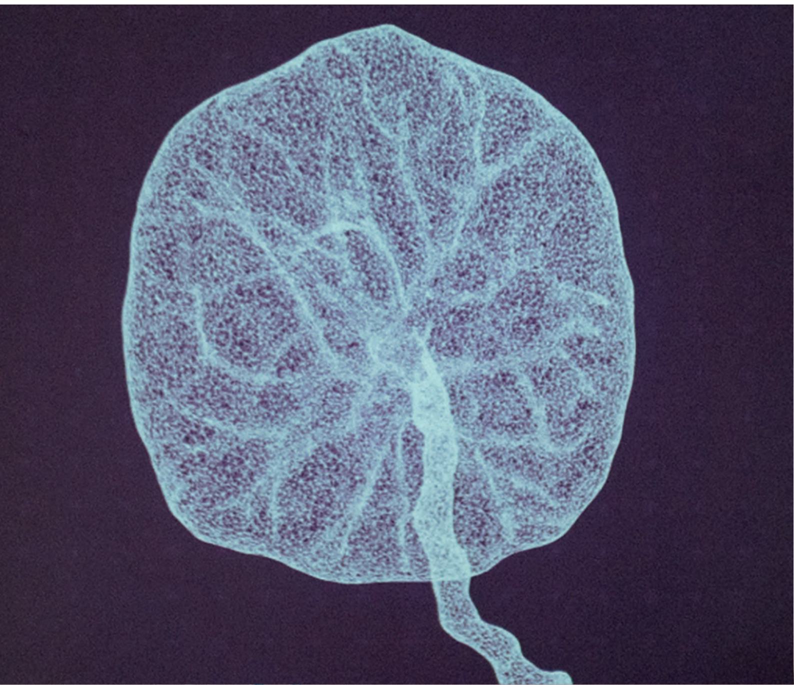
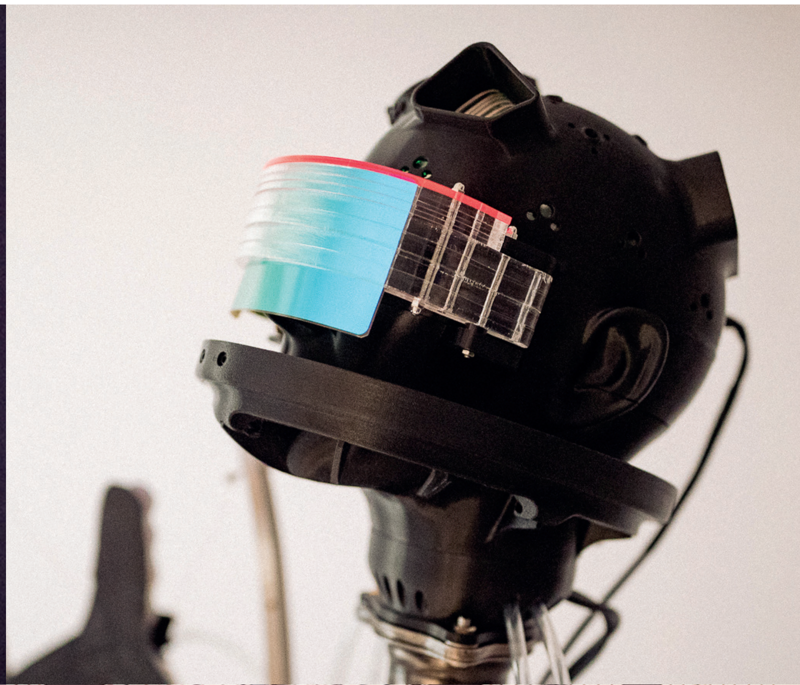
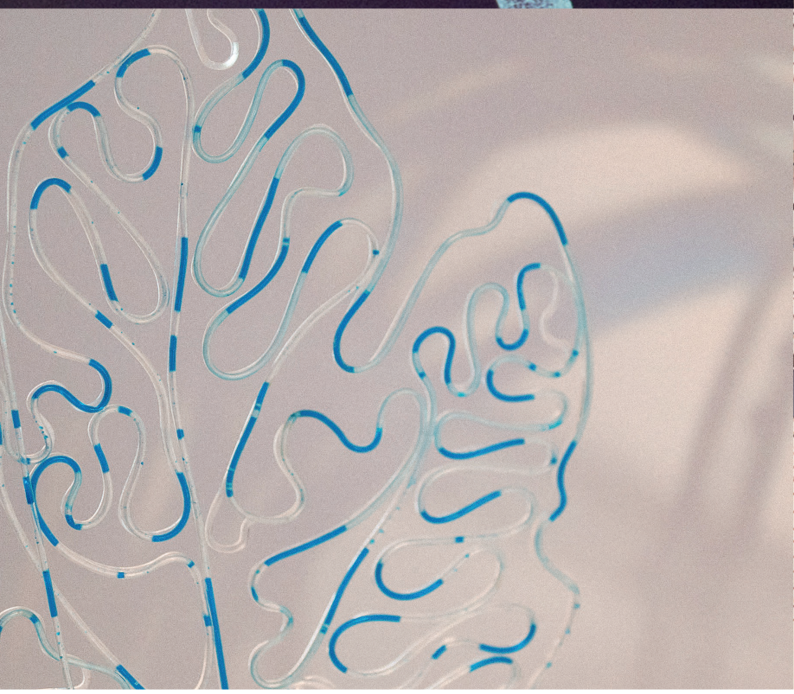
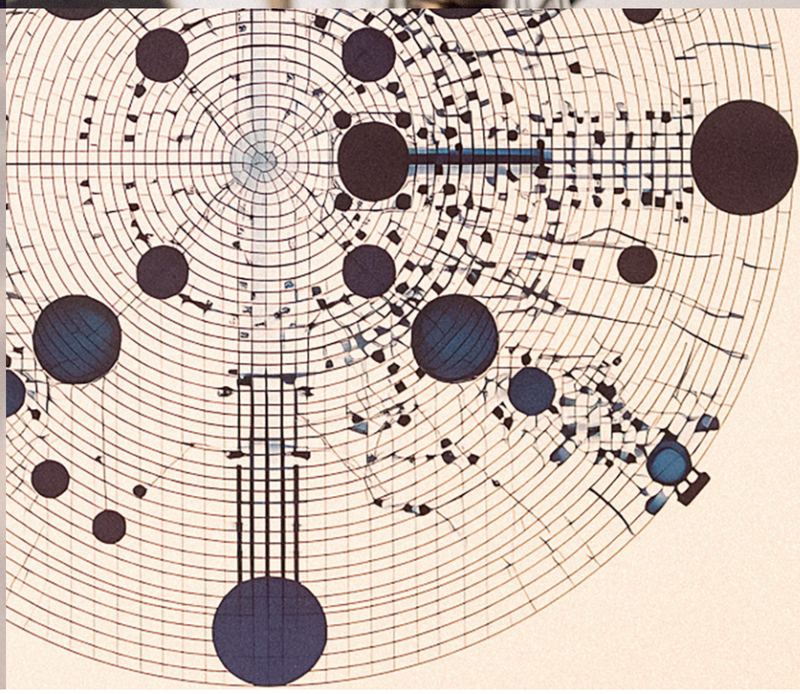
PoreLab
NTNU-UiO Porous Media Laboratory

Annual Report 2023

NTNU
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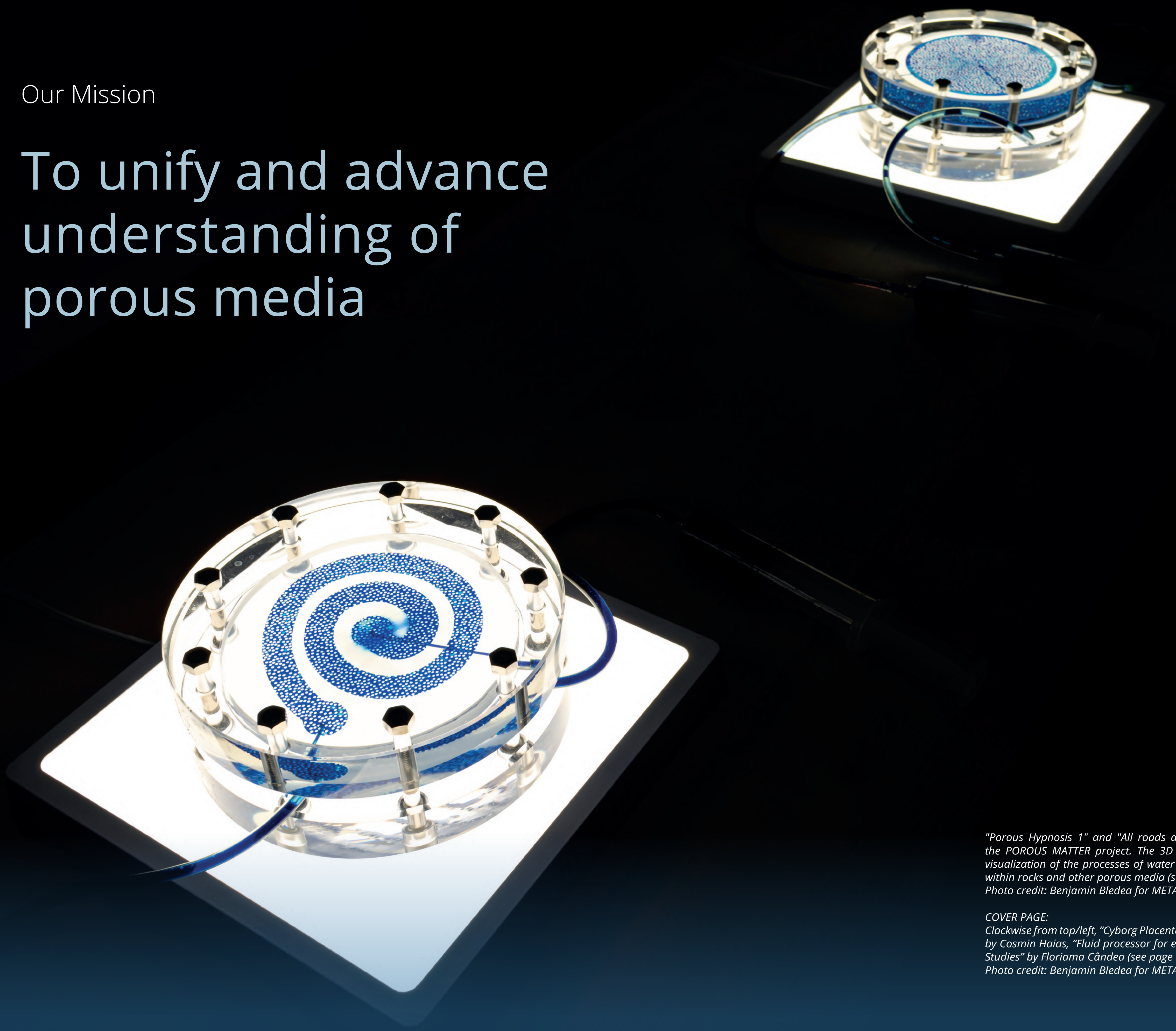
UiO University of Oslo

Norwegian Centre of Excellence
The Research Council of Norway

Our Mission

To unify and advance understanding of porous media



"Porous Hypnosis 1" and "All roads are porous" are creations by Dr. Marcel Moura for the POROUS MATTER project. The 3D printed transparent porous structures represent a visualization of the processes of water infiltration into soil during rain or how fluids move within rocks and other porous media (see page 8)
Photo credit: Benjamin Bledea for META Spatiu contemporary art gallery

COVER PAGE:
Clockwise from top/left, "Cyborg Placenta" by María Castellanos, "H111 – unfortunate Cookies" by Cosmin Haias, "Fluid processor for ecological computing" by Stahl Stenslie, "Internal flow Studies" by Floriama Cândea (see page 8)
Photo credit: Benjamin Bledea for META Spatiu contemporary art gallery

WHAT IS PORELAB?

The Research Council of Norway describes their Centre of Excellence (CoE) program as follows: *The CoE scheme gives Norway's best researchers the opportunity to organize their research activities in centres that seek to achieve ambitious scientific objectives through collaboration and with long-term basic funding.*

After an application process that started in 2015, we were awarded CoE status in August 2017 by the Research Council of Norway. PoreLab, acronym for Porous Media Laboratory, was born!

PoreLab has two nodes, at the Norwegian University of Science and Technology (NTNU) in Trondheim and at the University of Oslo (UiO). It is led by eight principal scientists from physics, chemistry, and reservoir engineering. At UiO, PoreLab is part of the Njord Center which is a cross-disciplinary geoscience-physics center.

The mission of PoreLab is to advance the understanding of flow in porous media, both at a fundamental level and in applications. Starting from a basis in physics we aim for a better description of flows that range from geological to biological and technological.

Our objective is to link together observations of how fluids behave at the pore scale with a proper description of flow in porous media at much larger scales – the scales that typically are relevant for applications. In other words, our aim is to construct a large-scale theory for flow in porous media based on the detailed physics at the pore level. To achieve this, we combine hydrodynamics, non-equilibrium thermodynamics and statistical physics using theoretical, computational, and experimental methods. But we also consider other problems such as the interactions between fluids and grains in unconsolidated porous media.

Our strength is to combine knowledge in physics, chemistry and geoscience using all three ways of approaching a problem: experimental, theoretical and computational.

PoreLab receives an annual funding from the Norwegian Research Council of about 15 MNOK. NTNU and UiO contribute with the same financial support. In December 2022, we received the information from the Research Council of Norway that the mid-term evaluation planned originally during the spring 2023 was cancelled. PoreLab will therefore continue until the date of completion, i.e., August 2027.

Mixing of a dye injected from an oscillating needle into a porous medium. Glycerol flows from left to right in the image, causing the plume of continuously injected ink to deform along the system. The oscillation of the needle (seen on the left) is from top to bottom, perpendicular to the direction of the flow of glycerol. Picture by Gaute Linga

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BECOMING EVEN MORE MULTIDISCIPLINARY

By Alex Hansen

Here is my favorite physics joke: Two hydrogen atoms are bouncing around. Suddenly one of them says: Oh, I have lost my electron. The other one: Are you sure? The first one: Yes, I am positive. Here is another one: A theoretical physicist is hired to solve a problem in dairy farming. After a while the physicist reports that the problem is solved, but only in a limit: that of spherically symmetric cows.

The second joke illustrates well how theoretical physics is viewed from the outside. Theoretical physics is based on the idea that one should solve the more general version of your problem before solving the more specialized one. And use models that are as simple as possible to get at the physical mechanisms behind your problem in the purest form. There is no doubt that this works. The results are all around is, e.g., in the form of electronics. Engineers, however, regard the use of simple models with great skepticism: why bother with toy models when you should solve real problems. On the other hand, we have the physicists Ernest Rutherford's deliciously arrogant statement that "All that is not physics is stamp collecting". In other words, there are significant differences between different disciplines, not only scientifically, but also how problems are approached.

The idea behind interdisciplinarity is that one plus one is more than two. Why not regard the different approaches to science be an asset? This is especially true in porous media research where the field itself is fragmented into pieces "owned" by different disciplines. Here are some examples: Movement of water in the ground, the motion of oil in reservoirs, saltwater intrusion in marine concrete structures, transport of water in plants, transport of blood in humans, water movement in melting snow, filtration of gases, coffee percolators, hydrogen fuel cells... And these examples belong to disciplines such as physics, chemistry, geophysics, biology, hydrology, civil engineering etc.

Interdisciplinarity is therefore one of main pillars that PoreLab is built upon.

What most people who have not tried to work across disciplines do not realize is that it is very difficult to do in practice. The problem is as I have already pointed out, that each discipline has its own language, its own way to approach problems and how they define research goals. There are genuine and deep cultural and lingual barriers between the different disciplines. As a result, it takes years of office co-habitation to become truly interdisciplinary.

The key word in the last sentence is "co-habitation". This is essential if one is to succeed in building a truly interdisciplinary research center. It is the daily contact that over time makes it possible to truly understand each other.

University administrators have understood this point: Interdisciplinarity is important, and it is a frequent theme in their speeches. Too bad it rarely comes to more than that.

In 2023, PoreLab went one big step further in interdisciplinarity in that we started the collaboration with Romanian and Norwegian artists on the initiative of MV Sci-Art Center of the Polytechnical University of Timisoara, Romania resulting in the exhibition Porous Matter (see page 8).

Science and art are in my mind not that far apart. Perhaps one could say very imprecisely that "science attempts to understand our surroundings, whereas art attempts to understand ourselves". They both reveal aspects of our existence that only together form a complete picture. Is it the Bohr complementarity principle that is knocking on the door?

By Cosmin Haias

My name is Cosmin Haias, I live and work in Timisoara, Romania. As a citizen born and raised in Eastern Europe in a communist era till adolescence, my entire path was an unusual mixture of options, from entrepreneurial initiatives in various fields, to engineering studies in automation and computers, followed by art faculty graduation 13 years later, a master's degree in European Cultural Policies and a doctorate in visual arts, some of these options carried out simultaneously.

My artistic path over the years has not been limited by the perpetuation of a single style or a unique working method, something confirmed by the difference between the first personal exhibition that was composed entirely only of oil paintings and the recent exhibition conceived in collaboration with the researchers from PoreLab, in which cross-disciplinarity is the pivotal element of the exhibition. The collaborative project initiated by Mirela Stoeac Vladuti - curator and organizer of the exhibition and Alex Hansen - researcher and director of PoreLab Norway, proved to be one of the rare opportunities that simultaneously store the creativity fueled by scientific research, the spirituality of the humanities, the involvement of social responsibility and the interpersonal ties and friendship ultimately generated by this collaboration.

I met the PoreLab team in 2022 when I traveled to Norway to understand the research of PoreLab scientists, the global impact that their results may have and the crucial importance of this research. From multicellular organisms to geophysics, from water drilling to soil research for carbon dioxide storage, the porous materials that make up almost all entities define and determine the way we live. I read Alex Hansen text in which he recalls the years when together with some of his colleagues, fought for the establishment and financial support of this center of excellence, transforming it along the way into an interdisciplinary hub by attracting the Department of Chemistry, the Department of Geoscience and Petroleum or the Department of Structural Engineering from NTNU.

2023 was the year when PoreLab became in my opinion even more multidisciplinary, adding naturally the emotional resonance of artistic expression to the structure that already formed the body of the entity, through the materialization of our project entitled: "POROUS MATTER. Void Fractions in Materials, Ideas and Society". It is remarkable that this project seems to validate Harald Wergeland's statement as Alex remembers it, namely that "the verb "to research" does not exist in imperative...that research, like art, cannot be forced" . Indeed, the ideas that were the basis of the art installations we created within this project came naturally, following the discussions about the research that scientists at PoreLab are carrying out. Even more so because by their nature, PoreLab's research is oriented towards the fundamental priorities of humanity, generated by global phenomena such as global warming.

What are the implications of these collaborations from the point of view of art history, beyond everything I mentioned?

Perhaps due to these collaborations, the new territories conquered by new media art contribute to the trend started a few decades ago to end their marginalization, a century after the powerful manifestations of the historical avant-gardes.

Good Old Fashion Avant-garde (GOFAG) is gradually turning into Good Old Fashion Artificial Intelligence (GOFAI), opening the horizon of transdisciplinary avant-gardes where new media aesthetics gather under the generous umbrella of a certain new aesthetic, one of a discrete value of digital information (bits), of programming languages and of analytical rigor of scientific research, all unthinkable a century ago. The viewer's aesthetic appreciation will ultimately be influenced by what we might call the magic of autonomous processes or processes triggered by digitally generated stimuli.

Ultimately, in a simple statement, we can say that in a world shaped by technological advances and environmental concerns, our collaboration is just a small piece of the puzzle and a product of the current perpetual evolving Zeitgeist.

Artist and engineer Cosmin Haias and his creation "H111 – unFortune Cookies" at the exhibition's opening "POROUS MATTER. Void fractions in materials, ideas and society" on September 15th, 2023 at Politehnica University in Timisoara, Romania

Photo: Benjamin Bledea for META Spațiu contemporary art gallery,

POROUS MATTER.
Reducing the void between art and science

by Mirela Stoeac-Vlăduți
Head curator and artistic director of META Spațiu

> "To develop a complete mind: Study the science of art; Study the art of science. Learn how to see. Realize that everything connects to everything else."
>
> **— Leonardo da Vinci**

A meeting of beautiful minds. This is how I would describe the encounter of the artists, scientists and curators that worked together for almost two years before opening the exhibition "Porous Matter. Void fractions in materials, ideas and society". The practice was very similar to a lab experiment or to that of a work of art, a process full of trials and errors that remained invisible, but which was essential to the success of the project, which was funded by EEA and Norway Grants, within the programme Timișoara 2023 – European Capital of Culture. In this blend of creativity and inquiry, the intersection of art and science becomes a realm where the boundaries between imagination and analysis blur into a seamless tapestry. Like alchemists of old, the artists, scientists, and curators crafted, in this harmonious collaboration, a narrative that transcends the conventional realms of their disciplines becoming one of the most succesful exhibition of the cultural year in Timișoara (Romania), with a total number of 4 220 visitors.

The four artists from Romania and Norway - Floriama Cândea, Maria Castellanos, Cosmin Haiaș, Stahl Stenslie, together with four scientists - Alex Hansen (PoreLab), Florin Drăgan (UPT), Marcel Moura (PoreLab), Liviu Marșavina (UPT), and with the curatorial team - myself (curator) and Loredana Nedelcu and Marina Paladi (assistant curators) explored the perspectives of the complex relationship between porous materials and the impact of their research on ideas and society as a whole. Through contemporary art installations, artistic and scientific experiments, the exhibition invited the participants to reflect on the multifaceted nature of void fractions and their role in shaping our physical and conceptual environment.

But, what I would like to emphasize in this article (or maybe better call it "review") is a personal testimony on the importance of fostering this kind of collaborations in the future. As I was stating above, the process, which usually remains unseen, is of greater importance (especially in our contemporary settings in which everyone is looking for fast results, fast solutions, and fast recognition). So, I would like to share with you, the readers of this publication, which I presume are mainly scientists, the relevance you bring into the arts sector and into creating beauty and truth to this world.

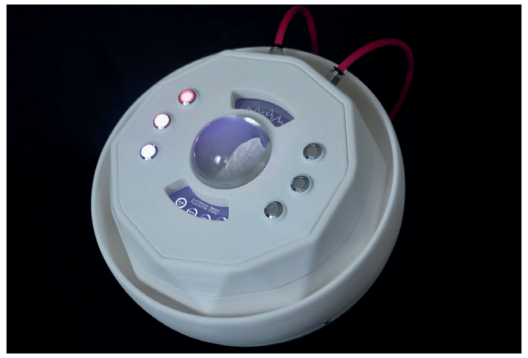
You may not realize the impact you have on culture and, sometimes (I hope not too often, though), you are wondering why art no longer looks like art (?). Why artists no longer use their brushes and paints to express their view on the world, or sculpting out of rough rocks the beautiful, round and soft shapes of ideal human bodies? I will make a short detour and then come back to my own perspective on the answer. One of the things that art and science have in common, the most important one perhaps, is, as the reference to Leonardo da Vinci states, "learning how to see". So, both art and science are based on observing the world in a perpetual attempt of finding solutions for its problems and, both artist and scientist use the same "instrument" for this endeavour: the eye. Trying to convey a simple answer to a complex question like the one above, is not a simple quest, but, looking around, exploring the world as it is, we may find it. The nature is no longer a romantic landscape, the cozy interiors of Van Gogh paintings are long gone and they have been replaced with installations and technology, the environmental, societal and political issues that we are confronted with today are the same problems that preoccupy the artists.

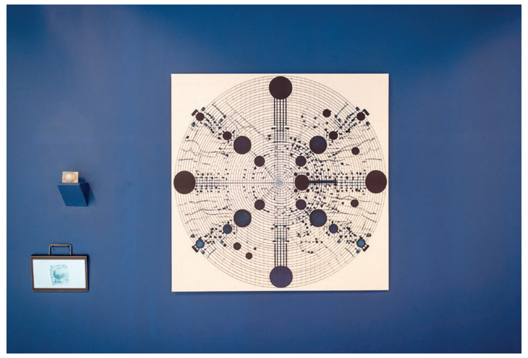
And this, I would say, became the foremost hypothesis of our "Porous Matter experiment". The ability to look at the same problem with the same eyes ("human, all too human" – as Nietzsche would say), but with a different set of professional vocabulary. And it, of course, brought us to unexpected and major discoveries: the artists involved could transpose important scientific ideas based on the research of PoreLab and the Polytechnic University Timișoara, the scientists took a more artistic approach to their work and focused their eyes more on finding beauty and cultural symbols in their experiments, and what a surprise this was, especially coming from Marcel Moura from Porelab who, at least for the period of the exhibition, became a true contemporary artist and intrigued the public the same way as any other established artist would.

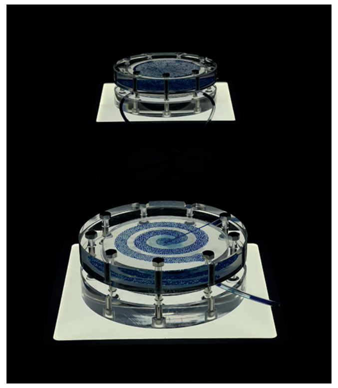
You will be sympathetic, I hope, with what is clearly more of an impression and personal consequence of this wonderful collaboration, than a scientific article you might be used to, but I am a curator, after all, and, opperate with the same instrument: the eye. And I can't refrain from observing that I had had the chance of working together with some of the most talented and professional scientists and amazing human beings (and I am referring now, of course, to the PoreLab team). And, especially, I would like to mention the serendipity of the encounter with prof. Alex Hansen, who was the pioneer of this project (which I am sure marks a milestone in art history, in the Romanian one, at least) and would make a great art curator, if he ever feels to switch professions.

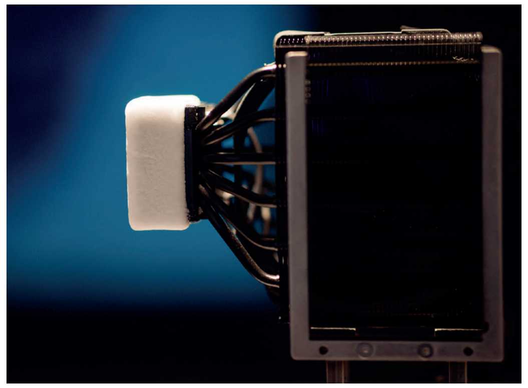
If you've managed to get to this final row, Q.E.D. Art and science are as necessary to one another, as void fractions are to porous materials. Or, as it is Porous Matter to fostering this amazing collaboration between Norway and Romania.

Website of the project: *www.porousmatter.art*









Photos: Benjamin Bledea for META Spațiu contemporary art gallery, MV Sci-Art gallery

DIRECTOR'S COMMENTS

We are back at full speed. Covid is now in a distant past and already fading from memory. The year 2022 ended with us gearing up for the RCN[1] midway evaluation only to receive the message in mid-December that it was cancelled. Our plan was to use the spring semester of 2023 to prepare for it. This allocated time was freed up, and suddenly we had lots of extra time on our hands. This time was invested into research, producing papers, and writing proposals. Not a bad trade.

Our scientific output is up compared to 2022: **62** refereed papers, **64** conference contributions and **6** books/book chapters. In 2022, we had **57** refereed papers, **55** conference contributions and **6** books/book chapters. However, neither 2023 nor 2022 beats our best year, 2021, with **78** refereed papers, **55** conference contributions and **13** books/book chapters. I speculated in the 2022 Annual Report as to why 2021 should have been so productive. The explanation I suggested was "When we started in 2017, many PhD students started, and they graduated in 2021. They have been replaced by a new generation. This generation was in their first year of studies in 2022, and hence had not started producing papers. In other words, the dip in the number of published papers is part of a natural and expected oscillation." I do no longer believe that this was the whole story. Rather, 2021 was the second year of covid and society was closed down for a large part of it. The simpler explanation is that when you sit at home wondering what to do, you finally write those papers that should have been written a long time ago.

We have started to calculate the H-index of PoreLab finding it to be 29. The most cited paper so far in PoreLab is Stylolites: A review, Journal of Structural Geology **114**, 163 (2018) by Renaud Toussaint et al. It has 113 citations on to Google Scholar.

Here are some glimpses of what we accomplished scientifically in 2023:

- Work package 1 (Thermodynamics of flow in porous media): We finally managed to formulate the immiscible two-phase flow problem under steady-state conditions in terms of an equilibrium statistical mechanics problem (Advances in Water Resources **171**, 104336 (2023)). This has been a major goal for the work package as it now opens for what earlier looked like some elements of a thermodynamic-like description of the two-phase flow problem (see e.g., Transport in Porous Media, **125**, 565 (2918)), to a full-blown thermodynamics-like formalism.

- Work package 2 (Steady-state experiments and coarse-grained experiments): An important area in this work package is transport through capillary bridges under two-phase flow in porous media. The goal is to assess how such capillary bridges affect the overall transport properties of two-phase systems with an emphasis e.g., on transport of pollutants. A dynamic network model capable of handling such bridges has been constructed, see Advances in Water Resources **182**, 104580 (2023). This work is being followed up by experimental work.

Alex Hansen, Director for PoreLab.
Photo by Per Henning

DIRECTOR'S COMMENTS

[1] RCN: Research Council of Norway.

- Work package 3 (Experimental characterization of immiscible two-phase flow in porous media): When the porous medium is unconsolidated, fluid flow will result in restructuring of the porous medium. In a continuation of the study of frictional fluids, where friction between the grains constituting the porous matrix provides the leading counter force to the viscous forces generated in the fluids by the flow, the scenario is now injection of an aqueous solution into layers of dry, hydrophobic grains. This produces a viscously stable scenario where there is a transition from growth of a single frictional finger to simultaneous growth of multiple fingers as viscous forces are increased, see Nature Communications 14, 3044 (2023).

- Work package 4 (Nanoporous media and gels): A crowning achievement under this work package rests of 15 years of work on developing programmable self-assembly of DNA functionalized colloids in aqueous suspensions by the Eiser group. This opens for a simple yet efficient detection tool to identify bacterial DNA without needing state of the art equipment. The work is based on weak, multivalent binding of short, single-stranded DNA sequences attached to colloids and super-selectivity. Using an "in-house" bio-informatics algorithm that extracts the right DNA-target sequence, detecting only, for instance, a specific E.coli strain, they were able to detect low concentrations down to 5 copies/ml, see PNAS **120**, 2305995120 (2023).

- Work package 5 (Thermodynamic driving forces): The aim of work package 5 is to develop a non-equilibrium thermodynamic description of two-phase flow that includes gravitational, osmotic, chemical, and thermal driving forces, as well as capillary forces and disjoining pressures, with the aim to construct a consistent and general description of two-phase flow that accounts for the relevant driving forces. We are making progress on the topic, see Journal of Chemical Physics, **158**, 104107, (2023) where density functional theory is used to study the interfacial properties of hydrogen, helium, neon, deuterium, and their mixtures, i.e., fluids that are strongly influenced by quantum effects at low temperatures.

- Work package 6 (Microfluidics and field studies): This work package focuses on developing new methods for determination of wettability in porous media from pore scale images, establish experimental support for the multi-phase flow theories by pore scale imaging of flow, and to characterize multiphase flow for various characteristics of porous media, including pore structure and wetting states, and their relations to trapping. The work we highlight here develops a theory for the evolution of the macroscopic mobility of porous media when the underlying microscopic structure changes due to e.g., clogging, precipitation, or dissolution processes, based on percolation theory, see Phys. Rev. E **108**, 024132 (2023).

- Work package 7 (Deformable porous media): Seals living in the arctic and the sub-tropic needs to breathe. When the ambient temperature is deep below freezing, it becomes imperative that they do not lose heat when breathing out and cool down their lungs when breathing in. Inside the seal nose there is a complex porous structure that acts as a heat exchanger between the blood and the air rushing in and out, the maxilloturbinate. In J. Therm. Biology **112**, 103402 (2023), we have used hydrodynamic/thermodynamic description to model this structure and how it works.

- Work package 8: (Applications): Most fundamental work on two-phase flow in porous media assumes that the fluids are incompressible. What if we have a mixture of an incompressible and a compressible fluid? We have with Transport in Porous Media, **147**, 15, (2023) taken a first step in the direction of constructing a dynamic pore network model that can handle this situation. This is important as it is in turn a first step in the direction of a full coupling between thermodynamics and hydrodynamics in a dynamic pore network model.

We present further projects – and some of those above – in much more detail on pages **24** to **51**.

Two members of the Scientific Advisory Board announced at the SAB meeting in Oslo on November 7-8 that they would retire in 2023: Professors Majid Hassanizadeh and Dani Or. They have been central in guiding us in the building of PoreLab since the beginning in 2017 and we thank them both deeply for this help.

The current government has made substantial cuts in the annual grants for the universities. This is felt on all levels. A result of this is that our current whereabouts in Trondheim has come under some pressure, as they are rented from SINTEF. PoreLab's position is to be open for relocation elsewhere as long as we are not split up.

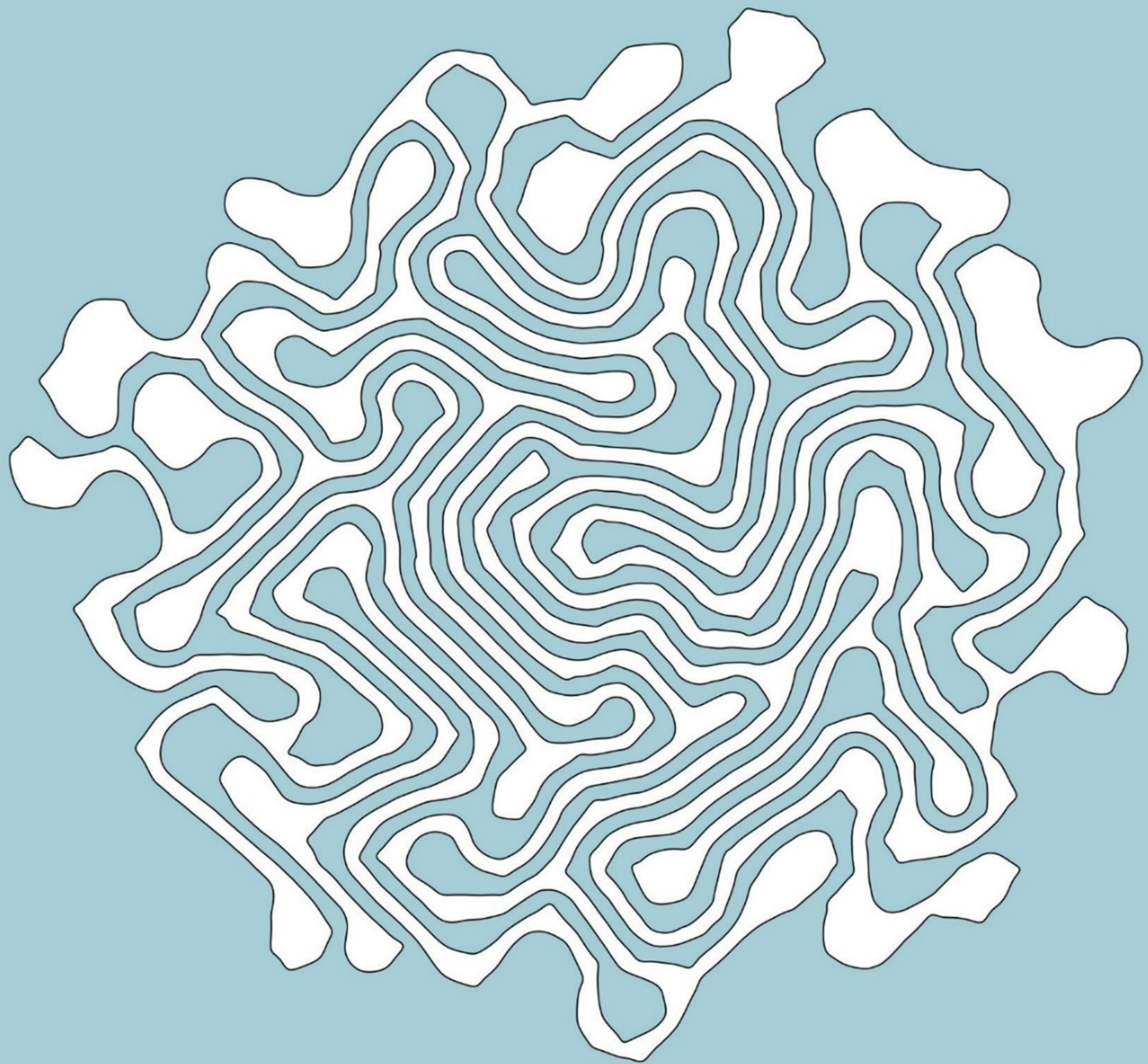
We are very happy to welcome Gaute Linga as Onsager fellow in Trondheim. This is a tenure track position at the Physics Department (see the Director's Comments in the 2022 Annual Report). He ensures that the physics part of PoreLab now covers all three approaches, experimental physics (Eiser), theory (Hansen) and now Linga (computational physics). Linga is at present postdoc at PoreLab in Oslo, where he works on mixing in porous media. He is also running a program at the Young Center for Advanced Studies at the Norwegian Academy of Science and Letters: Mixing by Interfaces.

And we are very happy to report that Øivind Wilhelmsen – the PI of work packages 5 and 8 - was awarded an ERC Starting Grant: Unraveling the fundamentals of transport across the vapor-liquid interface.

AMBITIONS FOR 2023

We are now more than halfway in the Center of Excellence grant, 2017 to 2027. In the fall of 2025, proposals for the 6th call for Centers of Excellence will have their deadline. 2024 will be the year when we start working seriously towards this call.

We are restarting the journal club in Trondheim.



A minimal folding model for labyrinthine structures

PoreLab: EXPLORING THE ESSENCE OF SOCIETAL CHALLENGES WITH POROUS MEDIA RESEARCH

BY MAJA RÜCKER, ASSISTANT PROFESSOR AT EINDHOVEN UNIVERSITY OF TECHNOLOGY

In the tranquil moments of early morning, as we await the aroma of freshly brewed coffee filling our cups, one may wonder: what constitutes the perfect start to our day?

The seasoned barista knows out of experience the precise grind size, the gentle pressure required to compact the coffee grounds, and the optimal temperature and pressure for the water flowing through the coffee-pad. As the hot water permeates the coffee grounds, molecular reactions unfold across the surface of the grinded coffee. The interplay between exposure time of the coffee to the water and the flow dynamics dictate which compounds dissolve, ultimately crafting the cherished flavor profile of our espresso. Yet, amidst this ritual, we still not fully understand how to physically describe these processes and thus rely on a trial and error approach.

While coffee accompanies us in our daily lives, the same fundamental principles are essential to a myriad of technological advancements crucial for the energy transition, environmental preservation, agriculture, and healthcare. Consider, for instance, the gas diffusion layers within fuel cells, where the optimization of gas and water flow parallels the complexities of our morning brew. Or contemplate the delicate balance of soil nutrition, especially in light of shifting rainfall patterns induced by climate change. Akin is the process of life-saving drugs traversing our organs or the underlying mechanisms of CO_2 trapping for storage within subsurface porous reservoirs. By addressing the foundational challenges of porous media research, the Center of Excellence PoreLab plays a pivotal role in advancing various sustainable development goals delineated by the United Nations.

As a recipient of the PoreLab-Interpore award for young researchers, it was an honor to visit PoreLab and receive the opportunity to collaborate with esteemed scientists hosted by PoreLab. The center, combining efforts at NTNU and UiO, consolidates knowledge and infrastructure to delve into the latest advancements in the field and to push the boundaries of our understanding of porous systems. Shedding light on the behavior of fluids within the often complex porous structures, and employing state-of-the-art experimental and computational techniques, their researchers unravel the impact of energetic and geometric variations on the processes porous media facilitate. The work emanating from PoreLab creates a shift in our comprehension of established concepts in statistical mechanics and thermodynamics in the context of porous media.

Characterized by unwavering dedication to the discipline, rigor, and a profound sense of community, PoreLab represents a house of knowledge within the porous media research community. Located in Norway, Trondheim and Oslo, with its inspiring cities and landscape, PoreLab provides a sanctuary for scholarly pursuits, fostering an environment where researchers can immerse themselves in the essence of the subject. Here, we devote ourselves to unraveling the enigmas of porous substrates, striving to forge predictive tools rooted in a comprehensive understanding of porous materials, thus laying the groundwork for a brighter tomorrow - over a good cup of coffee, and beyond.

Maja Rücker, Assistant Professor at Eindhoven University of Technology, The Netherlands, and winner of the InterPore-PoreLab award for young researchers in 2021

ORGANIZATION
OF PORELAB

PoreLab gathers scientists from 5 departments at NTNU and UiO. The NTNU Department of Physics is the host. Partners are the NTNU Departments of Chemistry, Geoscience and Petroleum, Civil and Environmental Engineering, and Department of Physics at UiO. SINTEF Industry is our external research partner.

The Center is managed by the Director, Alex Hansen (NTNU) jointly with the Deputy Center Director, Eirik Flekkøy (UiO) and the Center Administrative Leader, Marie-Laure Olivier (NTNU).

The organizational structure of the Center is flat. The team of the Principal Investigators (PIs) and the Administrative Leader forms the Leader Group and has bi-weekly meetings to discuss administrative and scientific issues and update each other on developments and progress. The system for immediate updates ensures interdisciplinary progress.

PoreLab's research is organized in eight Research Themes (RT) led by the Principal Investigators. The numbering of the Research Themes until last year reflected the history but by now it was not particularly logical. The Research Theme on Applications should be indeed the last one since its objective is to apply knowledge from the other Research Themes. The numbering was therefore modified in 2023 as follow:

- *"Steady-state experiments and coarse-grained modelling"*, previously RT 8 becomes RT 2"
- "*Deformable porous media"*, previously RT 2 becomes RT 7
- *"Applications"*, previously RT 7 becomes RT 8

In 2023, we got the wonderful news that an Onsager fellowship position within computational porous media physics was allocated to PoreLab by the leadership at NTNU. An Onsager Fellow is an entry level position (tenure track) which during the first years of employment is financially covered by funding from NTNU's Rectorate. The Onsager Fellowship program at NTNU is designed to attract very talented early-career scholars with documented excellent supervised work, ready to work independently and with the potential to become a research leader. The tenure-track associate professor's duties primarily include research, but also supervision, teaching, and other duties necessary to qualify for a permanent professor position within 6-7 years. Following an intensive recruitment process, Dr. Gaute Linga, researcher at PoreLab UiO was appointed Onsager Fellow. He will join NTNU in 2024. In the mid-time and since September 2023, Gaute joined PoreLab's leader group as new PI.

The PoreLab Executive Board includes members from the faculties involved at NTNU and UiO. It consists of 5 members: Professor Øyvind Gregersen, Dean at the Faculty of Natural Sciences at NTNU, Professor Erik Wahlström, head for the department of Physics at NTNU, Professor Sveinung Løset, vice dean for research and innovation at the Faculty of Engineering at NTNU, Professor Susanne Viefers, head of the Physics department at the University of Oslo and Professor François Renard, director for the Njord center that hosts the Oslo node of PoreLab. The board is responsible for overseeing that the activity takes place according to the contract with the funder, the Research Council of Norway. A central task of the Executive Board is to enhance the collaboration among participating departments at NTNU and UiO.

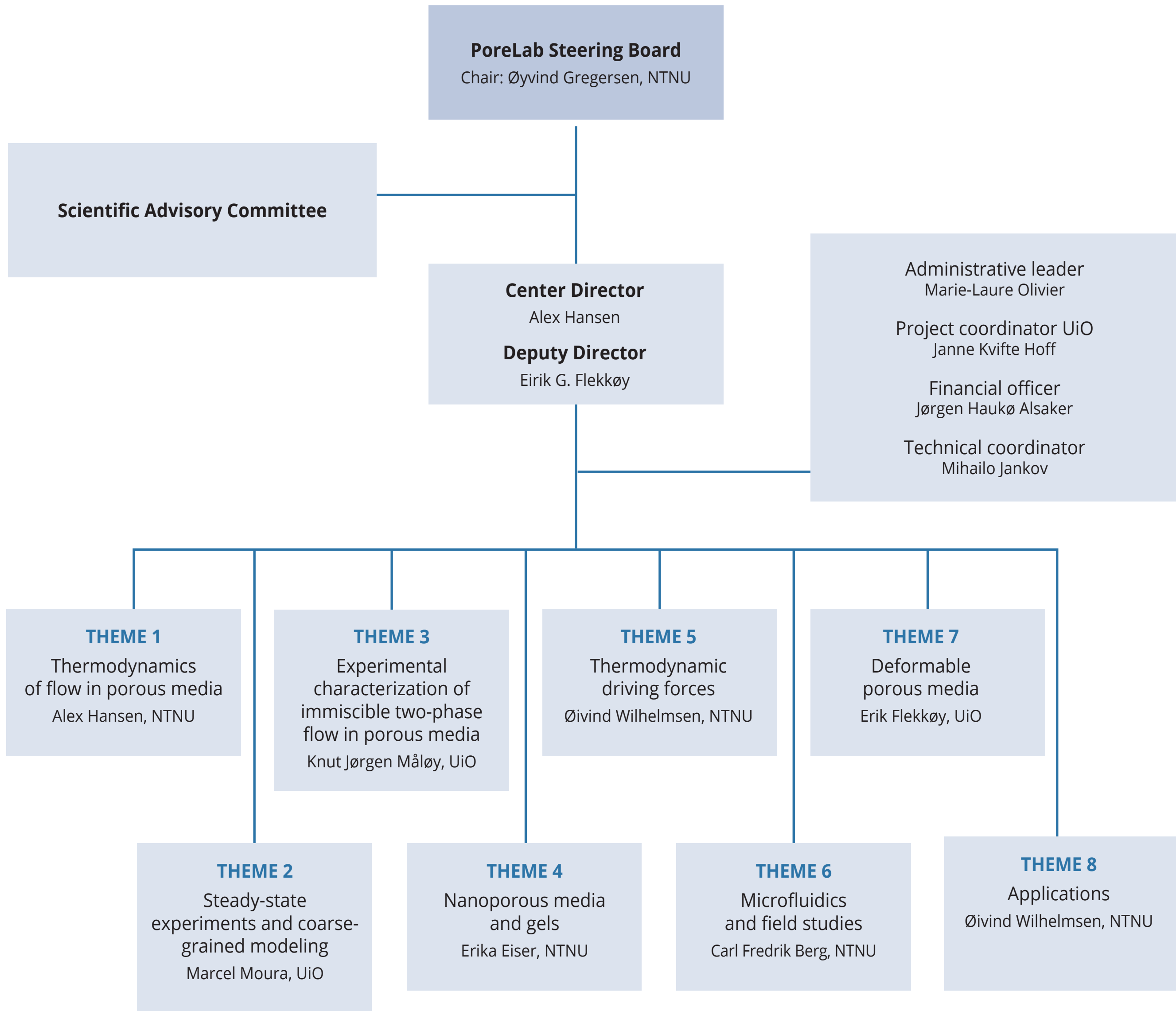
The Research Council of Norway that funds PoreLab demands there to be a Scientific Advisory Board, or SAB. The main role of the SAB is to evaluate and make recommendations on the scientific status and progress of PoreLab. It aids in the development of a strategy for the scientific development of the center, thereby helping the leadership group by giving advice on implementing appropriate means of actions to achieve the stated scientific aims and fulfil the strategy plan. The SAB is composed of international experts and leading scientists who act as external advisors to the management of PoreLab.

In 2021, Professor Emeritus Daan Frenkel from the University of Cambridge stepped down from his position in the SAB, followed by Professor Anna Korre from the Imperial College of London in 2022.

We welcomed thereafter two new members: Douglas Durian, Professor of Physics at the Department of Physics and Astronomy at the University of Pennsylvania, USA, and Steffen Berg, senior research staff scientist at Shell Global Solutions International B.V. in The Netherlands.

The SAB meets with the PI group once a year. In 2023, we met at PoreLab Oslo for a 2-day SAB meeting on November 7th and 8th.

Structure of the organization



MANAGEMENT AND ADMINISTRATION

THE LEADER GROUP


Alex Hansen
Director
Professor,
PI Theme 1


Marcel Moura
Researcher
PI Theme 2


Knut Jørgen Måløy
Deputy Director
Professor,
PI Theme 3

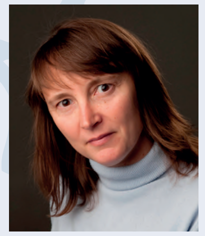

Erika Eiser
Professor
PI Theme 4


Øivind Wilhelmsen
Professor
PI Themes 5 and 8


Carl Fredrik Berg
Professor
PI Theme 6


Eirik Flekkøy
Professor
PI Theme 7


Gaute Linga
Researcher,
joined the PIs group on
20 September 2023


Marie-Laure Olivier
Administrative leader

PORELAB EXECUTIVE BOARD


Øyvind Gregersen
Dean
NV faculty, NTNU


Erik Wahlström
Head of department
Department of Physics
NTNU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Department of Physics
University of Oslo


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Department of Geosciences,
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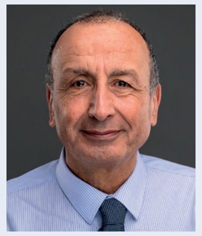
University of Oslo

SCIENTIFIC ADVISORY BOARD


Dani Or
Professor
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Environmental Physics
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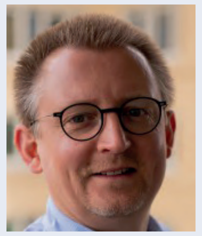
Switzerland


Daniel Bonn
Professor
Van der Waals-Zeeman Instituut
University of Amsterdam
The Netherlands


S. Majid Hassanizadeh
Professor
Department of Earth Sciences
University of Utrecht
The Netherlands


Pål-Eric Øren
Chief Technology Officer
Digital Rock Services
Petricore,
Trondheim, Norway


Steffen Berg
Principal Science Expert at Shell
Global Solutions International
B.V. in the Netherlands
From August 2022


Douglas Durian
Professor of Physics and
Astronomy
University of Pennsylvania, USA
From August 2022

PARTNERS

NTNU

UiO : University of Oslo

SINTEF

HIGHLIGHTS

2023
6 new projects granted to PoreLab members including an ERC Starting Grant, an YRT Project and a CAS Project in 2023

13-17 March 2023
COLOSSAL workshop on Flow and Deformation Across Scales in Brazil

1-4 May 2023
Workshop on Upscaling at PoreLab NTNU, Norway

14-15 June 2023
9th edition of the EarthFlows Meeting at the University of Oslo, Norway

15 September 2023
Opening of the exhibition POROUS MATTER. Void Fractions in Materials, Ideas and Society in Timisoara, Romania

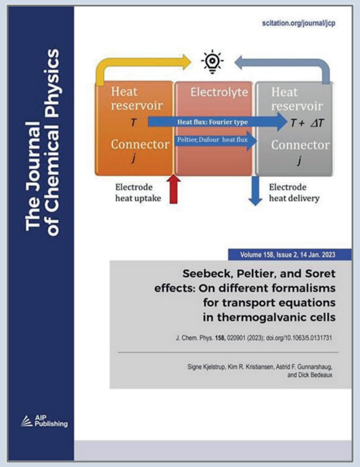
9 November 2023
6th meeting of the Norwegian Chapter of InterPore organized by PoreLab in Oslo, Norway

Novembeer 2023
PoreLab is co-financing the membership of the Norwegian-Icelandic Consortium for CECAM

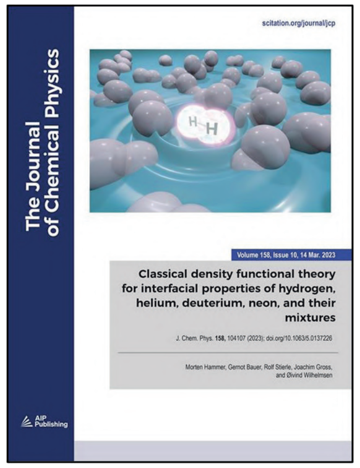
27 November to 1 December 2023
Alex Hansen chairs the research quality evaluation board of the Niels Bohr Institute

8 December 2023
First Workshop of the Sustainable Stable Ground project on Quick Clay Stabilization in Trondheim, Norway

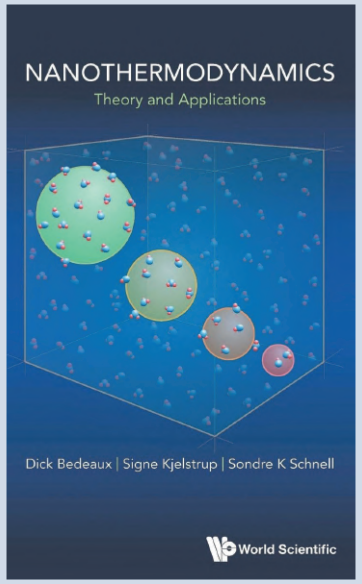
PUBLICATIONS IN THE SPOTLIGHT



The article from Kjelstrup et al. *"Seebeck, Peltier and Soret effects: On different formalisms for transport equations in thermogalvanic cells"*, published on January 14th, 2023, was featured on the **cover** of the *Journal of Chemical Physics*, selected as **Editor's pick**, and posted on the journal homepage.



Congratulations to Morten Hammer and Øivind Wilhelmsen and their partners from the U. of Stuttgart. Their paper on *"Classical density functional theory for interfacial properties of hydrogen, helium, deuterium, neon, and their mixtures"* was selected as **cover** for the Journal of Chemical Physics on March 8th, 2023, and promoted as part of a **Featured collection**.



"Nanothermodynamics: Theory and Applications", the manuscript from Dick Bedeaux, Signe Kjelstrup and Sondre K. Schnell was released on **Amazon** in August 2023.

The article from Eirik Flekkøy, Knut Jørgen Måløy, James Campbell, Jon Alm Eriksen and their collaborators from the Universities of Swansea and Oxford, entitled *"Frictional fluid instabilities shaped by viscous forces"* was published in **Nature Communications** on May 26th, 2023.

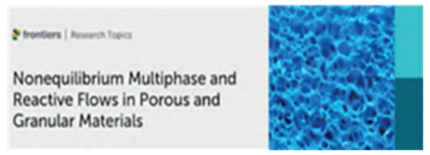
The article from Vegard G. Jervell and Øivind Wilhelmsen entitled *"Revised Enskog theory for Mie fluids: Prediction of diffusion coefficients, thermal diffusion coefficients, viscosities, and thermal conductivities"* was selected as **Editor's Pick** in the Journal of Chemical Physics on June 14th, 2023.

The *Journal Physics of Fluids* promoted the article from Reza Haghanihasanabadi, Hamidreza Erfani Gahrooei, James McClure and Carl Fredrik Berg, entitled *"A note on the summation relation in phase-field equations"* and published on September 20th, 2023, as **Featured Article**.

Renaud Toussaint & his coworkers from the Hebrew University of Jerusalem and the Ben-Gurion University of the Negev in Israël had their article entitled *"Drainage explains soil liquefaction beyond the earthquake near-field"* published in **Nature Communications** on September 27th, 2023.

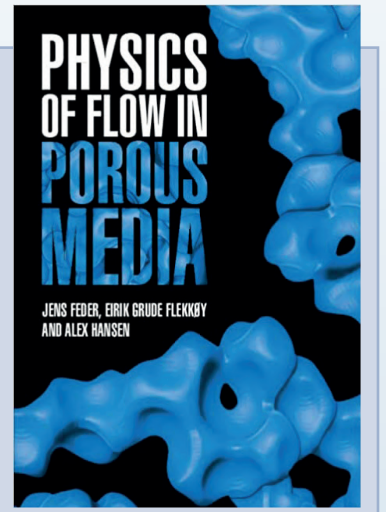
The article from Federico Lanza, Santanu Sinha, Alex Hansen and their partners from the CNRS/University of Paris-Saclay, entitled *"Transition from viscous fingers to foam during drainage in heterogeneous porous media"* was selected as **Editor's Pick** in Physics of Fluids on October 25th, 2023.

Congratulations to Bjørn Hafskjold and his collaborator Tamio Ikeshoji from the National Institute for Advanced Interdisciplinary Research in Japan! Their publication entitled *"Non-equilibrium molecular dynamics calculation of heat conduction in liquid and through liquid-gqs interface"* published in 1993 in the Journal of Molecular Physics, has passed **400 citations**. In October 2023. Congratulations!



Marcel Moura co-edited a **special topic** published jointly by Frontiers in Physics and Frontiers in Water in November 2023. This collection entitled *"Nonequilibrium Multiphase and Reactive Flows in Porous and Granular Materials"* gathers papers aiming to model, understand, predict, and even control multiphase and reactive flows, where nonequilibrium often prevails leading to instabilities, the emergence of complex patterns and preferential pathways, and dependencies on the path and rate of external driving forces.

The publication from Knut Jørgen Måløy, Alex Hansen, Einar L. Hinrichsen, all from the University of Oslo and Stéphane Roux at the Ecole Normale Supérieure Paris-Saclay in France, entitled *"Experimental measurements of the roughness of brittle cracks"* and published in 1992 in the Physical Review Letters, has passed **400 citations**. Congratulations!



The book entitled *"Physics of Flow in Porous Media"* by Jens Feder, Eirik G. Flekkøy and Alex Hansen published in September 2022, is now being translated into **Chinese**.

NON-LINEAR GROWTH OF IMMISCIBLE VISCOUS FINGERS IN POROUS MEDIA

Santanu Sinha[1], Yves Méheust[2], Hursanay Fyhn[3], Subhadeep Roy[4] and Alex Hansen[5]

[1] PoreLab, Department of Physics, University of Oslo, Oslo, Norway
[2] CNRS, Géosciences Rennes, Université de Rennes 1, Rennes France
[3] SINTEF Energy Research, Trondheim, Norway
[4] Department of Physics, Birla Institute of Technology and Science, Telangana, India
[5] PoreLab, Department of Physics, NTNU, Trondheim, Norway

Generation of viscous fingers is one of many unique features of immiscible two-phase flow. When a fluid invades another fluid inside a medium and the two fluids are immiscible, the displacement pattern of the invading fluid can vary widely depending on the fluid properties and the geometry of the system in which they are flowing. If the invading fluid has a lower viscosity than the defending fluid, viscous instabilities appear in the system, and it leads to a certain type of displacement patterns named viscous fingers. It has long been assumed that the growth of such fingers exhibits a linear Laplacian behavior, which means, the interface velocities of the advancing fronts depend linearly on the local pressure gradient. This behavior is similar to diffusion limited aggregation (DLA) and the continuum Saffman-Taylor viscous fingers, both of which exhibit the linear Laplacian growth.

We have shown that there also exists a regime where the growth of viscous fingers scales non-linearly with a power-law, which crosses over to the linear growth regime only at higher capillary numbers [1]. This is reminiscent of the steady-state two-phase flow, where the total flow rate varies non-linearly on an excess pressure drop with a power law and crosses over to a linear regime at higher flow rates. With theoretical arguments and dynamic pore-network modeling, we have explained how this non-linearity is induced by the disorder in the capillary barriers at the pore throats and compared the statistical properties of the porous-media fingers with the fingers in continuum media.

This opens up for further questions. Since the source of the non-linearities for the finger growth and the steady-state state flow is believed to be the same pore-scale disorder, it is an open question whether the exponents for these two cases will be the same for the same system. Furthermore, how the non-linear exponent is related with the functional form of the disorder distribution has yet to be studied.

RECOMMENDED READING

[1]] Santanu Sinha, Yves Méheust, Hursanay Fyhn, Subhadeep Roy, Alex Hansen. Disorder-induced non-linear growth of fingers in immiscible two-phase flow in porous media. Physics of Fluids 2024, Volume 36 (3), 033309 (2024).

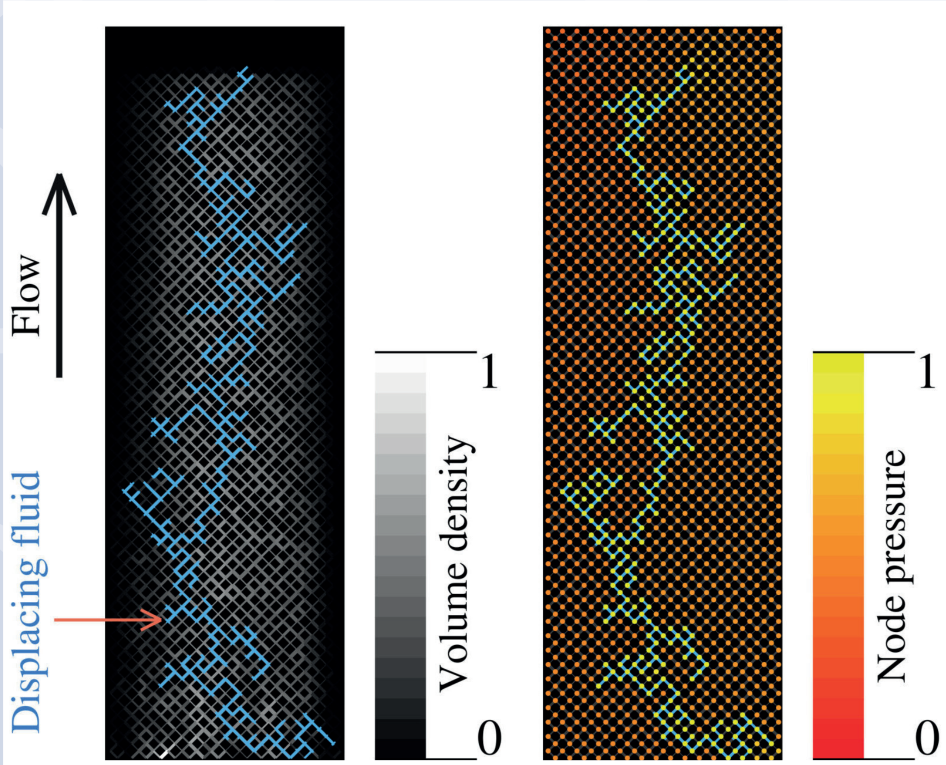


Figure: *Dynamic pore-network simulation of viscous finger in a pore network.*
Left: Links with blue color represent invading fluid and with black represent defending fluid. The gray scale represents the statistical average of many fingers which can be compared with the Saffman-Taylor viscous fingers in a continuum medium.
Right: Scaled pressures at different nodes across the network where the nodes invaded by the low-viscosity fluid show relatively much higher pressure than those with defending fluid.

RESEARCH PROJECTS

DRY AND WET AND DRY AGAIN: IN SEARCH FOR THE ORIGINS OF HYSTERESIS IN POROUS MEDIA FLOWS

Marcel Moura[1], Ran Holtzman[2], Marco Dentz[3], Mykyta Chubynsky[2], Ramon Planet[4], Jordi Ortín[4,5]

[1] PoreLab, The Njord Centre, Department of Physics, University of Oslo, Oslo, Norway
[2] Centre for Fluid and Complex Systems, Coventry University, Coventry, United Kingdom
[3] Institute of Environmental Assessment and Water Research (IDAEA), Spanish National Research Council (CSIC), Barcelona, Spain
[4] Departament de Física de la Matéria Condensada, University of Barcelona, Barcelona, Spain
[5] Institute of Complex Systems, University of Barcelona, Barcelona, Spain

You get a pepperkake and you dunk it a little bit in your coffee, see Figure 1a). You notice that the coffee starts to move up into the porous structure of the pepperkake. Then you regret it because you don't like wet pepperkaker anymore and you decide to undunk it. But somehow, the coffee does not simply move back into the cup; it mostly stays in the pepperkake apart from a few drops perhaps. Pepperkake dunking in the language of porous media science is an example of an imbibition process and pepperkake undunking is a drainage process. Undunking might not be a word, but that's not very important now.

Imbibition and drainage are the two fundamental processes of two-phase flows in porous media. The two fluid phases in the pepperkake dunking business are the coffee that invades the medium and the air that fills the pores of the dry pepperkake. Imbibition means the wetting fluid (here coffee) displaces the non-wetting fluid (here air) from the porous medium (here, you guessed, pepperkake). Drainage is the opposite, when the non-wetting fluid displaces the wetting one. These processes happen all the time. If you fall on the ice and land on a pond of muddy water, your clothes get wet (imbibition). You walk around a bit hoping to recover your dignity while the water evaporates, and air again fills the voids between the fibers of your clothes (drainage). Although drainage and imbibition are opposite processes, they are typically not reversible processes. The wet pepperkake did not get dry just because you lifted it out of the coffee. Your clothes did not get dry the moment you lifted yourself from the ground. In physics, we say that a drainage-imbibition process is irreversible, showing a hysteresis loop, i.e., drainage is not simply imbibition played backwards in time. There are many different sources for this hysteresis. In this project we focused on one of them: how the fluid motion in a given location in a porous medium is affected by the motion in a neighboring location.

In order to perform this investigation, we did not rely on pepperkaker or wet clothes because none of those are transparent enough for detailed observation. Instead, we used 3D printed models designed with specific geometrical properties in order to maximize the effect we wanted to study. Figure 1b) shows a 3D printed model with 3 rows of obstacles. On the bottom row we have an isolated obstacle. In the middle and top rows we have pairs of obstacles. The gap between the obstacles is larger in the middle row and smaller in the top row. We then run an imbibition-drainage loop on each of the rows. That just means putting some fluid in and taking the fluid out again. (We tried olive oil first, but finally settled for silicon oil. Less edible, but more appropriate for the experiment.) The process is done slowly and takes a couple of hours. The obstacles do not completely fill the height of the cell, so the liquid can go above them (each obstacle is then a local partial constriction of the cell). Every time the liquid-air interface meets an obstacle, it gets deformed into a little bump (see images on the right part of Figure 1b) and c)). In the case of the single obstacle, we have a single bump, and for the pairs of obstacles, we have a pair of bumps. For each imbibition-drainage experiment, we measure the size of the interface bump η_m as a function of the interface position h_f (see right part of Figure 1c)). If the process is reversible, the curves for drainage and imbibition overlap. If it is irreversible, they do not overlap, and we see a hysteresis loop. We designed the obstacles in a way that the single obstacle was reversible, but for the pairs of obstacles, we got an irreversible process due to the lateral interaction between the bumps. This shows how the integration of separately reversible processes can lead to a collective irreversible process. We noticed that the size of the hysteretic loop (a measure of irreversibility) gets larger the closer the obstacles are to one another. In short, there is no chance that the coffee will entirely leave the pepperkake once you lift it out of the cup as drainage and imbibition are generally hysteretic processes.

ACKNOWLEDGEMENTS

The work has been done with support from the Norwegian Research Council, for Young Talents, project no 324555, and the Center of Excellence Funding Scheme project no 262644

RECOMMENDED READING

[1] Holtzman R., Dentz M., Moura M., Chubynsky M., Planet R., and Ortín J., Emergence of dissipation and hysteresis from interactions among reversible, non-dissipative units: The case of fluid-fluid interfaces. submitted to Physical Review Fluids (2023). Preprint on arXiv: arXiv:2401.13077 [physics.flu-dyn].

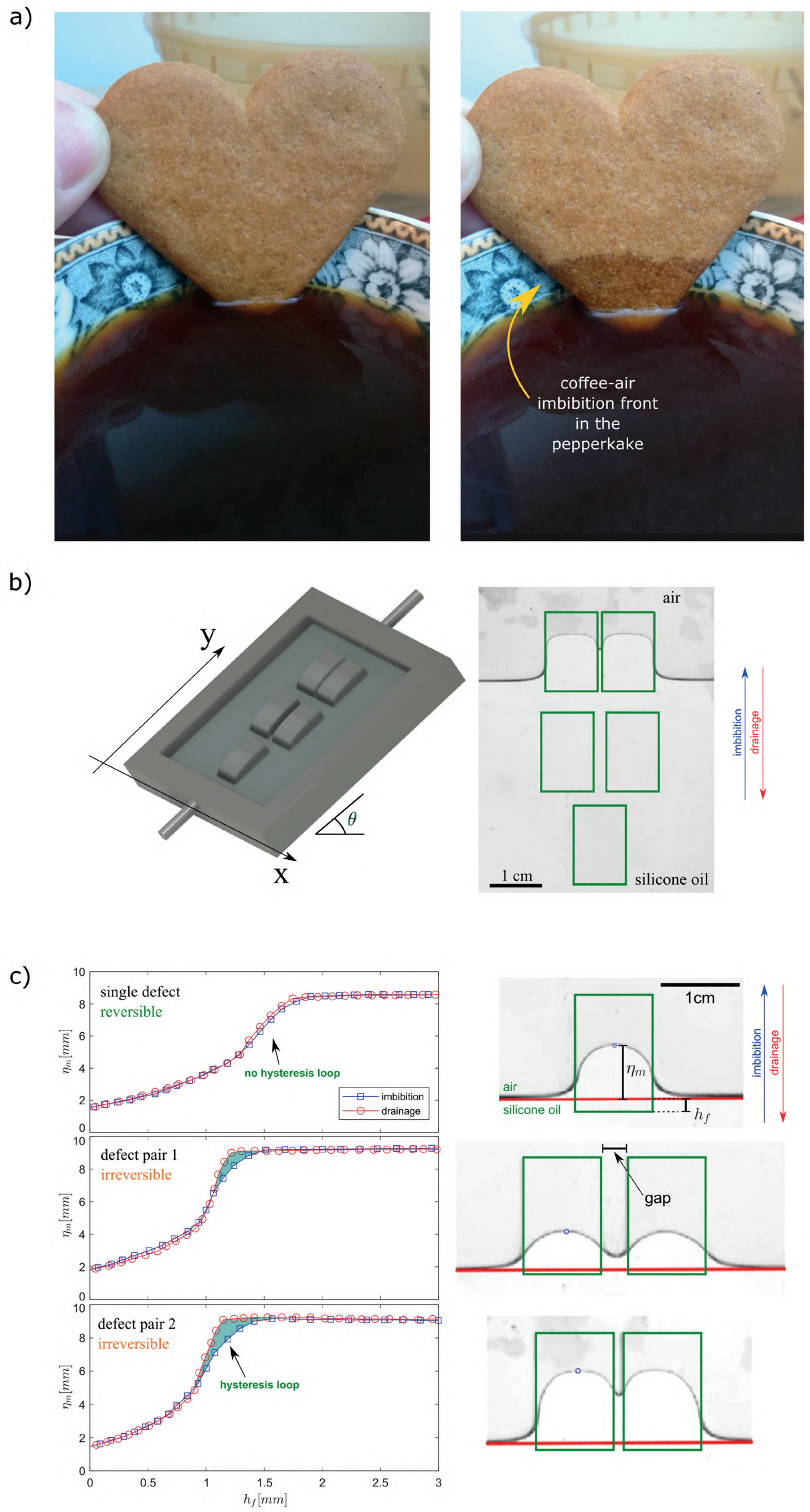


Figure 1: a) *A pepperkake (a delicious porous medium) is carefully dipped into a cup of coffee. As a result, coffee starts to invade the pepperkake, displacing air that previously filled its pores in an imbibition process.* ***b)*** *A 3D printed model of a cell with a sequence of obstacles is produced to study imbibition-drainage cycles. The obstacles cause the liquid-air interface to deform as it passes over it.* ***c)*** *The single obstacle generates a reversible imbibition-drainage cycle (both curves overlap), but when two obstacles are placed together, the lateral interaction between them leads to an irreversible cycle with a hysteresis loop. The interaction between the obstacles grows as they approach one another, and so does the hysteresis loop.*

SPATIAL AND TEMPORAL pH AND CARBON CONCENTRATION DURING DENSITY-DRIVEN CONVECTION OF CO_2 IN WATER

Yao Xu[1], Hilmar Yngvi Birgisson[1], Marcel Moura[1], Eirik Grude Flekkøy[1], Knut Jørgen Måløy[1]

[1] PoreLab, The Njord Center, University of Oslo, Norway

Geological carbon storage has been recognized as one of the most effective means to reduce anthropogenetic carbon emissions in the atmosphere. This process involves four main mechanisms: 1) structure trapping, 2) dissolution trapping, 3) residual trapping, and 4) geochemical trapping. Among these, CO_2 dissolution is recognized as a stable means of permanently storing CO_2. However, mixing CO_2 and liquid within porous media or Hele-Shaw cells involves a complex interplay of chemical and physical phenomena.

The CO_2 dissolution in water results in changes in the solution's properties. Due to the acidity of CO_2, the CO_2-water mixing will acidify the liquid and lower its pH. Besides, since CO_2 has a higher molecular weight than water, the dissolution will also increase the density of the solution. If we imagine the water behaves like a truck carrying the cargo 'CO_2'. The denser fluid 'loading' more CO_2 will be driven downward because it's heavier, while the lighter fluid with less or no CO_2 loaded will float up. This phenomenon, called 'density-driven convection,' raises many intriguing questions. For example, among the sinking fluids, would several of them 'mingle' with each other, or among the sinking and floating fluids, would several of them 'clash and fight' with each other? If they occur, how would those impact the distribution of 'CO_2' concentration in the domain? Illuminating the problems is complicated since there are coupling factors that could influence the pathways of density-driven convection in Hele-Shaw cells and porous media. Any change in the porous media, pressure, temperature, or injection point could make the CO_2 convection so different.

Some advanced imaging tools, such as X-ray or magnetic resonance imaging (MRI), were applied to display the plume morphologies, their movement velocities, etc. However, using those devices is usually more difficult and requires more image processing efforts.

Recent research tends to visualize the process using a single pH indicator [1]. Due to the acidification of CO_2, the CO_2-water mixing will cause indicators to change their color. Although this can generally show the CO_2-affected and unaffected area, achieving more quantitative measurements is challenging [2]. Therefore, robust models and conclusions are still lacking in understanding the density-driven convection of CO_2.

This research will utilize a novel experimental technique developed by PoreLab. We will use a tailored combination of pH indicators, which enables us to detect any subtle change in pH from 4 to 9.5 while CO_2 is mixed with water. The mixing process will be captured by a high-resolution camera at certain intervals. Then, the developed image processing framework will convert the color map to the quantitative pH map, as shown in Figure 1. We will also apply the pseudo-equilibrium theory to correlate the pH values to its CO_2 concentration. In this way, both spatial and temporal measurements could be achieved.

For example, Figure 2 and Figure 3 indicate the CO_2 convection driven by density in the Hele-Shaw cell. The liquid mixed with CO_2 sinks from the interface. The figures also highlight the spatial pH and CO_2 concentration in this domain. Thereafter, the total dissolved CO_2 can also be determined by summing all the locally dissolved CO_2.

Overall, this research aims to enhance the understanding of the density-driven convection of CO_2 in the water, with the application to greater geological CO_2 sequestration. The innovative use of the porous media and data analytical method was supposed to yield more quantitative findings of various chemical and physical effects on CO_2 mixing, solution pH, and CO_2 concentration. Furthermore, additional information, such as the onset time of density-driven convection, wavelength, wave number of plumes, etc., is also expected to be elucidated under different experimental conditions.

The research will boost the theoretical understanding of CO_2 convection mechanisms and contribute to more stable and permanent CO_2 storage in engineering. This holds considerable importance in the broader context of addressing climate change by mitigating CO_2 emissions.

RECOMMENDED READING

[1] Taheri, A.; Torsæter, O.; Lindeberg, E.; Hadia, N. J.; Wessel-Berg, D. Effect of Convective Mixing Process on Storage of CO_2 in Saline Aquifers with Layered Permeability. *ACR* **2021**, 3 (1). https://doi.org/10.21926/acr.2101012.

[2] De, N.; Meunier, P.; Méheust, Y.; Nadal, F. Bi-Dimensional Plume Generated by the Convective Dissolution of an Extended Source of CO_2. *Phys. Rev. Fluids* **2021**, 6 (6), 063503. https://doi.org/10.1103/PhysRevFluids.6.063503.

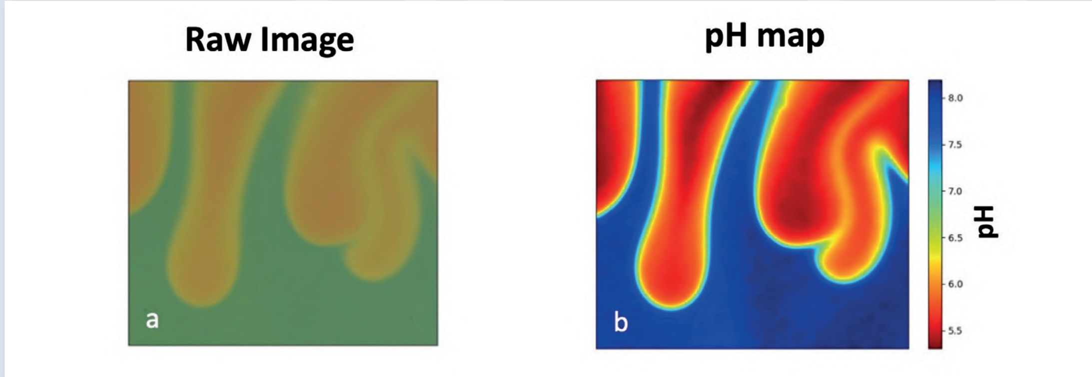


Figure 1. *The compassion between the raw image and pH map.* ***a)*** *The raw experimental data was obtained using a tailored combination of pH indicators. The color map shows various colors, indicating the different amounts of CO_2 dissolved in space.* ***b)*** *The pH map converted from a) using the image processing method developed by PoreLab.*

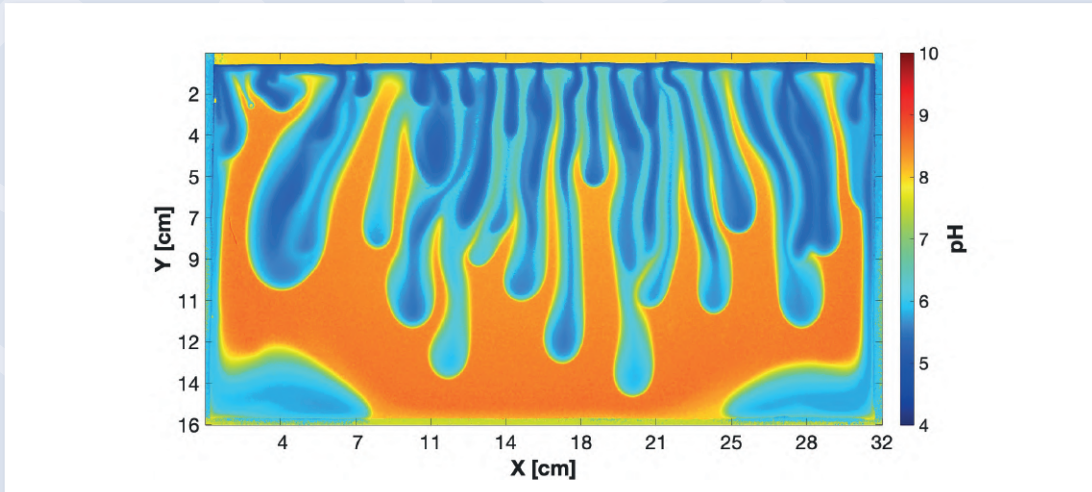


Figure 2. *The pH field with a tilt angle of 60° and Hele-Shaw dimensions of 32 cm*16 cm *2mm, 46 min after CO_2 injection. The plumes appear to shift slightly laterally to the edges. The colors show spatial pH values.*

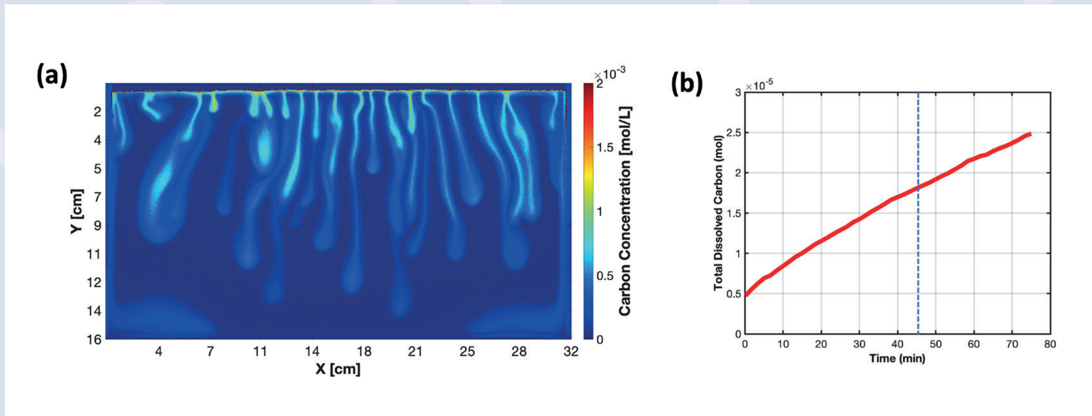


Figure 3. ***a)*** *The carbon concentration field with a tilt angle of 60° and Hele-Shaw dimensions of 32 cm*16 cm *2mm, 46 min after CO_2 injection. The color shows spatial carbon concentration values. The plume patterns correspond to the pH pattern in Figure 2. As the concentration of dissolved carbon increases, the pH level decreases.* ***b)*** *The evolution of total dissolved carbon in the whole Hele-Shaw cell. The experiment was conducted with a tilt angle of 60° and Hele-Shaw dimensions of 32 cm*16 cm *2mm. The blue dash line in b) corresponds to the time in a). It showed that around $1.8*10^{-5}$ mol of carbon were dissolved in a).*

CAPILLARY WASHBOARDING DURING SLOW DRAINAGE OF A FRICTIONAL FLUID

Louison Thorens[1,2], Guillaume Dumazer[1], Knut Jørgen Måløy[1], Eirik Grude Flekkøy[1], Bjørnar Sandnes[3], Mickael Bourgoin[2], Stephan Santucci[2]

[1] PoreLab, The Njord Centre, University of Oslo, Norway
[2] ENSL, Laboratoire de Physique, Lyon, France
[3] Department of Chemical Engineering, Swansea University, UK

We consider a model configuration where an immersed sedimented layer is slowly drained out of a horizontal capillary tube. By systematically modifying the wettability and surface tension of the draining liquid, as well as the initial height of the granular bed, we were able to identify the necessary conditions for the emergence of a displacement process resulting in various drainage instabilities with the formation of ripples and plugs.

We established and analyzed a new unstable drainage regime with periodic dune generation similar to the road washboarding instability due to the repeated passage of vehicles. A 2D theoretical approach based on the competing roles of friction and capillarity, quantitatively supported by 2D numerical simulations of a meniscus bulldozing a front of particles, captures all of the qualitative aspects of the varied drainage dynamics observed experimentally. In the modeling we took into account the fact that the force exerted by the granular front on the invading meniscus depends on the local angle of attack. Animals such as lizards take advantage of such frictional enhancement with the local angle of attack to move and even run effectively on a flowing granular media.

The intricate interplay between capillary forces and frictional and viscous dissipation is also responsible for the creation of different displacement regimes as the injection rate is increased. In flow circumstances dominated by viscous dissipation, the result of viscous forces is the gradual fluidization of the entire granular material.

ACKNOWLEDGEMENTS

The work has been done with support from the Norwegian Research Council and its Center of Excellence Funding Scheme project no 262644.

RECOMMENDED READING

[1] Louison Thorens, Knut Jørgen Måløy, Eirik Grude Flekkøy, Bjørnar Sandnes, Mickael Bourgoin, Stephan Santucci, Capillary washboarding during slow drainage of a frictional fluid, *Soft Matter* **19**, 9369, (2023), DOI: 10.1039/d3sm00717k.

[2] Guillaume Dumazer, Bjørnar Sandnes, Knut Jørgen Måløy, and Eirik Grude Flekkøy. Capillary bulldozing of sedimented granular material confined in a millifluidic tube. *Phys. Rev. Fluids,* **5**, 034309, (2020)

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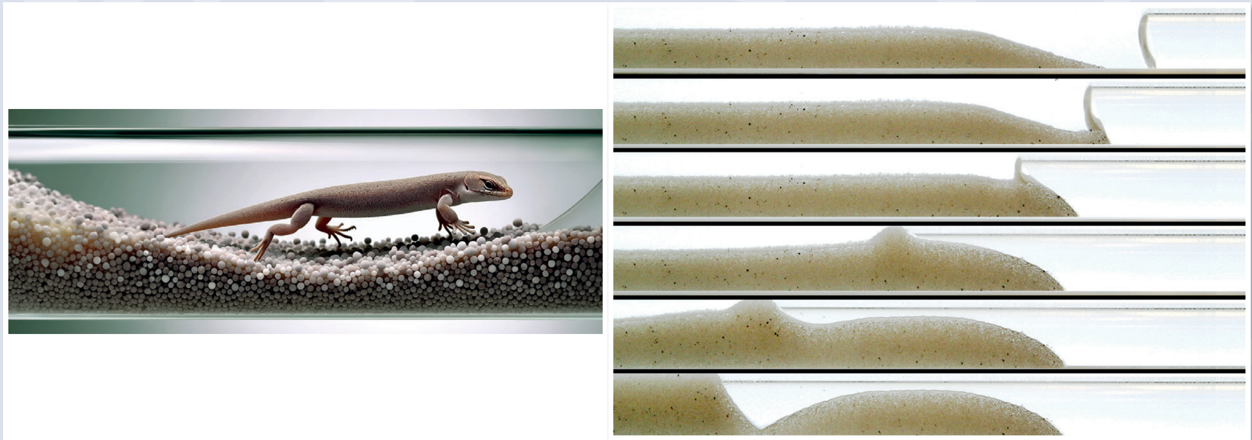

Figure: Left: *A lizard walking on a granular material taking advantage of frictional enhancement with the local angle of attack (frontpage of Soft Matter volume 18, Number 48)*
Right: *Formation of dunes during slow drainage of a the fluid.*

RESEARCH PROJECTS

FRICTIONAL FLUID INSTABILITIES SHAPED BY VISCOUS FORCES

Dawang Zhang[3], James M. Campell[1,2,3], Jon A. Eriksen[1,2], Eirik G. Flekkøy[1,2], Knut Jørgen Måløy[1,2], Christopher W. MacMinn[4], Bjørnar Sandnes[3]

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An invading meniscus between two fluids may displace a loose packing of granular material. The flow becomes 'frictionally unstable' as the invading fluid front takes the shape of fingers that plough through the granular material. Previous studies have found that air injection into a viscous granular mixture produce frictional fingers at low injection rates, giving way to viscous fingers at higher rates; the system becomes 'viscously unstable'. But what happens if the viscosity contrast is swapped, and the high viscosity fluid is the invading one?

From classic fluid dynamics we know that the displacement front of a high viscosity invading fluid will be viscously stable, giving rise to a simple expanding disc in a radial Hele-Shaw cell. With grains in the system, however, Zhang et al. discovered a new family of pattern formation caused by the interplay between Coulomb friction and viscous forces. The experiments used glass beads made hydrophobic by chemical treatment. Invading water therefore pushed the dry hydrophobic grains to the side, creating a single finger at low injection rate. By increasing the injection rate, the viscous forces in the system became more dominant relative to friction. A surprising finding was that the role of viscous stabilization was to sprout more fingers: Viscous pressure within the invading fingers caused breakout of new fingers as the injection rate was ramped up. At extreme levels of viscous stabilization (injection of pure glycerol as fast as the pump could go) the fingers grew in a spoke pattern, all fingers moving radially outwards from the central injection point, side-by-side like petals on a flower.

Multiphase frictional flows are a distinct class of fluid displacement problems, and the study has revealed new flow behavior caused by the interplay between frictional, capillary and viscous forces. Such frictional flows with loose granular materials embedded in viscous fluids are ubiquitous in nature and industrial processing, and this new insight brings us a step closer to unpicking the fluid dynamics of these systems which are notoriously complex and difficult to control.

ACKNOWLEDGEMENTS

The work has been done with support from the Norwegian Research Council and its Center of Excellence Funding Scheme project no 262644

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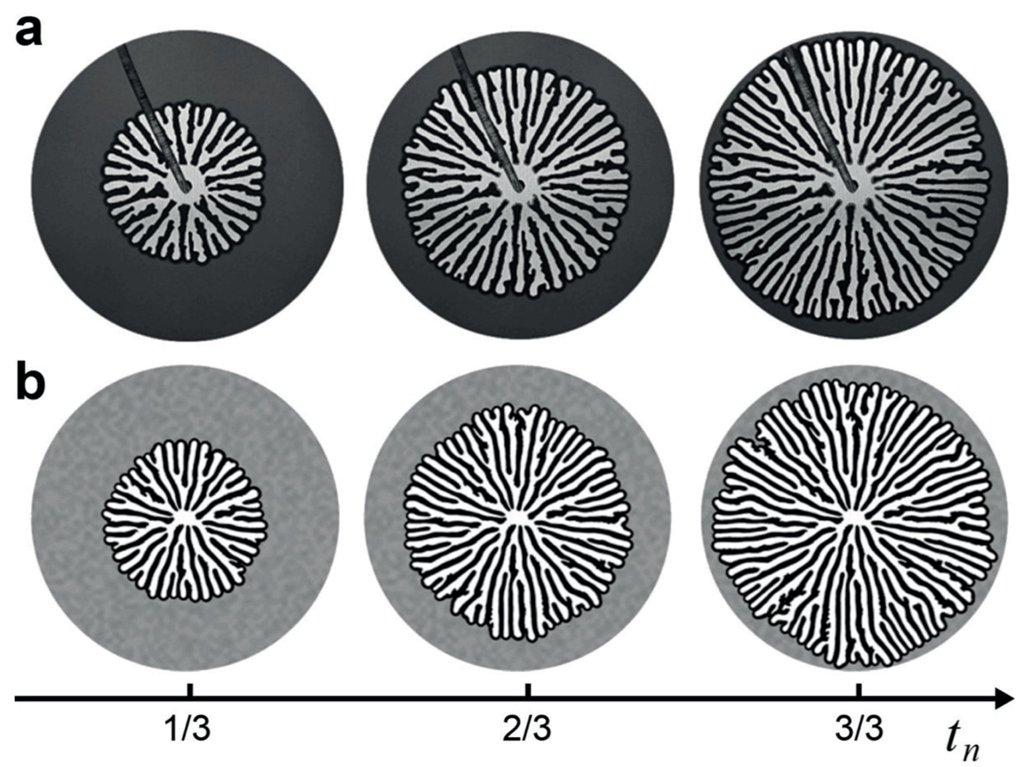

Figure: *Time evolution of spoke pattern. (a) Experiment and (b) simulation of glycerol injection producing a viscously stable spoke pattern. Time tn is normalized by the time the first finger reaches the boundary.*

RESEARCH PROJECTS

CONNECTIVITY ENHANCEMENT DUE TO LIQUID FILMS IN POROUS MEDIA FLOWS

Paula Reis[1], Marcel Moura[1], Knut Jørgen Måløy[1,2], Eirik Grude Flekkøy[1,3], Gaute Linga[1], Per Arne Rikvold[1]

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The flow of liquids and gases inside porous networks is a rather common process. It happens for example when rain falls on a soil: as the water moves in, it displaces air from the pores between the soil grains. It is also very important for many industrial and environmental applications, such as the geological storage of CO_2 and the remediation of contaminated soils.

In many of those fluid displacement processes, thin layers of liquid are left on the surface of the grains forming the porous medium, which can interconnect distant parts of the system. This effect brings some positive and negative consequences. The enhanced film connectivity is used by plants to obtain water and nutrients, but it also provides a pathway for the fast spreading of pollutants inside the soils. It is very important to understand these effects, and this is the primary goal of this project: to produce a physics-grounded explanation for the stability and transport properties of the thin liquid film network.

In 2023, a simplified numerical model for slow drainage in granular materials under gravitational effects was developed by members of FlowConn (see PoreLab annual report 2021, page 56), by incorporating liquid-film connectivity on an invasion-percolation model. Basically, the idea was to acknowledge that liquid is connected not only by pore bodies and pore throats filled with liquid, but also by pendular rings formed between grains. With the proposed model, experimentally observed phenomena related to drainage through films and capillary bridges could be adequately reproduced. Examples are the formation of a limited region for film-induced drainage, and how this region is affected by gravity, as seen in the Figure. Additionally, due to the low computational cost associated with the simulations, we could expand the set of parameters previously investigated with experiments only, and compare results obtained using numerous randomly generated pore-networks representing granular media, which added robustness to the FlowConn Project findings.

This was an important step in our quest for a comprehensive understanding the role of films in the connectivity of liquid in porous-media flows. Currently, a new dynamic pore-network model is under development to describe the same flows, so that we can also investigate the effects of viscous forces on the prevalence of film-induced drainage.

ACKNOWLEDGEMENTS

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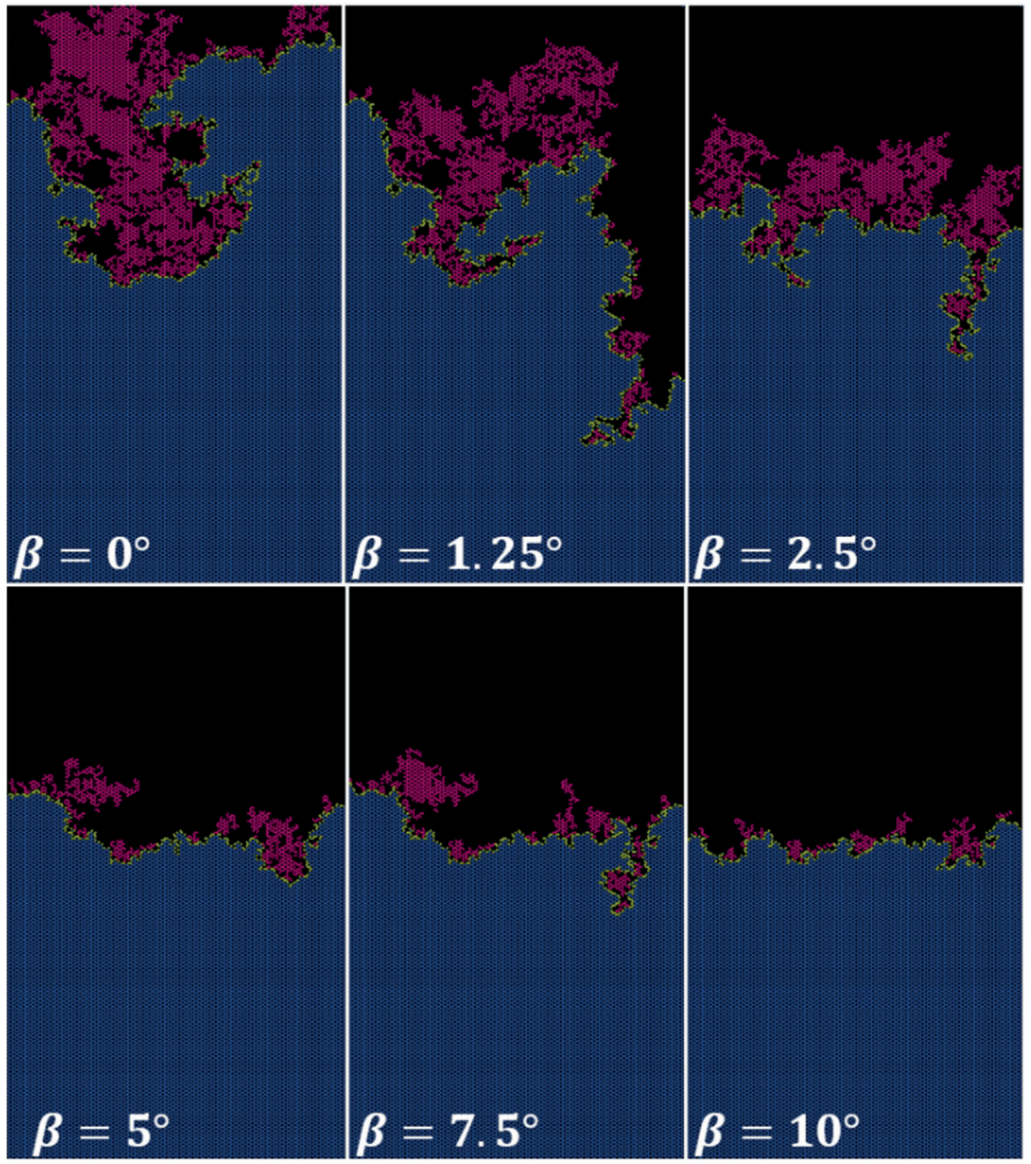

Figure: *Extent of the film networks (pink) developed during drainage in a 2D rectangular porous medium. In each image, liquid is drained from an outlet at the bottom of the rectangle, while air invades the medium from an inlet at the top. In blue we see the portion of liquid connected to the outlet directly by pores bodies and pore throats. The yellow line bordering this region delineates the air invasion front, above which the film network appears. We can notice that, as the effect of gravity becomes larger (marked by the increasing tilt angle β with respect to the horizontal plane), the film network becomes more compact. This trend was observed experimentally and well reproduced by the proposed numerical model.*

RESEARCH PROJECTS

IMPACT OF MULTIPHASE FLOW ON SOLUTE SPREADING IN POROUS MEDIA

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The transport of dissolved chemicals and nutrients by fluids flowing through porous media is an important concept pertaining to a wide range of industrial and natural systems. When one fluid flows through a porous medium, theoretical model for understanding and predicting spreading of such solutes are fairly well developed. The case where two or more immiscible phases flow together through the pore space, however, is much less understood despite the significance of such processes to environmental remediation, water management, as well as CO2 and H2 storage in geological media, to name a few examples. In this case, interface forces between the phases induce temporally fluctuating velocity fields which may accelerate solute spreading.

In recent work, we investigated the effect of multiphase flow on the spreading of solutes in porous media [1]. We used Lattice Boltzmann for the fluid flow and Lagrangian particle simulations for solute transport to investigate porous systems across an extensive range of capillary numbers (viscous to interface forces) and Péclet numbers (advective to diffusive fluxes). We found that multiphase flow can strongly enhance spreading transverse to the mean flow. Moreover, the effect is stronger at lower capillary numbers, where the flow dynamics is more bursty. We identified the mean cluster size to be the main driver for the enhanced solute spreading. Based on the results, we derived a new scaling law reflecting that dispersion in multiphase flow must be described in a Péclet-capillary number space.

The presented scaling law opens new avenues for characterizing and modelling solute spreading and mixing across a range of multiphase porous systems. In the future, we will explore the impacts of e.g. wettability, viscosity, buoyancy and phase-dependent solubility upon the spreading dynamics.

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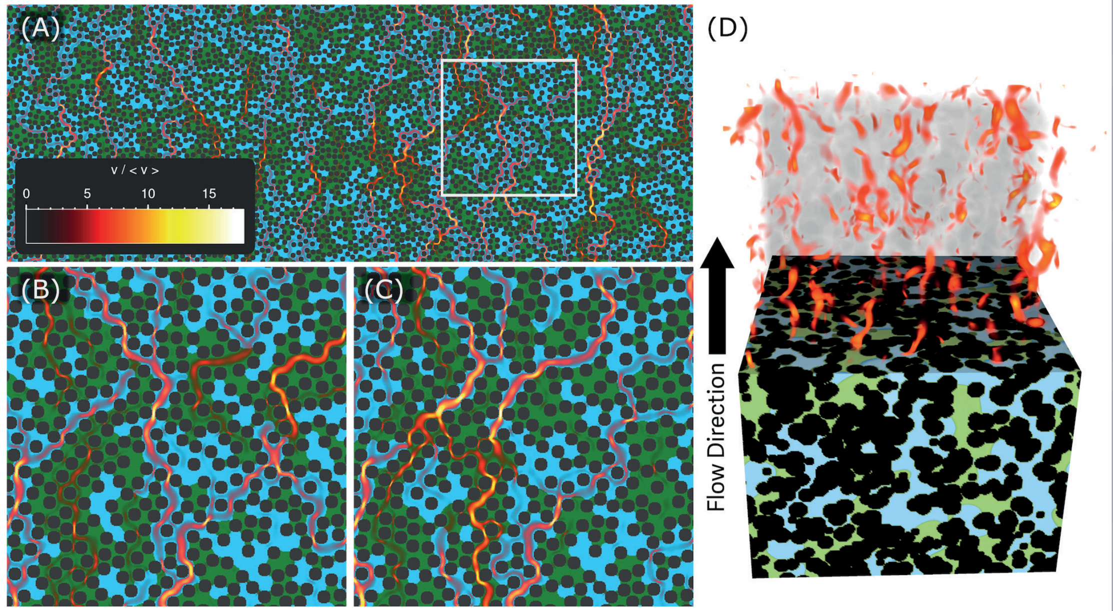

Figure: *Simulations of two-phase flow in porous media. Wetting (green) and non-wetting (blue) fluid flows together between circular obstacles (dark gray) in 2D simulations (A-C) and spherical obstacles (black) in 3D (D). (A) shows the full size of the simulations and (B) and (C) show the same subdomain at two different times. The transparent-red-yellow color scale (shown in A) indicates the local fluid velocity rescaled by mean velocity. Figure reprinted from [1].*

RESEARCH PROJECTS

PATHOGEN DETECTION WITH COLLOIDS

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Every year roughly 3 000 people die of sepsis [1] in Norwegian hospitals alone (see: Report by Steinar Brandslet - Published 12.09.2023 in Norwegian SciTech News [2]). Sepsis can be caused by bacterial, viral or fungal infection. One reason for this shortcoming is the lack of fast, inexpensive diagnostic tools to identify the pathogen causing the infection. As a result, doctors often prescribe a broad spectrum of antibiotics, making them increasingly ineffective [3].

Present day diagnostic tools rely on detecting DNA sequences that are unique to a given pathogen. The challenge lies in not only discriminating the pathogen's DNA from all other DNA present in a human or animal sample, but also to detect them at very low concentrations, before they overwhelm the patient's defenses. During the Covid 19 pandemic we learned that rapid flow tests can give results within 15 minutes, but they only work when the patient has already a high viral load. These tests work well for the shorter DNA or RNA of viruses but are not useful for the detection of bacterial DNA that is some 10 times longer. The more accurate PCR (Polymerase Chain Reaction) tests can detect lower concentrations of viruses and bacteria but rely on amplification of the pathogen DNA.

Recently, Curk et al. [4] put forward a new detection strategy that is based on two facts: Short, single-stranded (ss)DNA sequences bind weakly but with high specificity to complementary ssDNA strands along the genome. The other aspect is based on the fact that short ssDNA sequences often repeat themselves many times along a given genome. Therefore, many short DNA probes can bind to the whole genome, which we call multivalency. Curk et al. [4] developed an algorithm to find the best multivalent, 20-bases-long sequence that has the highest number of repeats for a given bacterial genome. The Eiser group adapted this approach to densely functionalize 500 nm large polystyrene particles with these Maximally Multivalent MMV-DNA probes [5].

When we mix a solution of the whole genome DNA we want to detect (here the E. coli strain bl21-de3) with a suspension of the colloids coated with the MMV-DNA probes, we will see in minutes very strong aggregation of these colloids, as illustrated in the Figure. However, when we add other bacterial genome DNA to our E. coli specific probes, hardly any aggregation is visible. Hence, we have demonstrated that utilizing the concept of using the cooperativity of many week binders (multivalency) is key to the development of very efficient, highly selective probes (we can detect down to 5 genomes per ml) that can be used outside a lab setting and with minimal tools in rural areas, but also in hospitals when fast diagnosis is essential to detect bacterial DNA.

Presently, we work on developing the multivalency approach in theory (statistical physics) and experiment to work also for viral and fungal DNA.

ACKNOWLEDGEMENTS

This work was done in collaboration with the group of Prof. Fangfu Ye (Beijing National Laboratory for Condensed Matter Physics and Laboratory of Soft Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China). All experiments were performed by Dr. Peicheng Xu, a joint postdoctoral researcher.

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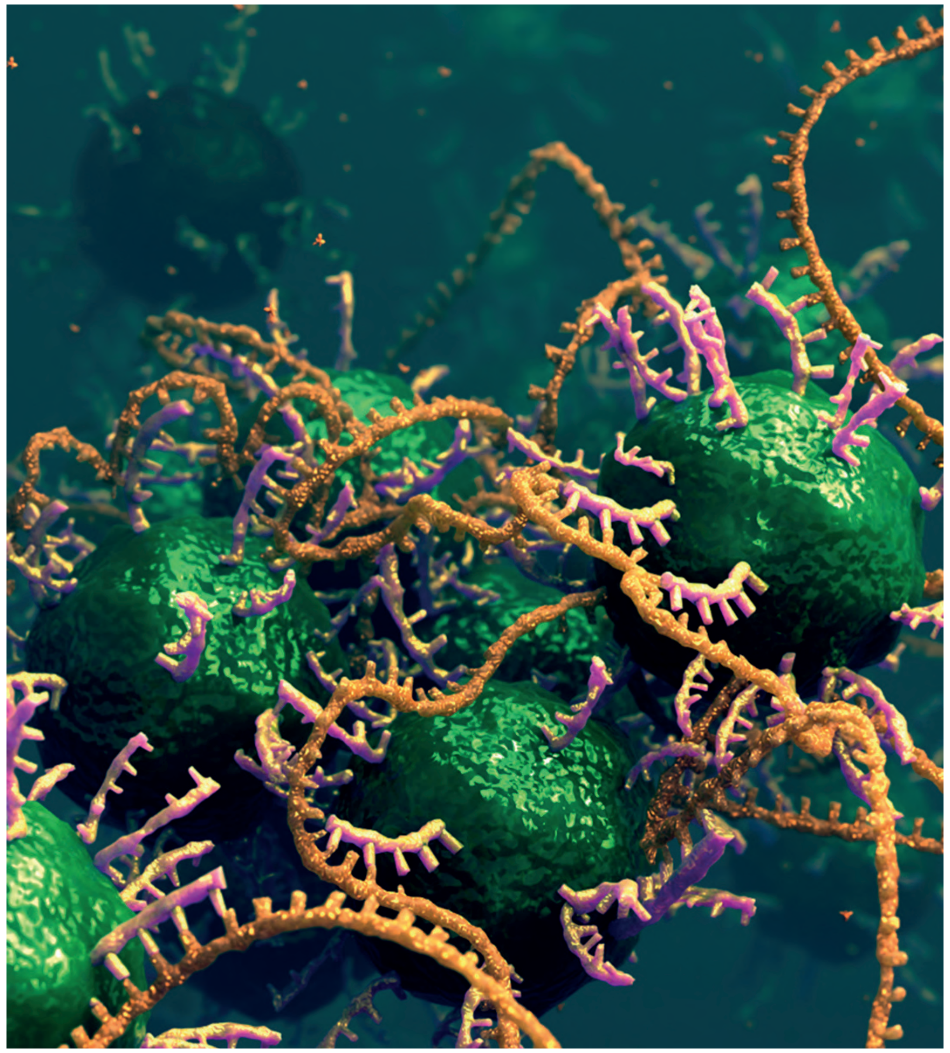

Figure: *Illustration of polystyrene colloids (green), densely coated with short single-stranded DNA probes (purple) that were designed to bind to a specific bacterial genome (orange). The DNA probes were sufficiently specific to distinguish between the genomes of different bacteria and between different strains of E. coli. This work was published in PNAS.*

RESEARCH PROJECTS

MICRORHEOLOGY OF COMPLEX FLUIDS

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In everyday life we are constantly confronted with complex fluids, such as shampoo, foods, paints, or biological ones, e.g. the fluids lubricating our joints and the eyelids. What they all have in common is that they are based on a continuous background fluid that could be Newtonian. However, when we mix one or more microscopic additives into the fluid, it can change its mechanical properties ranging from a viscous to viscoelastic material with fluid and solid responses. A wonderful example is corn-starch, which is a powder of granules whose sizes range from hundreds of nanometers up to tens of micrometers. The flow behavior of their aqueous suspensions is dominated by the viscosity of water when we stir them slowly. However, when sheared fast the suspension show the characteristics of a solid [1]. Such fluids are called shear thickening. Contrary, polymer solutions often display shear thinning properties: their viscosity decreases the harder we shear them, a propensity that can be used in lubricants.

A special class of complex liquids are those made of biopolymers. Examples are egg white, which is a viscoelastic protein solution, the extracellular matrix and synovial fluids that lubricate our joints. Latter are highly viscous fluids made of very long poly-saccharide chains. Many researchers and industries use a classical rheometer to get fundamental insights into what parameters are responsible for the specific mechanical and flow properties of the system or quality control of a product. These require large quantities and only measure the bulk properties.

However, many biological samples often require careful extraction and high degrees of purification to access the underlying properties, which makes them costly.

Hence, various microscopic particle tracking, and light scattering techniques have been developed that allow us to extract their viscoelastic properties using only microliters. These techniques, referred to a microrheology, use non-interacting colloidal probe-particles, that are immersed into the liquid. The motion of such micro-particles is dictated by the thermal fluctuations brought about by constant collisions with the surrounding environment.

The microrheology tool we use is a scattering technique called Diffusive Wave Spectroscopy (DWS) [2] and is illustrated in the Figure. It works as follows: the sample is mixed with a large enough concentration of the probe particles, which cause the incoming laser light to undergo multiple light scattering. We record the scattered light, I(q,t), hitting a small area of a point-like detector positioned in forward direction, as function of light with MHz recording frequency. Using a fast correlator, we compute the fluctuations in the scattered light caused by the probe particles, providing us with the so-called intensity autocorrelation function, $g^{(2)}(q,t)$. Form this, we can then extract the mean squared displacement (MSD) of the probe particles. Fourier transforming these MSDs provide us then with the rheological moduli, G'(w) and G''(w), which describe the systems elastic and viscous properties.

ACKNOWLEDGEMENTS

The Eiser group studies the formation and viscoelastic properties of DNA-hydrogels [3], and in collaboration with the group of Bjørn Torger Stokke (Physics, NTNU) the crosslinking process of fungal polysaccharides in the presence of chitosan with relevance in tissue engineering.

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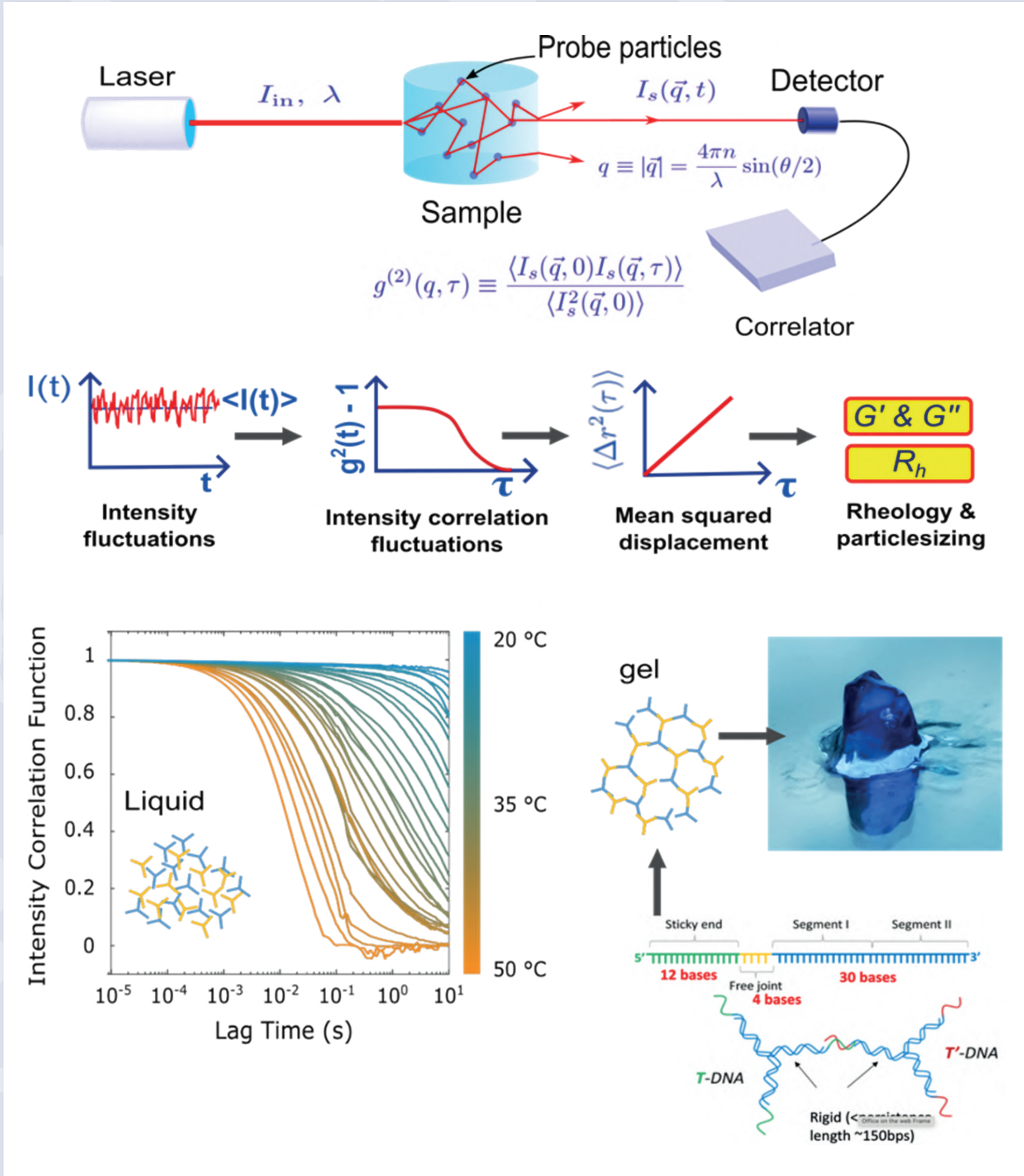

***Figure:* (top)** *Illustration of the workings of a DWS microrheometer (using an LS Instruments setup). (bottom) Intensity autocorrelation functions measured as function of temperature for a solution of DNA nanostars (T and its complementary star T') made of 3 arms of double-stranded DNA-arms and sticky single-stranded DNA overhangs. These temperature-reversible hydrogels form upon cooling and melt at higher temperatures [3]. The photograph shows such a DNA hydrogel (here colored with a DNA-stain).*

SPATIAL CHARACTERIZATION OF WETTING IN POROUS MEDIA USING LOCAL LATTICE-BOLTZMANN SIMULATIONS

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This research addresses a critical issue in the field of multiphase flow in porous media; the limitations of modeling wettability as a constant parameter in pore-scale simulations. The use of in-situ visualization techniques, such as X-ray imaging and microtomography, to accurately characterize the spatial distribution of wetting is a significant advancement. The novel approach we propose involves employing local lattice-Boltzmann simulations on segmented X-ray images, with the added benefit of computational efficiency achieved by dividing the segmented X-ray image into subdomains for faster simulations. In this scheme, local lattice-Boltzmann simulations are conducted on isolated ganglia to obtain the local wettability for various three phase contact lines in the domain. A surface affinity parameter (*Φ*), which describes the wetting state in color lattice-Boltzmann, is optimized for each ganglion with the aim of a more accurate simulation of the ganglion inside the pore space. Figure 1 shows the flowchart for the optimization.

The proposed method is validated using synthetic cases with known wettability, along with the comparison to a geometrical contact angle determination method, which strengthens the credibility of the obtained results. The developed workflow demonstrates accurate characterization of the wetting state in synthetic porous media, even in extreme wetting conditions. The consistency of the obtained contact angle distributions with the geometrical method in three datasets of imaged fluid distributions is promising. The narrower span of the obtained contact angle distributions considered more realistic compared to the geometrical method, which underscores the potential of the proposed scheme. Figure 2 provides the simulation for a specific ganglion in porous media and the final obtained wettability map after analyzing all trapped ganglia in the sample.

In summary, this research contributes to improving wettability modeling in multiphase flow simulations in porous media. The efficiency of this approach and its ability to provide more accurate wettability maps using limited experimental data can enhance the precision of digital rock analysis in studying multiphase flow phenomena.

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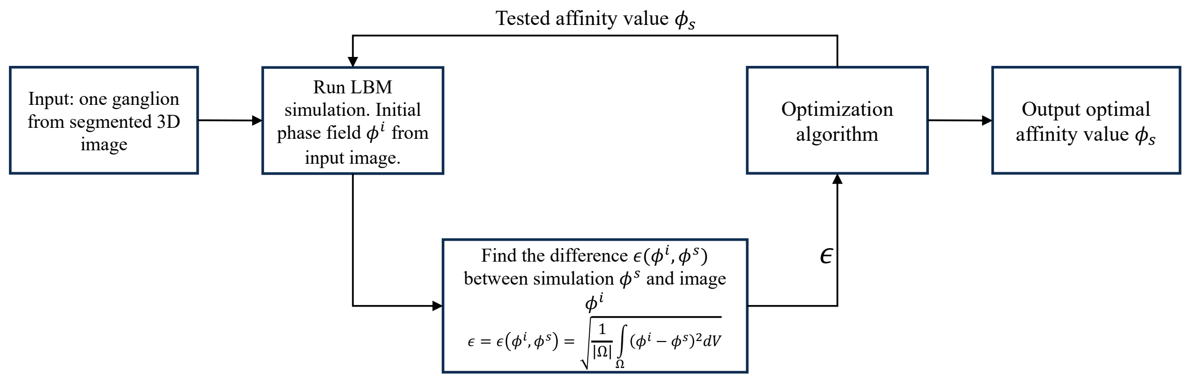

Figure 1: *A flowchart of the optimization loop, finding the affinity value Φ_s that minimizes the difference ϵ in the phase field between the imaged ganglion Φ^i and the simulated one Φ^s.*

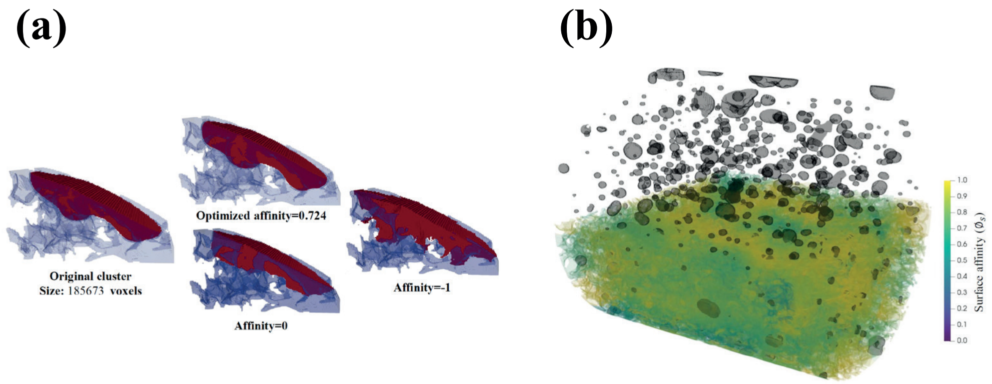

Figure 2: (a) *One of the trapped gas ganglions in the gas-water Bentheimer sample and simulation cases for different surface affinity values using local LB simulations. For this cluster, the final optimized value of surface affinity is Φ_s=0.724 which describes the cluster the best.* ***(b)*** *Surface affinity parameter (Φ_s) distribution map for all solid-fluid voxels in a gas-water Bentheimer sample.*

SUMMATION RELATION IN PHASE-FIELD EQUATIONS

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This research investigates the accuracy of using a summation relation when solving interface-capturing phase-field equations. The summation relation says that the summation of the order parameters (volume fractions) of two or more fluids in a mixture is equal to unity. The summation relation is used to reduce the number of equations to be solved. For example, for a two-fluid mixture it is common to solve only one interface-capturing equation and then find the order parameter of the other fluid by the summation relation.

In this study, we try to investigate how utilizing or not utilizing the summation relation affects results for two-fluid mixtures. Among phase-field equations, there are two commonly used ones, the Cahn-Hilliard (CH) and Allen-Cahn (AC) equations. We employ the AC equation as it outperforms the CH in terms of mass conservation and retaining small bubble or droplets. Two schemes are defined; one-eq scheme (in which one AC equation is solved and the other order parameter is calculated based on the summation relation) and two-eq scheme (in which two AC equations are solved simultaneously to determine the two order parameters). The lattice Boltzmann method (LBM) is selected as the solver for the AC equations as well as the Navier-Stokes equations.

Different benchmarks are employed to highlight differences between these two schemes. First, a Rayleigh-Taylor instability (RTI) is conducted. It is shown (Fig. 1) that the velocity field is not divergence free in spite of incompressible assumption of the fluids. A theoretical analysis shows that for the one-eq scheme an additional term appears in the non-solved equation of the other fluid, which leads to asymmetry in the numerical results for a symmetrical problem like the RTI. For this benchmark, the one-eq scheme 11% faster than the two-eq scheme, and also the one-eq scheme utilizes 25% less computational memory in comparison to its counterpart.

Based on the observations in the RTI example, a series of benchmarks is investigated where we reduce the complexity of the velocity field and impose it as in input for the one-eq and two-eq schemes. In the first set, the velocity field is not divergence free and its magnitude is of the same order as the RTI. In the second one, the velocity field is divergence free, however, there is a singularity which acts as a source or sink. In the third one, the velocity field is divergence free and without any singularities. And finally in the fourth set, the velocity field is zero. Except for the fourth benchmark, all examples have unwanted and unphysical appearances of the interfaces. Also, the results are dependent on which fluid is solved in the one-eq scheme, indicating the asymmetry in the solution of this scheme. Figure 2 shows the temporal evolution of the order parameter for one-eq and two equation scheme when the velocity field is not divergence free.

In summary, both the theoretical and numerical simulations indicate that the only occasion in which both the one-eq and two-eq schemes lead to same results is when the velocity field is zero. Utilizing the summation relation is therefore not accurate, although it consumes less computational resources and time..

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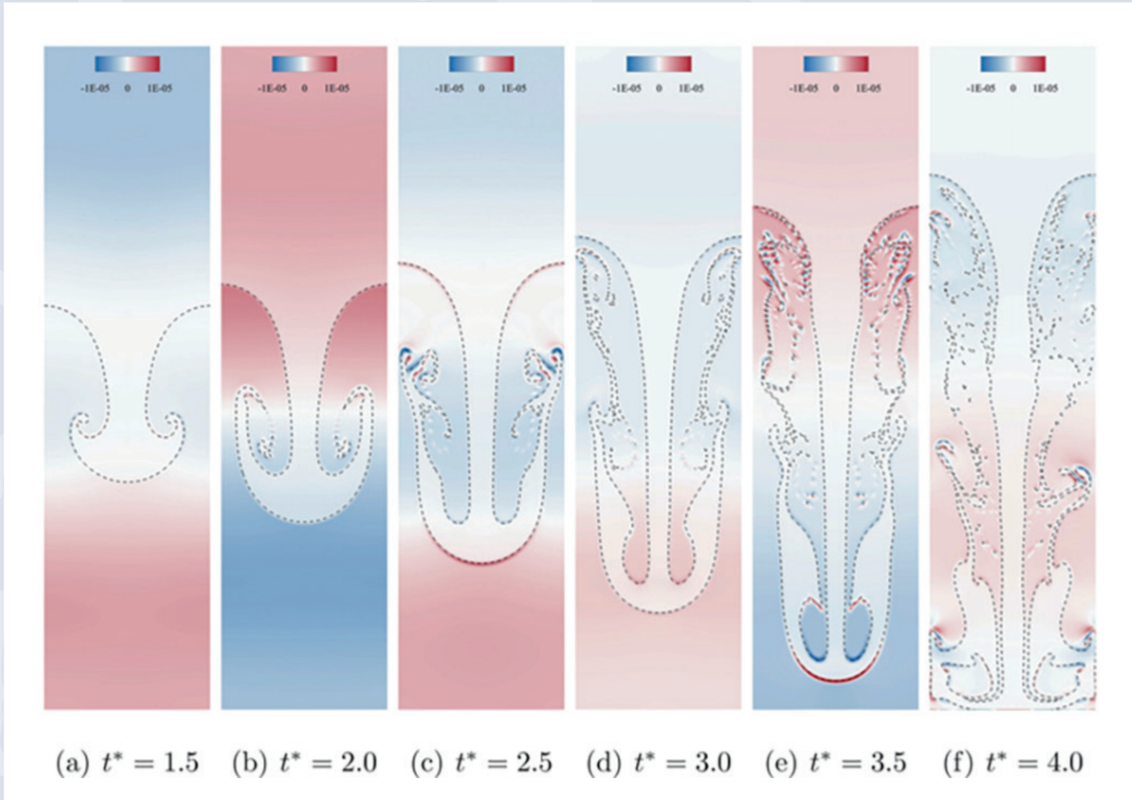

Figure 1: *Snapshots of the interface location as well as the divergence of the velocity field (∇·u) at different times when one-eq scheme is solved for the heavy fluid*

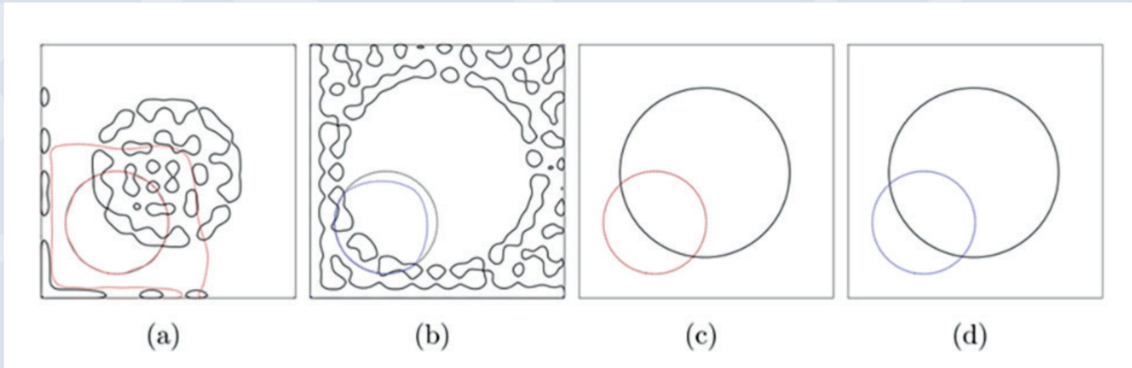

Figure 2: *Temporal evolution of the order parameter for one-eq scheme when just the equation of the red fluid is solved and the circle is filled by (a) the red fluid or (b) the blue fluid, and two-eq scheme when the circle is filled by (c) the red fluid or (d) the blue fluid.*

SYSTEMATIC STUDY OF WETTABILITY ALTERATION OF GLASS SURFACES BY DICHLOROOCTAMETHYLTETRASILOXANE SILANIZATION; A GUIDE FOR CONTACT ANGLE MODIFICATION

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This work was published in ACS Omega 2023 8 (40), 36662-36676, DOI: 10.1021/acsomega.3c02448

Wettability plays an important role in many natural and industrial processes, like mineral processing, filter applications as well as in multiphase flow in porous medium processes such as hydrocarbon production, ground water remediation and carbon dioxide (CO_2) storage. For multiphase fluid flow and hydrocarbon production from natural porous media, extensive research has been performed on the influence of the wettability on the phase distribution and its morphology in both, static and dynamic conditions [1-5]. Knowledge on the effect of wettability is also crucial for the topics of increasing interest e.g. using natural reservoirs for hydrogen or carbon dioxide CO_2 storage, for example for the description of injection dynamics and assessment of caprock stability [6].

In order to investigate wettability effects on multiphase flow behavior in porous media in a controlled and standardized manner, researchers utilize model systems like bead packs or micromodels. Glass[1] is one of the materials used for the creation of such models, being transparent and relatively easy formable to the desired geometries. Additionally, the wettability of the glass surfaces can be altered from its original hydrophilic state to more hydrophobic state by reaction of variants of silane or siloxane groups with the hydroxyl groups of glass known as silanization [10].

The degree of wettability alteration as consequence of the silanization reaction depends on numerous variables [7-9] such as the reaction time, temperature, concentration of the silane/siloxane in the solvent, the nature of the solvent the silane/siloxane is dissolved in and the cleaning procedure of the glass prior to the silanization. Although silanization is widely used as a method for glass wettability modification, comparable detailed systematic approaches over a large range of geometries, treatment conditions and measurement systems are scarce in the literature [7-9].

1 We considered the soda lime glass beads to be inert, but by inserting them in the brine, the pH changed from 5.6 to ~10 within minutes. Some literature sources make note of this effect [13,14].

In this work, a study was performed to investigate the processes of dichlorooctamethyltetrasiloxane (Surfasil) treatment, with the purpose to systematically obtain a variation in wettability conditions for different glass geometries and comparable glass composition and to provide a treatment guide for achieving a wide range of contact angles. Secondly it was investigated whether different geometries display comparable contact angles under similar treating conditions using independent methods of contact angle determination.

Wettability was quantified through contact angle measurements on glass plates, single beads and 2D micromodels. Initially, the influence of the solvent, treatment time and Surfasil to solvent ratio on glass plates was investigated using the sessile drop method. After establishing a clear relationship between the parameters and contact angles, the same treatment parameters were applied to single bead, microchip and multiple glass beads, the latter to form a bead pack. Contact angles from single glass beads were obtained using image analysis of projections, while contact angles within a bead-pack were extracted from segmented 3D micro-CT images using algorithms [11]. Contact angles from 2D micromodels were obtained by image analysis.

By varying treatment times and the Surfasil to heptane ratio, it was possible to achieve a wide range of comparable and repeatable contact angles; from the initial 20° to 100° as ultimate non-wetting state measured for air-water systems; for glass plates and individual beads, see Figure 1.

The flooding treatment in the micromodel was so far limited to the ultimate non-wetting state, showing comparable results to the glass plate and individual glass beads within the optical limitations of the measurement. Contact angle derivations from the bead pack using the 3D micro CT scan images showed higher contact angles in comparison to the single bead experiments, but it confirms larger spread of the contact angle as observed in the application of the algorithms as presented in literature [12].

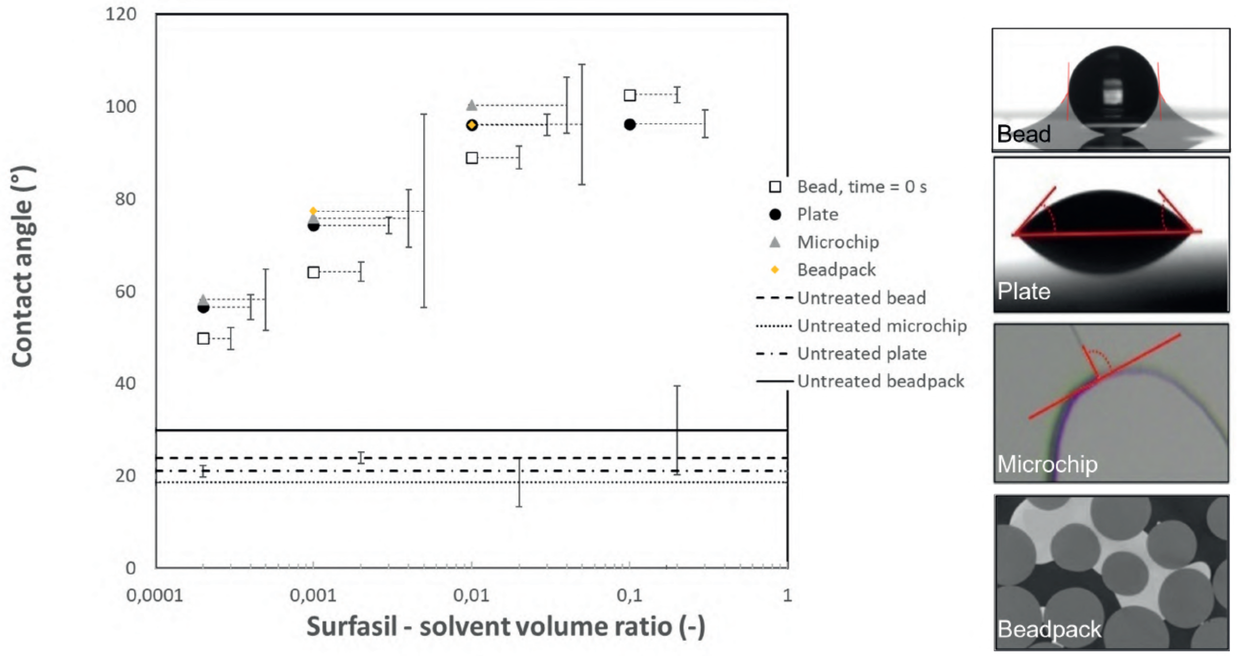

Figure: *The dependency of the manually measured contact angle on Surfasil-heptane volume ratio, at a treatment time of 180 seconds for the glass plate, single bead and microchip. With increasing Surfasil concentration the contact angle increases till it reaches a plateau value of approximately 100°. This trend is observed for all geometries.*

Laboratory procedures are available. Please contact Antje van der Net for more information. antje.van.der.net@ntnu.no

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NANOTHERMODYNAMICS: THEORY AND APPLICATIONS

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A book with the title *Nanothermodynamics*. Theory and Applications was recently published on World Scientific Publishers, see Figure 1. The aim of the book[1] is to explain and apply the systematic thermodynamic theory of small systems; proposed last century by Hill[2]. We use and extend his method and demonstrate its importance in several examples. In the first part of the book, we highlight the basic idea of the theory and provide a more systematic method, than used before. In the second part, we demonstrate the power of the theory in a set of central applications of nanoscience in and away from equilibrium, for other scientists to be inspired for further use.

This book grew out of an idea to study properties of small subsystems of a large reservoir. Observations were at the time not explainable with standard thermodynamics. But the theory of Hill on thermodynamics of small systems provided the systematic procedure needed to address the problem. Following Hill, thermodynamics can be formulated for the nanoscale! This is what we have done.

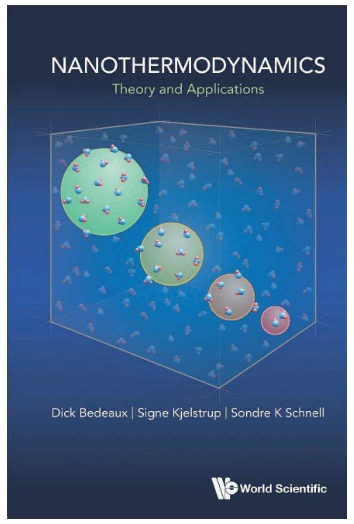

***Figure 1:** Nanothermodynamics. Theory and Applications by Dick Bedeaux, Signe Kjelstrup and Sondre K. Schnell*

The purpose of this book is to expand and demonstrate Hill's theory. The theory adds a new term to the fundamental Gibbs equation, that is specific for systems at the nanoscale. The properties that follow may be counter-intuitive. The equation of state for a small system, for instance, is not given once and for all. We shall see that it changes with the environmental variables that control the small system. The statistical mechanical machinery remains, however.

Within small system thermodynamics, we can now deal with the energies of a single molecule, unlike in classical thermodynamics. Equilibrium properties will change upon confinement and depend on system shape as well as size. Such features make nanothermodynamics very different from classical thermodynamics. It extends the classical theory down to the nanometer-scale and can affect systems up to the micrometer scale. As soon as the system's surface energy is sizable compared to the bulk energy, like when the Young-Laplace equation applies, we may benefit from the small system analysis.

The world of small systems challenges the standard knowledge; that the number of particles in a system must be very large for thermodynamic equations to apply. We shall see that thermodynamic equations apply perfectly well also for small particle numbers, provided that small-system effects are accounted for correctly. In the world where size and shape are central, we shall find that equations of state can be used down to one particle in a box! There are scaling laws, which help us determine and understand the large system limit better!

The purpose of this book is to explain and apply the systematic thermodynamic theory of small systems; proposed by Hill. We use and extend his method. In the first part we highlight the basic idea of the theory. In the second part, we demonstrate the power of the theory in various applications in and away from equilibrium.

Applications of Hill's theory have so far been scattered, but we believe that his theory deserves to be further explored and used. The book is a step in that direction. We give an extended theoretical basis followed by applications. To the best of our knowledge, this book presents a first attempt to address this issue after Hill's books. We broaden and expand the theoretical basis of Hill's equilibrium theory and take steps in the direction of formulating the entropy production for small systems. Doing this, we also hope to set a basis for the field of nonequilibrium nanothermodynamics.

Examples are added to illustrate various aspects of the theory and of possibilities (needs) for further use. They give a perspective on future work. A practical scaling method in the inverse size of the system (the Small System Method) is presented[3,4]. An interesting result of fluid confinement to pores, is that two, not only one pressure become necessary in the description of the representative volume element of the system[5,6]. A new equilibrium condition is found; the so-called integral pressure is constant across phase boundaries.

A thorough discussion is given of the so-called representative elementary volume (REV) for porous media, which may have nanometer sized pores. A crucial assumption is that the system is in local equilibrium on the REV scale. Using the resulting Gibbs relation we obtain the entropy production, the thermodynamic flux-force relations and the fluctuation-dissipation theorems[7,8], all on the REV scale for the porous medium.

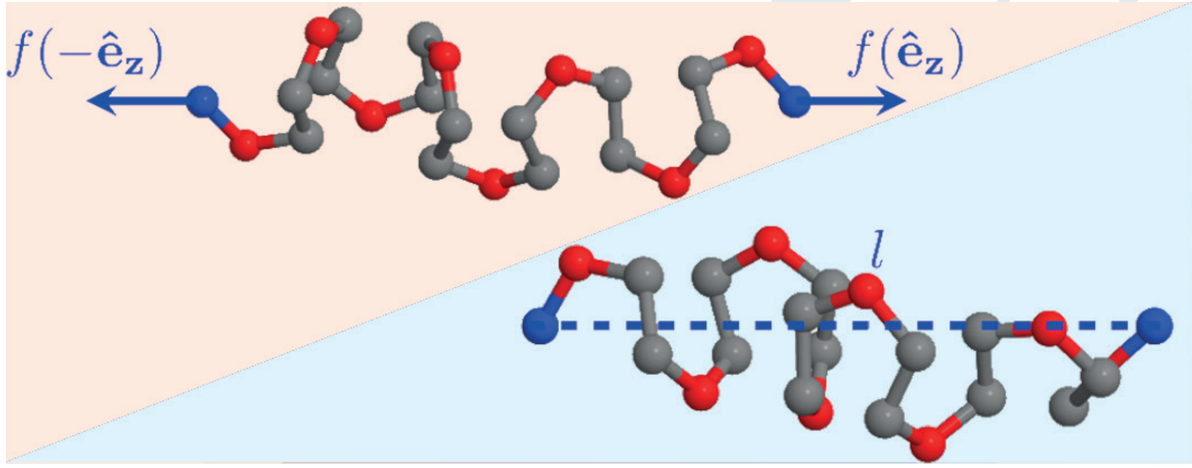

***Figure 2:** A polymer is stretched isotensionally (upper part of figure) and isometrically (lower part of Figure). Forces have symbol f, length has symbol l.*

Nanothermodynamics can also be applied to the stretching of a polymer (see Figure 2). The stretching energy is found to differ when one a polymer stretched isotensionally upper part of Figure 2) or isometrically (lower part of Figure 2). The corresponding friction coefficients are similarly predicted and found to differ.

With this book, we hope to inspire new simulations or experiments and contribute to the further development in the field of nanothermodynamics.

ACKNOWLEDGEMENTS

The work has been done with support from the Norwegian Research Council, for the Center of Excellence Funding Scheme project no 262644 to DB and SK, and for Young Researchers project no. 275754 to SKS.

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ULTRASOUND-MEDIATED TRANSPORT OF NANOPARTICLES IN TISSUE: CREATING A PREDICTIVE MODEL COMBINING THEORY, SIMULATIONS AND EXPERIMENTS

Sebastian E.N. Price[1], Caroline Einen[2], Magnus Aa. Gjennestad[3], Anders Lervik[1], Signe Kjelstrup[1], Catharina de Lange Davies[2]

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[3] SINTEF Energy Research, Trondheim, Norway

A challenge in cancer therapy using drugs or drug-loaded nanoparticles, is that a very small fraction of the injected drug/nanoparticle accumulates in the tumour. The drug/nanoparticles have to cross the capillary wall and penetrate though the extracellular matrix and reach all cancer cells to achieve successful therapeutic response. The extracellular matrix consists of a network of collagen fibres embedded in a gel of glycosaminoglycans and represents a significant hindrance for transport of drugs, and particularly for the larger nanoparticles. Ultrasound focused towards the tumour is reported to increase the delivery of nanoparticles. Improved penetration of nanoparticles into the tissue could be due to enhanced diffusion and/or acoustic streaming. Applying focused ultrasound towards tissue, can cause acoustic radiation force. Acoustic radiation force is generated by the absorption and/or reflection of ultrasound waves by the tissue, and momentum is transferred to the tissue. One consequence of acoustic radiation force can be acoustic streaming which is the net movement of fluid. The overall aim of the project is to obtain new knowledge on the transport through the extracellular matrix in tissue by combining experiments and modelling/simulations.

As ultrasound-enhanced transport in biological systems is a highly complex, we wanted to study the two transport processes, acoustic streaming and diffusion, separately. In our first theoretical project, acoustic streaming was modelled [1]. We derived the equations necessary to describe acoustic streaming in a soft porous material, as it makes the physical interpretation of the variables involved and the underlying assumptions clear. From these equations, we created a model that was compared to experiments on acoustic streaming in a macroporous gel performed by El Ghamrawy [2]. As Figure 1 shows, the model was able to predict the results for the acoustic streaming well within the experimental uncertainties.

Next, we performed experiments to study diffusion of nanoparticles and potential acoustic streaming in a gel modelling the porous extracellular matrix [3]. The movement of the nanoparticles was recorded by particle tracking (Fig 2), and by measuring their mean squared displacement, we could separate the apparent diffusion coefficient from the direct acoustic streaming (Fig 3). Interestingly, we did not see any streaming of the nanoparticles, but we did measure an increase in apparent diffusion coefficient with ultrasound. This was in good agreement with the previously developed acoustic streaming model [1], which estimated negligible acoustic streaming of the fluid in the gel. These results suggest that increased diffusion is the main mechanism behind ultrasound-increased nanoparticle transport in tissues.

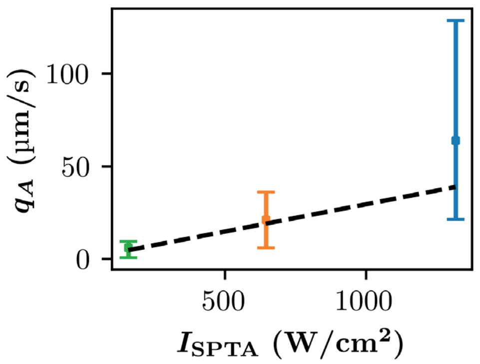

Figure 1: *Volumetric fluxes for different ultrasound beam intensities (blue, orange and green squares) extracted from the experiments [2]. The volumetric fluxes predicted by the model are shown as the dashed black line.*

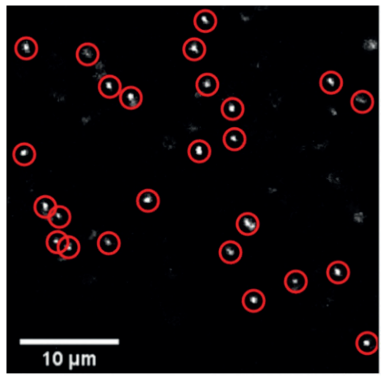

Figure 2: *Confocal microscopy image of fluorescent 100 nm nanoparticles embedded in a hydrogel and identified by a red circle for tracking the particle movement between imaging frames.*

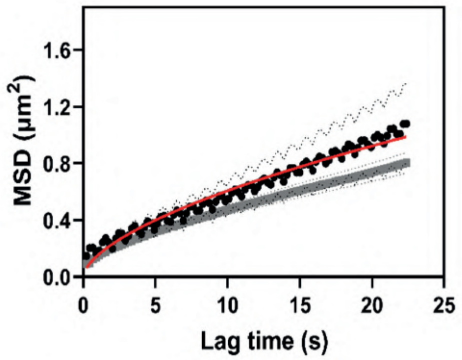

Figure 3: *Mean squared displacement (MSD) of 100 nm nanoparticles without (grey) and with (black) ultrasound exposure, showing increased movement of nanoparticles induced by the ultrasound. The red line shows a fitted diffusion model used to estimate the apparent particle diffusion coefficient.*

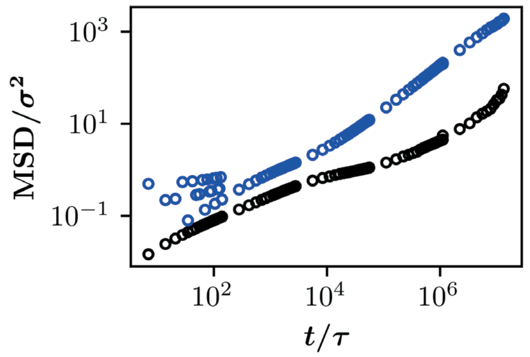

Figure 5: *Mean square displacement (MSD) of nanoparticles in a gel as a function of time from the non-equilibrium molecular dynamics simulations. Black circles indicate nanoparticles without ultrasound and blue circles indicate nanoparticles with ultrasound.*

To further investigate the ultrasound enhanced diffusion, we conducted non-equilibrium molecular dynamics simulations on a model gel system (Fig 4). To simulate the effect of focused ultrasound, we applied a sinusoidal external force to the particles such that they would obtain a specified particle velocity. From these non-equilibrium molecular dynamics simulations, we obtained the mean square displacement of the nanoparticles. Our non-equilibrium molecular dynamics mean square displacement results are shown in Figure 5. We see that the introduction of a particle velocity to the particles increases the mean square displacement values, qualitatively similar to what we observed experimentally, suggesting that the particle velocity generated by the sinusoidal force is the primary contributor to the observed ultrasound enhanced diffusion coefficient.

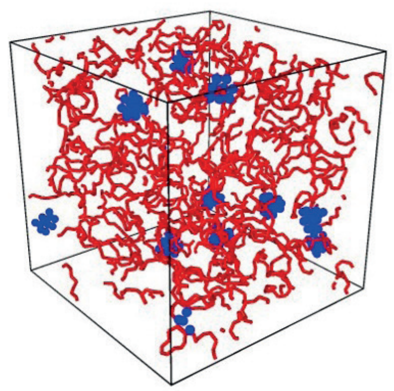

Figure 4: *A snapshot from the simulation of the system showing nanoparticles (blue) diffusing in the gel network (red).*

ACKNOWLEDGEMENTS

The work has been done with support from the Norwegian Research Council under project number 301581 and through its Centre of Excellence funding scheme, project number 262644, PoreLab.

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RESEARCHER

FABIAN BARRAS

Njord – Center for Studies
of the Physics of the Earth, UiO

Who are you? What is your background?

Fabian Barras - born in the Swiss Alps – millennial - enjoy fishing, skiing, daydreams, and night trains - researcher at Njord and PoreLab Oslo since 2019. I'm a graduate from École Polytechnique Fédérale de Lausanne (a.k.a. EPFL) with a background in computational mechanics and civil engineering.

Tell us about yourself?

Curiosity and clumsiness are probably my two traits that had the greatest influence on my scientific trajectory. Both drove my quest for understanding why and how things break, which became more systematic once I finally got a secure way to investigate it — computer simulations. My master and PhD theses were dedicated to the development of numerical models to simulate the propagation of dynamic fracture in materials.

How did you come being interested in friction?

As evident at the moment on the sidewalks of Oslo, frictional contact at the interface between two bodies can suddenly lose its ability to bear stress and lead to rapid sliding. A similar kind of frictional failure is suspected to be at the origin of earthquakes along crustal faults. Interestingly, the physics governing these unpredictable failures is very similar to the one controlling the propagation of dynamic fractures in brittle materials - a fascinating nail for my hammer!

What made you decide to come to Oslo?

Aside from the slippery sidewalks and skiløyper, I was also hooked by the research environment developed at the Njord Centre to study geological processes at the interface between physics and geoscience. I enjoy a lot working across disciplines and seeing phenomena through the lenses of different scientific fields that are complementary yet different to my academic background.

How are you performing your research?

My core research activity is the development of theoretical and computational mechanics models. As a modeler, I'm typically striving to squeeze the fundamental physics out of more complex models and questing for generic descriptions made of a minimal number of free parameters. This is what brings me closest to the Physicist's approach - I think.

What about the future, where do you see yourself in 5 years?

In 2024, I will start UNLOC, a freshly funded YFF project. My goal is to build a generic numerical toolbox to describe the propagation of failure in geomaterials. Apart from the earthquake problem mentioned before, a broad kind of catastrophic events initiates by the dynamic propagation of a rupture through porous media, such as landslides, snow avalanches, glacier collapses. In all these examples, pore fluid is expected to play a key role in the failure process and the project ambition is to capture the interplay between rapidly moving ruptures and fluid flow at the pore scale. At a personal level, I'm counting on this project to extend my research portfolio to experimental work. This project will keep me busy for the next four years - this is how far as I can see myself in the future.

Why is your research important?

Simply because *there is a crack in everything.*

POSTDOC

YUEQUN FU

Department of Physics, UiO

Who are you? What is your background?

I am Yuequn Fu, a postdoctoral researcher in PoreLab. I received my bachelor's degree in chemical engineering from Qingdao University in 2014 and my master's degree in chemical engineering from China University of Petroleum in 2017. I obtained my doctoral degree from the Norwegian University of Science and Technology in Trondheim, Norway. Currently, I am employed at the University of Oslo as a postdoctoral fellow.

Tell us about your research activities.

My research aims to work on both experimental and theoretical aspects of multiphase flow and pattern formation in frictional fluids and porous media. The atomistic insights into the flow in porous media are expected to archive. In combination with experimental studies, molecular dynamics simulations are employed to investigate the atomic-level formation, deformation, patterns, mechanisms, and rheology of the flow in porous media.

In my doctoral study, I focused on computational chemistry, theoretical physics, and fluid mechanics by using simulations and experimental methods. I have more than seven years of experimental and modeling experience in colloid & interface. Atomistic modelling was used to study the stability, deformation, and rupture of Janus oligomer enabled water-in-oil microemulsion droplets, aiming for revealing their intrinsic relationship to the Janus oligomer-based surfactants and oil structures. By observing the size variation of the microemulsion droplets during the self-emulsifying of the microemulsion, the droplets' diameter and particle size distribution was calculated and compared. According to the results of the particle size distribution of the microemulsion, direct aggregating and the water molecules transition between microemulsion droplets and a steep energy barrier were observed clearly.

Can you give us more details about your current research?

Based on experimental results, a cavitation bubble formed when a nano-scale spherical silica crystal was pulled up from the surface of a silica substrate. Limited to the characterization methods, the cavitation's pattern is difficult to be captured clearly in real time. To realize the underlying physical mechanism and detailed morphology of such a cavitation, a modelling of molecular dynamics was developed to perform and simulate such a process. Observing the dynamic behavior of water molecules and silica was expected to explore the cavitation mechanism in such an environment and prove further whether there is a secondary flow pattern during this process, which can provide a fundamental understanding on formation and break-up of cavitation from the atomistic view.

How is the working environment at PoreLab?

I am very happy to join this big family, as a PoreLaber. With kind support and help from PoreLab, I benefit a lot both in research and personal development. Professional attitude and excellent achievement make PoreLab advanced and famous internationally, which also is the reason why PoreLab attracts lots of collaboration and interests from many fields.

POSTDOC

MORTEN HAMMER

Department of Chemistry, NTNU

Who are you? What is your background?

My name is Morten Hammer, and I grew up in a small place outside Steinkjer, situated in the heart of Norway. Today, I am a family man residing in Trondheim with three kids and a wonderful life partner.

From an early age, I knew that my academic journey would lead me to study something related to natural science at NTNU. Eventually, I graduated as a chemical process engineer. Subsequently, I pursued my PhD in energy process engineering at NTNU, where my interest in the field of thermodynamics was sparked.

Upon completing my PhD, instead of directly delving into thermodynamics, I ventured into the industry, dedicating seven years to developing commercial engineering software. This included working on both a dynamic process simulator and a pipeline simulator.

After my industry experience, I gradually returned to the realm of science by securing a research position at SINTEF Energy Research. At SINTEF, my focus has primarily been on thermodynamics and flow-related research for Carbon Capture and Storage (CCS) and Hydrogen. Almost immediately after joining SINTEF in 2011, I initiated work on the thermodynamics software Thermopack, a tool that has been an integral part of nearly all my research endeavors. In 2020, this tool was made available open source on GitHub and has since been continuously developed collaboratively by SINTEF and NTNU.

What is your favorite activity in your research?

My favorite activity in my research revolves around the dynamic interplay of focus, in-depth exploration, programming, and the continuous pursuit of learning new topics. One aspect that brings me immense satisfaction is the programming aspect of my research. I enjoy translating theoretical concepts and ideas into tangible solutions through coding. The process of developing algorithms, writing code, and seeing the results manifest in practical applications is both intellectually stimulating and gratifying.

What are the most important results so far?

In 2022, I embarked on a 3-month research stay with Professor Joachim Groß and his esteemed group at the University of Stuttgart. This invaluable experience exposed me to classical density functional theory (DFT), a method employed to characterize interface properties of fluids and fluids confined in pores. In collaboration with the German group, we successfully presented a Helmholtz energy functional tailored for fluids strongly influenced by quantum effects at low temperatures. This breakthrough emerged as a joint effort before, during, and after my research stay. Concurrently, we have been diligently working on developing our own framework for DFT simulations and crafting new functionals. This innovative tool is poised to significantly contribute to our future research endeavors.

Now that you've completed your post-doc period, what are you up to?

Even though my two-year post-doc period has come to an end, I am fortunate to continue my involvement with PoreLab part-time in the coming years. Recently promoted, I have taken on the role of an adjunct professor as part of the ERC project InterLab, led by Professor Øivind Wilhelmsen. The project, titled Unravelling the Fundamentals of Transport across the Vapor-Liquid Interface, allows me to extend and build upon the work initiated during my post-doc period. Additionally, I will be actively supporting PhD students within the project. Furthermore, I am back part-time with SINTEF Energy Research and am eager to contribute to the ongoing development of Thermopack as part of our research activities.

PHD

FEDERICO LANZA

Joint PhD degree between the Department of Physics, NTNU, and LPTMS at University of Paris-Saclay

Tell us about yourself.

My name is Federico, and I am 30 years old. I obtained both my bachelor's and master's degree in physics at University of Padova in Italy. During my master's degree, in 2019, I spent a semester in France working for my thesis, through the Erasmus+ program. In 2020, I started a PhD in joint agreement between Université Paris-Saclay in France and PoreLab - NTNU in Trondheim, which I successfully concluded in 2023. During this period, I studied different problems concerning the non-Newtonian and multiphase flow in porous media, with a theoretical and numerical approach. Finally, on January 2024 I started as a Postdoctoral researcher at PoreLab - UiO in Oslo.

How did you come being interested in Physics?

Since high school, I have been fascinated by the possibility that Physics offers to describe the reality that surrounds us, with its complicated and contradictory aspects, adopting models as simple and elegant as possible. For similar reasons, I also enjoyed studying Philosophy, which share a similar attempt to model the world. In the end, I chose to study Physics at the university, also because it allowed me to continue my studies in Mathematics, a subject that I have always liked since I was a child.

What made you decide to come to Norway?

As it often happens in life, my first approach with Norway was not inter-ntional, but happened after a series of fortunate coincidences. My doctoral program, originally supposed to be carried out only in France, eventually turned into a double degree with NTNU because of some bureaucratic issues.

Despite some difficulties in adapting in a different environment from what I was used to, today I'm definitely glad to have had the opportunity of living in Trondheim. There, I really enjoyed doing outdoor activities and learning a bit about the Norwegian culture. It is also with that experience in mind that I decided to come back to Norway, this time in Oslo.

What are you doing now in your research?

My research involves in general the flow of non-Newtonian and complex fluids in porous media. Recently, I joined an ongoing project that aims to describe how a fluid like magma flow in a confined geometry like a fracture. Because of the temperature dependence of the viscosity, when hot magma flows into a cold fracture, an instability occurs, for which the fluid flows faster in some regions than others. Our goal is to reproduce this instability by solving numerically the governing equations in a simplified geometry.

In parallel to this work, I have also started an experimental campaign, the objective of which is to characterize the flow in a porous medium of a non-Newtonian fluid with yield stress. More specifically, we perform air injection in a 3D-printed porous Hele-Shaw cell initially filled with a Carbopol solution, a liquid known to present a finite yield stress, and observe how the liquid is displaced by the air. The displacing patterns created by the invading air will then be analyzed to look for possible effects of the yield stress.

How is the working environment at PoreLab?

Having experienced both sides of PoreLab, the one in Trondheim and the other in Oslo, I can confirm with a good degree of certainty that PoreLab is the ideal place for a researcher in porous media. From the scientific point of view, the environment is extremely stimulating, and, among other things, it offers the possibility of direct collaboration between theoreticians and experimentalists. At the same time, attention is given to making sure that all members work in safe and relaxing conditions.

SPOTLIGHT ON EIGHT YOUNG RESEARCHERS

PHD

SEBASTIAN E. N. PRICE

Department of Chemistry, NTNU

Who are you? What is your background?

My name is Sebastian Price. I spent my first 12 years of my life in Sandvika, near Oslo, before moving to Trondheim, where I've remained ever since. In 2015 I started my combined bachelor's and master's degree in chemical engineering and biotechnology at NTNU, where I specialized in Physical Chemistry. After graduating in 2020, I started on my PhD in Physical Chemistry, and I am currently in my last year.

How did you come being interested in physical chemistry?

Initially when I started my engineering degree, I wanted to do Biotechnology. However, as I immersed myself in mathematics and programming courses, I found myself increasingly drawn to the world of modeling. This gradual shift in focus led me to specialize in Physical Chemistry during the two final years of my studies, as there were plenty of opportunities for modelling there. I am now doing a PhD in Physical Chemistry, where I model drug transport into tumors.

Tell us more about your project.

Encapsulating the drug into nanoparticles (NPs) before transporting them to its target, is a common way to minimize the toxicity towards healthy tissue. However, achieving optimal dosage and uniform NP distribution within target tissues presents significant challenges. Lately, focused ultrasound (FUS) has been shown to improve the delivery of NPs and drugs.

I have been working theoretically on developing models for transport of NPs through tissue/porous media from experimental data. More specifically I have studied the effect of acoustic streaming on NPs in a viscoelastic porous media using computational fluid dynamics and employed molecular dynamics to better understand the mechanisms behind FUS enhanced NP diffusion. Recently, I am studying how to optimize acoustic streaming within tumors while mitigating the risk of patient injury from FUS-induced heating effects.

How is the working environment in PoreLab?

PoreLab has a very friendly and exciting environment. It is very interdisciplinary with people from diverse fields such as Physics, Chemistry, Geoscience, and Petroleum Engineering, fostering a culture of idea exchange. I especially enjoy our discussions during the coffee breaks providing opportunities for both research-related conversations and casual topics such as cooking and sports. We regularly have researchers visiting us from many various countries, which offer fresh perspectives and inspire new approaches to research challenges. With offices in both Trondheim and Oslo, PoreLab facilitates collaboration across different locations. Our PhD community also organizes board game nights, which has been a great way to get to know each other better.

PHD

TOMISLAV VUKOVIĆ

Department of Geoscience and Petroleum, NTNU

Who are you? What is your background?

My name is Tomislav Vuković. I come from Staro Petrovo Selo ("Old Peter's Village") – a small place in the continental Croatia. By background I am petroleum engineer with a specialization in reservoir engineering. I enrolled into petroleum studies due to the international nature of the oil and gas industry. After I finished my education in Croatia, I decided that it was time to experience other countries, so I worked in Germany and Hungary before coming to Norway. Currently I live in Austria, where I work as a reservoir engineer.

What made you decide to come to Norway?

Growing up, Norway was always portrayed as a rewarding country with beautiful nature and a sea of opportunities, so my childhood dream was to move there. Finally, during the Covid period I decided it will be my next destination. I started learning the language and searching for positions in Norway, and luckily, I got a PhD position at NTNU.

Tell us more about your project.

My project started with the purpose of simplifying time consuming and unreliable methods for wettability measurements. The main idea was to use electrokinetic phenomena to derive zeta potential from flow experiments in porous medium and correlate it with the wettability. The work can be divided into three main parts: establishing the method for the surface treatment that results in repeatable contact angles, building and calibrating an in-house streaming potential apparatus, measuring and correlating zeta potential of treated surfaces with contact angles.

What was your favorite activity in your research?

My favorite activity was to generate streaming potential measurements. It took me 2 years and research visit to finalize the setup and obtain the first reliable and repeatable results. Due to the large number of previously failed setups and experiments, finally producing results was rewarding and satisfying.

How was it to be a PhD at PoreLab?

Although I was not included in everyday activities as much as the other members, since I was mainly working in the laboratory at the Geoscience and Petroleum department, I have only praise for PoreLab. Experts from different fields enable excellent knowledge exchange, and students have unique opportunities to experience different views and approaches. Activity that I would like to single out is the group participation in the Pink Ribbon Run - an international symbol of breast cancer awareness. I am happy that I had the opportunity to be part of such a supportive environment as PoreLab, and I would like to recommend it to everyone.

SPOTLIGHT ON EIGHT YOUNG RESEARCHERS

PHD

JONAS RØNNING

Department of Physics, UiO

Who are you? What is your background?

My name is Jonas Rønning, and I am from Inderøy in Norway. I did my bachelor's in physics at NTNU from 2015 to 2018, before moving to Oslo where I took my master with Professor Luiza Angheluta at the University of Oslo. My master project was about finding classical analogies between an impurity in a weakly interacting Bose-Einstein condensate and particles in a classical fluid. After finishing my master's, I got the opportunity to continue with a PhD on a similar topic.

Tell us more about your project.

In my project we studied the dynamics and nucleation of topological defects in two dimensional Bose-Einstein condensates, and hydrodynamic models of active liquid crystals. Active liquid crystals are materials that are built up of units that becomes self-propelled by taking energy from the environment and turning it into mechanical energy. Typical examples are biological systems like bacterial suspensions or cell sheets. The bacteria have an elongated rod-like shape so that they can form an ordered phase where they break the rotational symmetry by aligning with each other. Bosons on the other hand are particles that follows Bose-Einstein statistics, meaning that two bosons are allowed to occupy the same energy state. A gas of bosons forms a phase called a Bose-Einstein condensates when a macroscopic fraction of the particles is in the lowest energy state. Typical examples are dilute gasses of alkali metals at micro- to nano kelvin temperatures. Even though one boson and one bacterium are very different beast the dynamics of the states that are formed when many of them interacts can be modeled by the same mathematical framework, because the phase have similar symmetries. We used this framework to study the dynamics and nucleation of topological defects. In both systems the topological defects are changing the dynamics and flows in the system. In the Bose-Einstein condensate the defects are the only source of vorticity and play a prominent role in a chaotic flow state called quantum turbulence.

This is easier to study than classical turbulence since the vortices have only one size. In the active system the topological defects are inducing a flow that makes them self-propelled and drives a chaotic flow state that is called active turbulence. We were able to obtain analytic solutions for the flow velocities around single defects.

Since you just finished your PhD what do you do now?

After finishing my PhD in the autumn, I have started as a post doc in the nonlinear and non-equilibrium unit at Okinawa institute of science and technology in Japan. Here I am working on a project where we study how surface waves behaves when they interact with a vortex. This set up can be mapped to equivalent effects in quantum mechanics and to effect taking place near a black hole. This makes it possible to construct experiments that are analogue to phenomena that are not experimentally accessible in the system one would like to study. For the black hole one wants to do analogue experiments because one can't control a black hole and they are, luckily, to far a way to do experiments on. In quantum mechanics there are quantities that aren't observable, e.g. the phase of a wavefunction, that have analogues that are easy to observe in fluid mechanics, phase of the surface wave. I think that this is a very interesting project because we can use a very simple everyday phenomena that can be observed in a bathtub as a basis to understand different parts of physics.

PHD

HRISTINA DRAGOVIC

Department of Energy and Process Engineering, NTNU

SPOTLIGHT ON EIGHT YOUNG RESEARCHERS

Tell us about yourself. What is your background?

My name is Hristina Dragovic, and I am PhD candidate at NTNU at Department of Energy and Process Engineering. I came from Serbia, and I was born and grew up in Belgrade. I am mechanical engineer with a specialized background in thermal power plants. I have been working in a consulting company for two years in the field of energy engineering on projects for constructions of several new power plants in the country, where I got very exciting first working experience and met great colleagues. I have always been interested in developing new things from beginning that are original work, and I used to think independently in solving the problems during my studies. I wanted to understand how real equipment work because I felt that I had a lack of practical work to support theoretical knowledge. I still didn't know which job is appropriate for me, but I knew that I want to continue my education in engineering with experience in industry. This aim made me decide to search for PhD position, and I got accepted at the experimental PhD topic at NTNU, where I work now on my PhD project.

Tell us more about your project.

In my PhD project, we are trying to understand mechanisms behind water vapor transport in mineral wool porous insulation material that influence the diffusion process important for the insulation material drying time once it becomes wet from rain, water deluges in industrial environment, etc. This is a promising approach in early recognition and prevention of corrosion under insulation phenomena, which is indicated as a major risk factor in process industries. Furthermore, we are trying to distinguish between different phenomena that influence humidity transport in the porous insulation material, such as condensation, adsorption, convection, and diffusion that affect the length of the drying time of the insulation material.

How are you performing your research?

My role in the project is to perform experiments on heated vertical pipe insulated with preformed mineral wool insulation material and metal cladding, with the sensors that measure temperature and relative humidity of humid air within the insulation material at different vertical and radial positions. The drying dynamics of insulation material is observed followed by addition of liquid water that evaporates in contact with hot pipe, and results and observations are compared with simple one – dimensional model based on diffusion in vertical direction.

Do you have any notion of what your research can mean for the industry?

As the presence of water in the insulation is generally believed to be the main cause of corrosion under insulation, a different approach is to implement monitoring solution that detects water in the insulation. In the context of understating and preventing corrosion under insulation, the two drying regimes of the insulation materials are identified in the results, where the first drying regime is associated with time of wetness of the equipment, and linear relationship between amount of water that evaporates and drying time is found, and the second drying regime is associated with insulation material drying itself where moisture sensors would give elevated readings, but the dependance of the amount of added water and time needs further exploration.

How is it to be a PhD at PoreLab?

I really enjoy my time at PoreLab social activities during these last two years, where I found very useful to have a safe space to practice presenting at PoreLab junior forum and receiving feedback from young researchers that really helped me to improve my presenting skills. I liked the ideal of contributing to the theory of transport in porous media applied on the real industry equipment. One of the greatest privileges has also been having colleagues with different backgrounds, which makes very challenging to develop a good network, but it makes more exciting to learn from each other.

PhD candidate Hristina Dragovic at the Thermal Engineering laboratory during her first experiments on the vertical setup in May 2022. Photo by Daniela Damaceno

HEADING FOR THE FUTURE:

OUR NEW EXTERNALLY FUNDED PROJECTS

PoreLab researchers developed 6 new externally funding projects in 2023, either as project leader or in collaboration with our partners. Three of them are financed by the Research Council of Norway including a Researcher Project for Young Talent to Fabian Barras, researcher at UiO. Professor Øivind Wilhelmsen, PI at PoreLab NTNU, achieved a major milestone when his InterLab application was awarded an ERC starting grant in September 2023. Professor Erika Eiser, PI at PoreLab NTNU, joined another EU funded project under the Horizon MSCA program. The last project was developed by Gaute Linga, researcher at PoreLab UiO, who received a 1-year support from the Centre for Advanced Study (CAS) at the Norwegian Academy of Science and Letters. PoreLab has been developing and become part of a large number of externally funded projects since its beginning in 2017. It is worth noticing that from 2022 onwards, the annual income from these external funds exceeds the annual PoreLab income. And the number just keeps growing (see page 77). We present in this page the six externally funded projects that were granted in 2023. Let us specify that previous granted projects become part of the research projects of our annual reports.

ERC Starting Grant - InterLab

Full title: Unravelling the fundamentals of transport across the vapor-liquid interface
Project Leader: Øivind Wilhelmsen
Duration: 2024 – 2028

Prof. Wilhelmsen, PI of Research Themes 5 and 8 in PoreLab, received an ERC Starting Grant for the research project InterLab: *"Unravelling the fundamentals of transport across the vapor-liquid interface"*.
In the project, Wilhelmsen and his group will bring new understanding and methods to predict transport of heat and mass across vapor-liquid interfaces. Since such interfaces are abundant in porous media, this is also great news for PoreLab. Many of the projects in PoreLab involve phase changes such as adsorption, evaporation or condensation. Some of these projects will benefit greatly from the advances that InterLab will bring. In the ERC project, Wilhelmsen plans to hire two new PhD-students, one Postdoc, one researcher and build two experimental rigs. An ERC grant also provides the great possibility and necessary funding to pursue long-term fundamental research with really high ambitions.
The project from Wilhelmsen is one of the 400 Starting Grants awarded by the European Research Council (ERC) to young scientists and scholars across Europe in 2023. The grants support cutting-edge research in a wide range of fields, from medicine and physics to social sciences and humanities. They will help researchers at the beginning of their careers to launch their own projects, form their teams and pursue their best ideas. The Starting Grants calls have attracted more than 28 000 submissions since 2007.

Dual-Functional Anti-Gas Hydrate Surfaces (D'andra): Ice Growth Confined in Porous Media

Project leader : Zhiliang Zhang, NTNU
Duration : 2023 – 2024

This is a continuation of the grant allocated by the Coordination and Support Activity for Researcher mobility from the RCN and intended

Professor Natalya Kizilova, V.N. Karazin Kharkov National University, Kharkiv, Ukraine

to support the research stay for Professor Natalya Kizilova of the V.N. Karazin Kharkov National University, Kharkiv, Ukraine, as guest researcher for an additional year at the NTNU Nanomechanical Laboratory in collaboration with PoreLab in Trondheim. The project is directly connected to the NANO2021 project, Dual Function Anti-Gas Hydrate Surfaces (D'andra).
Professor Kizilova has been the head of the Department of Theoretical and Applied Mechanics in Kharkov National University. Her city has been bombed since March 2022 after Russia invaded Ukraine. The project is therefore also in solidarity with the victims.
The idea of D'andra is to develop a model that describes flow of subcooled water. The aim of the research on this project for Professor Kizilova is to investigate aspects of the governing equations that describe transport of subcooled water to and from ice-growing regions in porous media, to support the modelling of equilibrium, as well as describe non-equilibrium in partially frozen networks of pores. Professor Kizilova is involved as well in the PoreLab project *"Ultrasound-mediated transport of nanoparticle in Tissue: a predictive model"* led by Professor Catharina de Lange Davies.

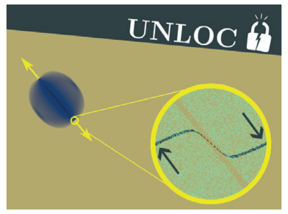
SafeAm – Increased safety of ammonia handling for maritime operations

Project leader: Dr. Marta Bucelli at Sintef Energy Research, and Øivind Wilhelmsen for PoreLab, NTNU
Duration: 2023-2027

PoreLab is a research partner for the project SafeAm and participates in the research activities through a PhD position under the Work Package 2 (WP2) focusing on thermophysical modelling. WP2 is led by research scientist Ailo Aasen, former PhD candidate at PoreLab, and long-term visitor at PoreLab.
Ammonia (NH_3) can decarbonize the transport and offshore industry. While used as fertilizer for decades, accidents leading to severe injuries and deaths, due to flammability and/or toxicity, have been reported. Large-scale implementation in the maritime environment raises additional concerns on effects of spills *on and into* water. SafeAm empowers the feasibility of emerging NH_3 technologies by (i) producing experimental data and models for NH_3 releases on and into water and (ii) develop risk trends and input to standardization. SafeAm's aim is to investigate the thermophysical behaviors of the NH_3-water interaction to optimize the design of safety systems and handling procedures to minimize the consequences on people, marine life, environment, and assets.
The PhD candidate will work towards improving the physical understanding of what happens when water mixes with ammonia, and develop thermo-physical models to describe this process, with emphasis on the interfacial phenomena.

UNLOC – Uncovering the coupled fluid and solid dynamics driving highly-localized rupture in geomaterials

Program: Researcher Project for Young Talent (FRIPRO), RCN
Project Leader: Dr. Fabian Barras
Duration: 2024 - 2028



The propagation of highly-localized ruptures precedes various kinds of catastrophic failures in geomaterials. Examples include landslides, rockfalls, glacier surges and earthquakes. Quantitative predictions of these processes remain elusive and challenging because material failure often stems from highly-localized shear bands that rapidly propagate over meter to kilometer distances while focusing intense deformation down to the pore scale.
In UNLOC, Barras and his team plan to perform fundamental research to simulate and image the highly-localized micro-mechanical processes that cause the rapid failure of geomaterials. The UNLOC team will develop and release a multi-scale theoretical and numerical framework developed hand-in-hand with two experimental campaigns.
The first one will image the localized deformation of dry and wet natural rocks and sands using synchrotron X-ray microtomography, and the second one will image and quantify dynamic fluid flow in a rapidly opening cavity.
Throughout the UNLOC project, the sonification of the data sets will be conducted in collaboration with a sound designer to disentangle the intricacy of processes governing failure and support the communication of the project activities with original sound pieces.

FLUXIONIC

Full title: Controlled transport of water and ions in nanoconfinement
Program: HORIZON-MSCA-DN-2022
Project Leader: Professor Ignacio Pagonabarraga at the University of Barcelona and Erika Eiser for PoreLab, NTNU

The main objective of the FLUXIONIC network is to train a new generation of early-stage researchers in the diverse skills that are needed in the field of controlled nano-transport. The focus is on transport, separation and energy conversion, as these are the essential steps in all key non-equilibrium processes, be they animate or inanimate, and therefore also fundamental to the new generation of energy materials and separation technologies.
An important component of the FLUXIONIC training program is related to the study of two-phase flow in confined geometries. The PoreLab/NTNU group aims to study the coupled hydrodynamic/ionic transport of two-phase fluid dispersions in porous media.
Professor Erika Eiser, PI at PoreLab, joined the network in 2023. She will be leading the second module focusing on light scattering, microscopy, and optical spectroscopy as supervisor for one ESR (Early-Stage Researcher). The project will integrate the expertise of the French team at the CNRS with coupled flow/electric transport through tapered nano-channels and the theoretical work of Professor Alex Hansen on flow entropy. Of particular interest is the exploration of the electrical signals due to flow of droplets through necks in the porous medium. In addition, the project aims to explore the coupling of heat transport and ionic currents. At PoreLab, there is extensive expertise in the use of 3D-printing of designed random matrices, which can be functionalized to control their surface charge. The ESR will be trained in the fabrication and functionalization of flow cells and the optical and electrical study of the coupled transport.

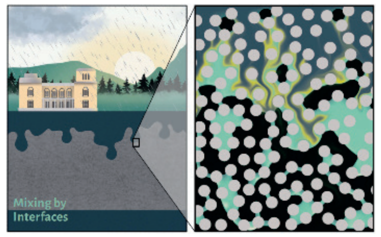
Mixing by Interfaces: How does water infiltration control mixing and reaction in soils?

Program: Center for Advanced Study (CAS) at the Norwegian Academy of Science and letters
Project Leader: Gaute Linga, PI at PoreLab
Period: 2024 - 2025

The Young CAS Grant is a collaborative initiative between CAS, the **Young Academy of Norway** (AYF) and **The Norwegian Academy of Science and Letters** (DNVA). The program is designed to empower and support young researchers in their pursuit of project development and network expansion through residential fellowships.

Centre for Advanced Study
at The Norwegian Academy of Science and Letters

The Young CAS project *Mixing by interfaces* aims to solve the fundamental challenge of understanding and predicting mixing and reaction dynamics during dynamic infiltration in soils. To do so, Linga and the other project participants will leverage state-of-the-art experimental data and numerical and theoretical techniques recently co-developed by team members. The project will provide unique data and theories on transient flow through partially-saturated media, which has broad implications for the fate and transport of nutrients and contaminants in soils.



The team of early career researchers will work together over the course of two years, over three immersive week-long gatherings (CAS/DNVA and Njord) in 2024 and a two-month stay at CAS in 2025. In addition to the PI, the core team consists of Tomas Aquino (IDAEA - Spanish National Research Council), Alexandre Puyguiraud (University of Rennes), Shabina Ashraf (University of Rennes/NIT Calicut), and Marcel Moura (Njord/PoreLab, UiO).

PORELAB GRADUATE SCHOOL

TRAINING THE NEXT GENERATION OF RESEARCH LEADERS

Training of Master and PhD students, as well as of postdoctoral researchers, is a core activity at PoreLab. An essential part of NTNU's and UiO's mission as universities, is student and researcher education. PoreLab is a valuable contributor in this respect. It is our ambition at PoreLab that each junior researcher has a scientifically stimulating and inclusive workday, above the level of regular PhD/Postdoc program. Our PoreLab researcher training program is therefore organized across the institutions, and together with international partners so as to create an interdisciplinary and international training ground for our juniors.

Master, PhD and Postdoctoral training

Each student and fellow follow her/his regular institutional training program, with specified demands for scientific work, supported by course work and other activities. Courses on ethics, rhetoric's, dissemination, and communication are for instance available at both NTNU and UiO. The course on *"Doing science: methods, Ethics and Dissemination"* (MN 8000), includes an introduction to the history of science, the principles and challenges of scientific enquiry, central and controversial issues on the interface between science and society, scientific writing, dissemination of science through media, and the ethics of scientific conduct. This course is mandatory for all PhD candidates at PoreLab NTNU.

The added benefit of PoreLab is that the scientific work is organized in clusters around each PhD candidate. Two supervisors are natural members of the cluster in addition to master students, postdocs or guests that are working on the same problem or takes an interest in it. This organization helps us to benefit from the inter-disciplinary nature of our work. Networks are created and mentoring is experienced.

Postdocs are offered a variety of courses and workshops suitable for their career plan at the host institutions, NTNU and UiO. Examples are courses on PhD supervision, or workshops on publishing practice in international journals. Pedagogical courses, offered by UNIPED (NTNUs Educational Development Unit) may be relevant. As far as possible and when suitable for the projects, the postdocs will co-supervise PhDs and master students. To teach at the BSc and MSc-level is encouraged for all postdocs. All PoreLab postdocs need to work out a suitable career development plan in close collaboration with their supervisor. This plan comes in addition to the usual and annual appraisal interview that all employees need to complete with their manager. Postdocs are inspired by the leadership at PoreLab to develop applications for externally funded projects. And it works! Fabian Barras developed a new Researcher Project for Young Talent in 2023 (see page 61) while Marcel Moura and Gaute Linga had the same success back in 2021 (see our PoreLab annual report 2021 page 56) .

National and international collaborations are highly encouraged and therefore supported within the group of students and young researchers. The Center offers some funds that allow foreign master students to spend time with us, as well as to send our own students abroad. The same offer is available for master students between NTNU and UiO. Similarly, all homely-recruited PhD candidates and postdocs are invited to spend some time at one of our collaborating institutions.

Everybody at PoreLab, including master students, PhD candidates and postdocs, are invited to attend, arrange and contribute to all PoreLab events, such as the PoreLab lecture series and the Thursday's talks. All junior members are encouraged to submit abstracts and present posters or lectures at national and international conferences. Expenses are covered by the Center.

The Center receives every year many visitors, among them renowned national and international researchers. The junior researchers obtain opportunities to meet and interact with world leading scientists. A list of visitors is given on page 75.

PoreLab Master Students 2023

Similar to the three previous years, a dedicated catalogue presents our suite of excellent master students. Coming from physics, chemistry, chemical engineering, mechanical engineering, and geosciences, they represent the interdisciplinarity of PoreLab. In 2019 we had the great pleasure to welcome five international master students at PoreLab's premises. This was a result of international collaboration. Unfortunately, restrictions on travel and entry to Norway due to the pandemic put a halt on this fruitful exchange in both 2020 and 2021. It is then with great pleasure that we saw a timid come-back in 2022 with two master students choosing to accomplish a part of their master with us.

The catalogue provides an overview of projects performed by our master students in 2022. Students can also find suggestions for new master projects in this catalogue. Hopefully, this can inspire new students to join the team.

PoreLab Lecture series, Porous Media Tea Time Talk and Thursday Talks

The use of video conferencing intensified during the pandemic. It allowed us to broaden our pool of lecturers and we noticed a boost in attendance. This trend continued in 2023 with no less than 26 lectures (see page 76 for the list). The PoreLab lecture series are now almost always given by external lecturers and systematically online to be available for all.

The PoreLab lecture series are organized alternating with the Porous Media Tea Time Talks (#PorousMediaTTT), a webinar series, sent via YouTube and organized by a team of young porous media researchers, including PoreLab members. Ten sessions of the Porous Media TTT with at least 2 talks each were organized in 2023.

The Thursday's talks aim to promote internal speakers who are given the possibility to present their own activities or give a lecture. They are meant for PoreLab members to present and receive feedback on their own problems. Both PoreLab lecture series and Thursday's talks are administered and organized by dedicated PoreLab juniors.

Porous Media
Tea Time Talks

PoreLab Junior forum

The PoreLab Junior Forum was established by and is run by the juniors themselves. The main goal of the PoreLab junior forum is to bring together the group of PhDs, postdocs and early career researchers of PoreLab with the objective of allowing them to better know each other and share their respective work and scientific interests. The PoreLab Junior Forum is particularly important to PoreLab as it serves to bind the two hubs in Oslo and Trondheim together. Usually organized every semester, the forum extends possibilities for scientific collaborations and networking.

The 2023 Forum meeting was held at PoreLab Oslo on November 9 and was attended by junior members from both PoreLab Oslo and Trondheim. The activities were initiated with coffee and greetings, followed by lunch. Presentations regarding the junior members' current research topics were organized in the afternoon. Attendants who had presented in previous junior forum events were encouraged to give briefer talks, while new members had more time to introduce their plans of research in PoreLab. The duration of the presentations was not strongly constrained and ample time for discussion after each presentation was allowed.

After the presentations, some time was allocated for discussion related to possible ways junior members could collaborate more with each other's research, specially involving members of different hubs. Besides that, the current format of the PoreLab Lecture series was debated, lading to suggestions for increasing the attendance off the talks.

Thereafter a mingling activity involving a general knowledge Quiz was organized and most of the attendants had dinner together at a restaurant in the city center, which was followed by some shuffling board games at an arcade bar.

Postdoctoral fellow Paula Reis who was in charge of the organization of the 2023 edition of the PoreLab junior forum summarized the event as follow:

"While not very structured, the format of this year's event worked well and led to a lot of interaction between all attendants. Altogether, this Junior Forum edition successfully promoted both scientific and social engagement between PoreLab's younger members, which is fundamental for us to fully benefit from our multidisciplinary joint center."

Two PoreLab courses

Two courses are offered by PoreLab scientists, open to both PhD and master students, at our host institutions. The courses have a special focus on porous media physics.

The PoreLab course *"Experimental Techniques in Porous and Complex Systems"* (FYS4420/FYS9420) is organized every year during the fall semester by UiO. The course gives students an introduction to important experimental techniques in the field of condensed matter physics. The teaching is based on four projects in which the students apply techniques on realistic problems in condensed matter physics. Students from NTNU travel to UiO to attend the laboratory courses with a financial support from PoreLab. The course lecturer is Professor Knut Jørgen Måløy, PI at PoreLab.

The PoreLab course on theory and simulation of flows in complex media is offered in a digital format in order to welcome students at both UiO and NTNU. The course has a double title and code: *"Dynamics of complex media"* (FYS4465/FYS9465) at UiO and *"Flows in porous media"* (KJ8210) at NTNU. The course covers hydrodynamics where capillary and viscous forces play a role. It also covers simulation methods, thermodynamics and statistical physics relevant to porous media. The course content is motivated by the needs to describe ground water flows, biological tissue, hydrocarbon management, fuel cells, electrophoresis, building materials and the quest for governing equations. The course lecturer is Professor Eirik G. Flekkøy, PI at PoreLab.

MEETINGS AND WORKSHOPS

Researchers at PoreLab have numerous opportunities to present their scientific activities and research results to both internal and external events. We list in the following pages the meetings and specialized workshops organized by PoreLab members alongside other experts in their field in 2023.

FLOW AND DEFORMATION ACROSS SCALE – THE FIRST MEETING UNDER THE COLOSSAL PROJECT – 13 TO 17 MARCH 2023, BRAZIL

The 4-day meeting entitled *"Flow and Deformation Across Scale"* is the first meeting organized under the COLOSSAL project (see PoreLab annual report 2020 page 50), a project financed by the Research Council of Norway under the INTPART program. The workshop was postponed due to the pandemic and was finally organized in Brazil at the Marupiara Resort Porto de Galinhas in the period 13-17 March 2023. The week was organized around lots of interesting presentations and networking activities for the 37 participants from Brazil, France, USA and Norway, from nine different universities. The COLOSSAL project is indeed an interdisciplinary collaboration bringing together researchers from 9 different universities in 4 countries (Brazil, France, USA and Norway).

The primary objective of this partnership is to build the educational and research framework needed to develop a world-leading collaboration on fluid flow in porous and fractured media, with applications to groundwater, geohazards, georesources, and environmental science.

The educational secondary objectives are to provide students with skills, competence, and experience in cross-disciplinary collaborations, combining specialized proficiency in experimental and observational methods, data analyzes and computer science.The research secondary objectives are to facilitate synergetic interactions between students and researchers working in different countries to advance knowledge and understanding of: (1) Fluid mixing in porous and fractured media from the nano- to meso- and field scales; and (2) The coupling between fluids and fracture propagation in solids.

WORKSHOP ON UPSCALING IN POROUS MEDIA AT PORELAB NTNU – 1 TO 4 MAY 2023, TRONDHEIM, NORWAY

An informal workshop on upscaling was organized at PoreLab, NTNU in Trondheim on May 1-4, 2023 by Professor Carl Fredrik Berg and Professor Alex Hansen. The agenda was organized with ample time for discussion after each talk and ample time for general discussions. Our invited guests were: Ryan Armstrong from the University of New South Wales in Australia, James McClure from Virginia Tech in USA, Saman Aryana from the University in Wyoming in USA, Steffen Berg from Shell Global Solutions in the Netherlands, Maja Rücker from Eindhoven University of Technology in the Netherlands, Subhadeep Roy from Birla Institute of Technology in India and Thomas Ramstad from Equinor. A large part of PoreLab attended the workshop. This workshop was a major success, and it was decided to repeat it.

Picture, clockwise from left: Professor Saman Ayana, Professor Alex Hansen, Professor Emeritus Dick Bedeaux, Assistant Professor Maja Rücker, Professor Emerita Signe Kjelstrup, Dr. Steffen Berg, PhD candidate Reza Haghanihasanabadi, Associate Professor James E. McClure, Professor Ryan Armstrong, Dr. Marcel Moura

LARGE PORELAB ATTENDANCE AT INTERPORE 2023 IN EDINBURGH – 22 TO 25 MAY 2023

PoreLab members were heavily involved in the 15th Annual International Conference on Porous Media organized by InterPore from 22 to 25 May 2023 in Edinburgh, Scotland, UK.

28 PoreLab members attended the conference, 27 physically in Edinburgh and 1 online due to visa restrictions. PoreLab members gave a total of 14 oral presentations and presented 10 posters.

A special mini symposium was organized in honor of Professor Emerita Signe Kjelstrup, former PI at PoreLab. It was chaired by Professor Emeritus Bjørn Hafskjold, associate member at PoreLab. In addition to this mini symposium, Professor Kjelstrup was one of the organizers for the mini symposium on *Physics of multi-phase flow in diverse porous media*. Associate Professor Subhadeep Roy, former postdoctoral fellow at PoreLab was one of the organizers for the mini symposium on *Interfacial phenomena in multiphase systems*.

The Annual Conferences of the International Society of Porous Media are the focal events for the diverse porous media community worldwide, bringing together professionals and students to learn about new and exciting advances in porous media.

PoreLab's delegation in Edinburgh included 3 master students, 10 PhD candidates, 8 postdoctoral fellows and researchers, 6 associate professors and professors, and PoreLab' administrative leader. It is crucial for PoreLab to send our juniors to major events such as the annual InterPore conference. It is a pivotal investment in their academic and personal development. The annual InterPore conference offers unmatched networking opportunities, exposure to cutting-edge research within porous media, and chances to present and receive feedback on their work at PoreLab.

PORELAB DELEGATION TO SFB1313 AT THE UNIVERSITY OF STUTTGART – 12 TO14 JUNE 2023

Postdoctoral fellow Morten Hammer and Professor Øivind Wilhelmsen spent 3 months during the spring 2022 at the University of Stuttgart visiting the research group of Professor Joachim Groß, head of the Institute of Technical Thermodynamics and Thermal Process Engineering, to learn about density functional theory for fluids, perturbation theory and collaborate on topics such as quantum fluids in porous media.

This research stay initiated further collaboration and a delegation of the Principal Investigators (PIs) at PoreLab visited SFB 1313, a collaborative research center funded by the German Research Foundation, for a 2-day meeting in Stuttgart in the period 12 to 14 June 2023. SFB 1313' s topic is on *Interface-driven multi field processes in porous media – flow, transport, and deformation*. The purpose of the meeting was to discuss common interests on the science of porous media between PoreLab and SFB 1313. The agenda included a presentation of SFB1313 by its chairman, Professor Rainer Helmig, as well as a presentation of several project areas presented by their respective PIs, i.e. Professors Holger Steeb, Holger Class, Joachim Groß and Bernd Flemish. PoreLab's PIs presented PoreLab's research themes. The last day was reserved for discussion in smaller groups and possible cooperations.

EARTHFLOWS MEETING 14-15 JUNE 2023

The EarthFlows Meeting is an annual event on its 9th edition in 2023, and part of a strategic research initiative for cross-disciplinary research at the University of Oslo, Norway. This year's seminar was held in Oslo between 14th and 15th of June 2023 at the Oslo Science Park. It was organized by Torstein Sæter, Janne Hoff, Luiza Angheluta, Luca Menegon and François Renard.

The EarthFlows meeting is a two-day international conference, with the intention of bringing together top researchers from various disciplines (geoscience, mathematics, material science, theoretical and experimental physics), who have different perspectives on interface dynamics, flows and deformations during solid and fluid earth processes. The seminar is funded by the Research Council of Norway (project COLOSSAL), the University of Oslo (project EarthFLows), and Equinor through the Akademia agreement (project MODIFLOW).

INTERPORE NORWAY 2023 ON 9 NOVEMBER 2023

The 6th meeting of the Norwegian Chapter of InterPore was held in Oslo on November 9th 2023. The meeting was organized by Researcher Marcel Moura and Njord/PoreLab coordinator Janne Hoff. The meeting was hosted by PoreLab and the University of Oslo at the Oslo Science Park conference center.

About 45 participants attended the workshop with a good balance between university, industry, and research institutes. The workshop counted 10 presentations by invited speakers, of which 6 were from universities and 4 from industry / research institutes. An open discussion session was organized on the topic of *"Challenges and opportunities to promote better integration between academia, industry and research institutes"*. We believe the discussion was very fruitful and it helped the community to understand some of the typical bottlenecks that may hinder better integration between the parts. A business meeting of the Norwegian Chapter of InterPore was included as part of the program and it gave the community the opportunity to better understand the current and planned future actions of InterPore Norway.


Norway InterPore Chapter — PoreLab NTNU-UiO Porous Media Laboratory — UiO : University of Oslo

Welcome to InterPore Norway 2023!

The mission of InterPore Norway, the Norwegian Chapter of InterPore, is to create a platform for scientists and engineers involved in porous media studies in Norway or with connection to Norway. InterPore Norway focuses on interdisciplinary fundamental and applied studies of porous media in connection with national and international technological demands. It aims to advance and disseminate knowledge for the understanding, description, and modelling of natural and engineered porous media systems.

When: November 9th, 2023 at 09:00
Where: Oslo Science Park (Forskningsparken) Conference Centre. Room: Faros / Toppsenteret. Address: Gaustadalléen 21, Oslo. Closest metro station: Forskningsparken.
Registration: https://bit.ly/interporenorway2023

Program

09:00	Opening
09:10	Majid Hassanizadeh (Utrecht University and Stuttgart University) – "Microfluidic studies of two-phase flow, colloid transport, and heat transport"
09:40	Dag Chun Standnes (Equinor ASA) – "Generalized Darcy's law"
10:10	Eirik Grude Flekkøy (PoreLab, University of Oslo) – "Cavitation dynamics in creeping flow"
10:40	Coffee Break
11:00	Hans Petter Jostad (Norwegian Geotechnical Institute) – "From micro to macro relationships of coupled mechanical and fluid flow behaviour of assemblies of stiff particles of different shapes"
11:30	Round table – Open discussion session on "Challenges and opportunities to promote better integration between academia, industry and research institutes".
12:00	Lunch
13:00	Espen Jettestuen (NORCE Norwegian Research Centre) – "Ostwald ripening of trapped gas in the presence of oil and water in subsurface storage"
13:30	Antje van der Net (PoreLab, Norwegian University of Science and Technology) – "Streaming potential measurements in bead packs"
14:00	Coffee Break
14:20	Business Meeting InterPore Norway
14:50	Marius Causemann (Simula Research Laboratory) – "The pulsating brain – a mathematical perspective"
15:20	Paula Reis (PoreLab, University of Oslo) – "A simplified pore-scale model for slow drainage including film-flow effects"
15:50	Coffee Break
16:00	Kevin Pierce (PoreLab, University of Oslo) – "Impact of the solid structure on solute mixing in porous media flows"
16:30	Douglas Durian (University of Pennsylvania) – "Flow networks that learn"
17:00	Closing
18:00	Self-organized dinner EGON Karl Johan restaurant

Steering Committee InterPore Norway
Sarah Gasda (NORCE Norwegian Research Centre), chair
Alex Hansen (Norwegian University of Science and Technology)
Marcel Moura (University of Oslo)
Jakub Wiktor Both (University of Bergen)
Aksel Hiorth (University of Stavanger)
Seyed Ali Ghoreishian Amiri (Norwegian University of Science and Technology)

Organizing Committee InterPore Norway 2023
Marcel Moura (marcel.moura@fys.uio.no)
Janne Kvifte Hoff (j.k.hoff@mn.uio.no)

PORELAB JOINED CECAM IN NOVEMBER 2023

PoreLab is co-financing the membership of the Norwegian-Icelandic Consortium (NIC) for CECAM. PoreLab contributes to the membership buying 6 shares annually. We commit with the same number of shares every year for three years, for a total number of shares equal to 18.

CECAM is the *Centre Européen de Calcul Atomique et Moléculaire*. It is an organization devoted to the promotion of fundamental research on advanced computational methods and their application to important problems in frontier areas of science and technology. As the name suggest, the traditional focus of CECAM has been atomistic and molecular simulations, applied to the physics and chemistry of condensed matter.

CECAM activities, across all of the nodes, include the organization of scientific workshops in emerging areas; specialist schools to train at the graduate and postdoctoral level; workshops on software development; brain-storming and problem solving events; the development of collaborative research projects for Europe and beyond; and the sponsorship of an international visitors programs. CECAM welcomes applications to organize events and to establish networks through CECAM from everybody interested in computational science.

WORKSHOP ON QUICK CLAY STABILIZATION ON 8 DECEMBER 2023


SUSTAINABLE STABLE GROUND

Sustainable, Stable Ground (Bærekraftig Grunn)
1st Seminar and Advisory Board Meeting

DATE: 8th of December 2023
TIME: 11:15 – 16:00
(for online participants: 12:30-16:00)
VENUE: Høgskoleringen 7a, Trondheim, 7034
1-101 Seminarrom GT-Lab

NTNU Norwegian University of Science and Technology — NGI — PoreLab NTNU-UiO Porous Media Laboratory — Forskningsrådet The Research Council of Norway — GOAL

Agenda:

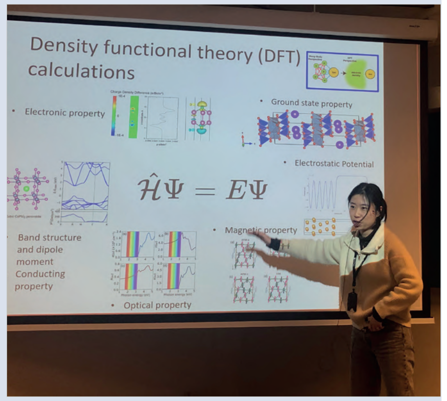
11:15 - 12:30	Arrival, launch
12:30 – 12:35	Welcome - Klaartje De Weerdt
12:35 – 12:50	Project overview – Ali Amiri
12:50 – 13:10	Experimental investigation of illite from Norwegian quick clay - Rene Tammen
13:10 – 13:30	Microstructural analysis of quick clay stabilized with cementitious materials - Kamila Zablocka
13:30 – 13:45	Coffee break
13:45 – 14:05	Molecular dynamics simulations on illite clay - Ge Li
14:05 – 14:25	Surface-ion interactions of illite from first principles calculations - Lu Xia
14:25 – 14:45	The GOAL project: a quick update - Priscilla Paniagua
14:45 – 15:00	Coffee break
15:00 – 16:00	Board meeting

The first workshop (WS) of the Sustainable, Stable Ground (SSG) project took place in Trondheim on December 8th, 2023. About 30 participants attended the WS, where the recent findings from the SSG project were shared through 6 lectures presented by the researchers involved in the project. The lectures were followed by discussions involving both the audience and the scientific advisory board of the project. As the project is still in its early stage, the WS focused specifically on clay-clay and clay-cement interactions.

The SSG project (see PoreLab annual report 2021 page 57) is a collaborative initiative between NTNU and NGI, funded by the Research Council of Norway through its Large-Scale Interdisciplinary Research Projects scheme. This project, which commenced in mid-2022, operates within Theme 4 *"Nanoporous Media and Gels"* of PoreLab.

Quick clay is the main cause of significant landslides in Norway, posing substantial challenges to infrastructure development projects. Current ground improvement methods in these areas rely on deep-mixing technology, involving the use of thousands of tons of lime and cement. The considerable carbon footprint associated with lime and cement production makes the carbon inventory of large infrastructure projects in Norway very high.

The primary objective of this project is to revolutionize deep-mixing technology by incorporating sustainable alternatives derived from waste materials, thereby establishing a circular economy. To achieve this ambitious goal, we are undertaking interdisciplinary research with a bottom-up approach, combining experimental and modeling methods across scales and disciplines.



PROMOTING PORELAB'S SCIENCE TO THE PUBLIC

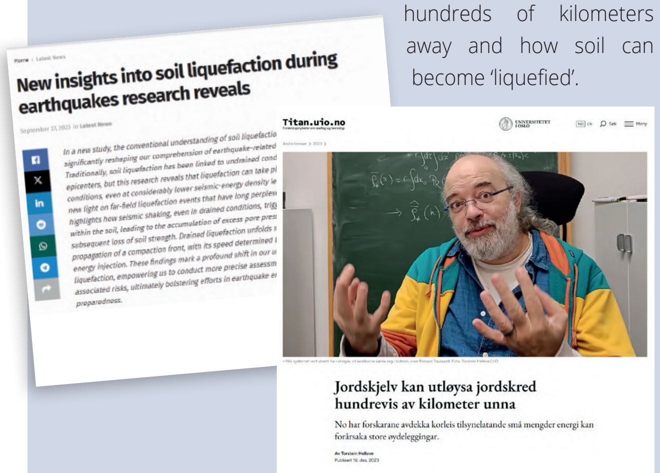
An important goal of PoreLab is to communicate its research and findings, as well as to increase the appreciation and understanding of science in general. These two pages show some of what the PoreLab scientists participated in during 2023.

In October 2023, Professor **Erika Eiser**, PI at PoreLab presented to Gemini a simple tool for identifying the entire genetic material of bacteria, enabling quicker identification of bacterial strains in sick individuals, animals, foods or the environment. One key advantage of the new method is that it bypasses the need for DNA amplification, saving time and resources. The method is simple, inexpensive, and more precise than previous techniques, potentially leading to a reduction in the use of antibiotics. In a world where antibiotic resistance is a growing concern, this development represents a significant progress in combating bacterial infection.

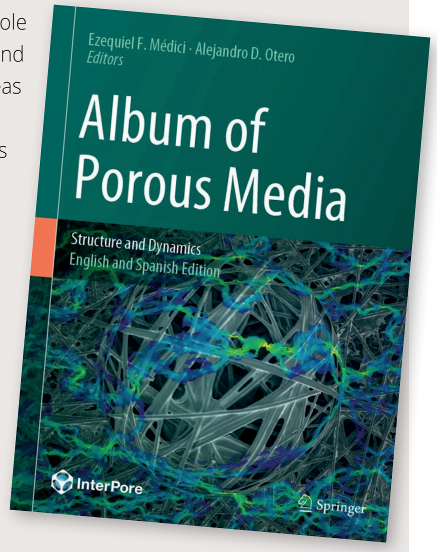
On November 17th, 2023, the Faculty of Natural Science at NTNU organized a movie night for all in one of the auditoriums at the Natural Science building. The movie presented was "The imitation Game", an iconic movie based on the real-life story of legendary cryptanalyst Alan Turing. Prior to the movie, the faculty asked Professor **Alex Hansen** to give a lecture on Enigma, the cipher device employed extensively by Nazi Germany during World War II. Hansen revealed the rich and exciting history behind Enigma. His lecture provided relevant background knowledge for the movie and deeper insight into the achievement of cracking the Enigma encryptions. There are only 40 marine-type Enigma devices left in the world and NTNU owns one of them in perfect condition. The movie night was a great success!


Photo: Getingbo

Following the article of Professor **Renaud Toussaint**, adjunct Professor at PoreLab UiO, published in Nature in September 2023, popular scientific articles were published both in SCIENMAG and Titan. Toussaint and his partners from the Hebrew University of Jerusalem reveal that liquefaction can take place under drained conditions, even at considerably lower seismic-energy density levels. Toussaint explains how earthquakes can trigger landslides hundreds of kilometers away and how soil can become 'liquefied'.



Album of Porous Media is the first book dedicated to compiling state-of-the-art visualization in porous materials. The book serves as a reference for teachers, scientists, and engineers working with porous materials. The book gives a graphical depiction of abstract concepts that have played a major role in the formulation and communication of ideas since prehistoric times. Many of the contributors are affiliated with PoreLab and the Njord Centre: Joachim Falck Brodin, Eirik G Flekkøy, Knut Jørgen Måløy, Marcel Moura, Per Arne Rikvold, Gaute Linga, Francois Renard, Renaud Toussaint, Joachim Mathiesen and Tanguy Le Borgne.



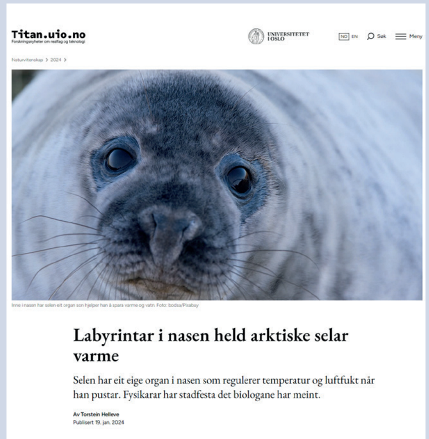
In September 2023, Professor **Øivind Wilhelmsen**, PI at PoreLab, explained to Gemini and the Norwegian SciTech News that we still do not understand the mechanisms behind the transport of energy and particles at the interface between liquid and gas. Professor Wilhelmsen has been awarded an ERC starting grant from the European Research Council (see page 60). The goal for his research group is to develop a far more precise theory and methods to better understand the interface between the liquid and the gas phases.

For the fourth consecutive year, PoreLab took part in the **Pink Ribbon Run** in Trondheim on October 1st, 2023. The Pink ribbon is an international symbol of breast cancer awareness, and the Pink Ribbon run helps increase awareness of early detection for breast cancer. Why a PoreLab team at the Pink Ribbon Run? Because at PoreLab we work on improving cancer therapy, especially by optimizing focused ultrasound for improved drug delivery by nanoparticles to the tumor interstitium. Read as well the research project on page 50.

CBC LISTEN

Arctic seals have evolved many adaptations to cope with their frosty environment. They have complex nasal cavities that help them stay warm and hydrated in frosty seas. *"Thanks to this elaborate structure in their nasal cavities, Arctic seals lose less heat through nasal heat exchange than subtropical seals when both are exposed to the same conditions,"* says Professor **Signe Kjelstrup**, former PI at PoreLab. In December 2023, Signe Kjelstrup's research activities on the thermal exchange in the nose of a seal became extremely favored among the popular science media. It was the topic of several popularized articles, in SCIENTAS.nl, the largest popular science news site in the Netherlands, as well in New Scientist, EurekAlert!, Cell Press and Science Daily. Professor Kjelstrup and her colleague prof. Folkow from the Arctic University of Tromsø in Norway, gave an interview as well on the Canadian Broadcasting Corporation's weekly science radio show, Quirks & Quarks.

On the same topic, Professor **Eirik Flekkøy**, PI at PoreLab, answers the questions from TiTan and forskning.no, and explains how PoreLab researchers are using a thermo-hydrodynamic model to describe the heat and water exchange in the turbinate region of the seal's nose. For more information, please read page 46 of PoreLab annual report 2021, journal reference: DOI: 10.1016/j.bpj.2023.11.012 and 10.1016/j.jtherbio.2022.103402)



SOCIAL MEDIA

Visit our website **www.porelab.no** where you find daily updated information on our researchers, scientific findings, happenings, studies and many more.

Follow us on X as well, and YouTube

AWARDS and prestigious nominations in 2023

The 2023 Interpore-PoreLab award: Dr. **Pranay Shrestha**

The 2023 winner of the Interpore-PoreLab award for young researchers is Dr. Pranay Shrestha, Postdoctoral fellow in clean energy at the University of Oxford, UK. Pranay is working to advance sustainable energy technologies like fuel cells and the porous materials within them. He received his PhD degree from the University of Toronto in February 2023, working on *"Experimental and theoretical investigation of transport phenomena within electrochemical energy conversion and storage devices for novel material development"*. He received his Master of Applied Science in December 2017 from the University of Toronto.

The close cooperation between Interpore and PoreLab has led to the creation of the Interpore-PoreLab award for young researchers. The award, allocated for the first time in 2018 is given in recognition of outstanding contributions to fundamental research in the field of porous media. Award winners receive a grant of 1000 euros and is offered to spend up to 60 days at PoreLab either in Trondheim or in Oslo, supported with a daily stipend.

Pranay spent 2 months at PoreLab UiO during the spring 2023.

> Truly humbled to receive this honour! I constantly look up to this community at InterPore for inspiration and expertise on porous media! So this one is extra special to me!
>
> *– Pranay Shrestha, 2023 winner of the InterPore-PoreLab Award for Young Researchers*

Alex Hansen chairs the research quality evaluation board of the Niels Bohr Institute

In August 2023, the University of Copenhagen asked Alex Hansen to chair the research quality evaluation board of the Niels Bohr Institute.

All departments at the University of Copenhagen undergoe an external evaluation by a Research Quality Assessment board consisting of international experts every five to six years. The Niels Bohr Institute itself recommended Alex Hansen as Chairman of their proposed panel.

The main focus of the evaluation was on the scientific performance of the department with a particular focus on the following four points:

1. Quality, international impact and interdisciplinarity of the research
2. Alignment between research and educational activities
3. Societal impact, innovation and private and public collaboration
4. Resources, capacity, governance and organization

The evaluation took place during a site visit from 27 November to 1 December 2023.

The panel was composed of Ania Bleszynski Jayich from UC Santa Barbara, Kai Bongs from Ulm University, Julianne Dalcanton from Flatiron Institute's Center for Computational Astrophysics, Lance Dixon from Stanford University and Jürg Schweizer from the WSL Institute for Snow and Avalanche Research SLF.

Erika Eiser is elected to be member of the C3 (Statistical physics) commission of the IUPAP

Erika Eiser (PI for the WP4 – Nanoporous media and gels, at PoreLab) was elected to be member of the commission on Statistical physics of the International Union of Pure and Applied Physics (IUPAP). The IUPAP is the only international physics organization that is organized and run by the physics community itself. Its members are identified physics communities in countries or regions around the world. Its mission is to assist worldwide development of physics, to foster international cooperation in physics, and to help in the application of physics toward solving problems of concern to humanity.

The Commission on Statistical Physics (C3) promotes the exchange of information and views among the members of the international scientific community in the general field of Statistical Physics.

The C3 section, among other activities, is organizing the next Statistical Physics Conference, StatPhys29, in Florence in 2025 and awards the Boltzmann medal. This Award, consisting of a gilded medal, honors outstanding achievements in Statistical Physics. It is awarded every 3 years.

COMPLETED PHDs IN 2023

NAME	DEPARTMENT	DATE	THESIS	SUPERVISORS
Astrid Fagertun Gunnarshaug	Department of Chemistry, NTNU	19.10.2023	*Thermoelectric Phenomena in Lithium Ion Batteries and Thermogalvanic Cells*	Signe Kjelstrup and Odne Stokke Burheim
Hursanay Fyhn	Department of Physics, NTNU	27.10.2023	*Dynamic pore network study of immiscible two-phase flow in porous media*	Alex Hansen, Knut Jørgen Måløy, Santanu Sinha
Federico Lanza	CNRS/University Paris-Saclay, France and Department of Physics at NTNU, Norway	03.11.2023	*Optimal path for the flow of yield stress fluid*	Alberto Rosso, Alex Hansen, Laurent Talon

Defense of thesis for ***Astrid Fagertun Gunnarshaug***

From left to right: Prof. Andreas Erbe, As. Prof. Johannes Landesfeind, Prof. Simone Wiegand, Dr. Astrid F. Gunnarshaug, Prof. Emerita Signe Kjelstrup, Prof. Odne Stokke Burheim

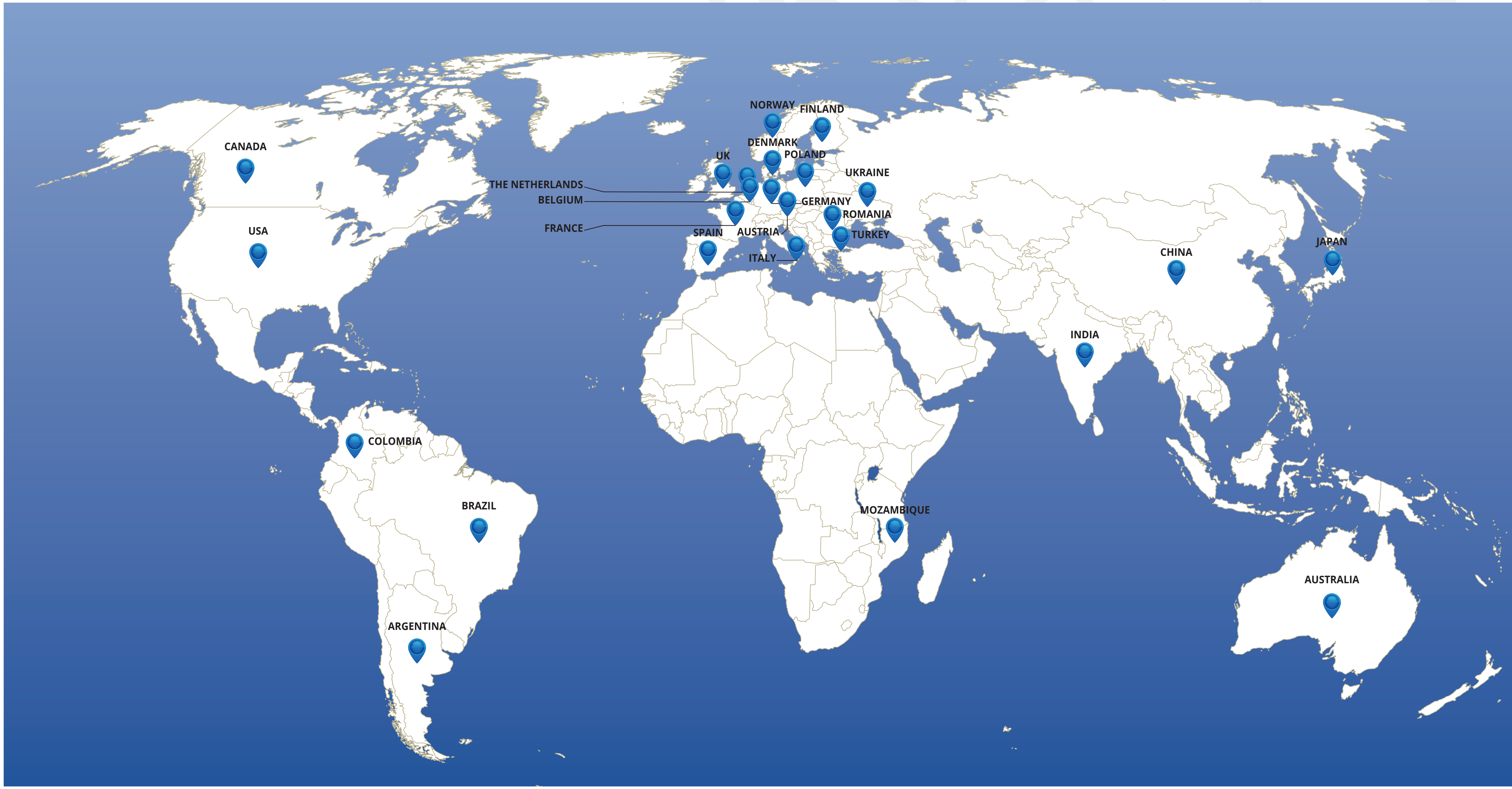
Defense of thesis for ***Hursanay Fyhn***

From left to right: Prof. Joachim Mathiesen, Dr. Marie-Laure Olivier, Dr. Hursanay Fyhn, Prof. Alex Hansen, Prof. François Renard

Defense of thesis for ***Federico Lanza***

From left to right: Prof. Dag Werner Breiby, Prof. Rainer Helmig, Dr. Laurent Talon, Directeur de recherche Alberto Rosso, Dr. Federico Lanza, Dr. Marie-Laure Olivier, Prof. Alex Hansen, Dr. Santanu Sinha

NATIONAL AND INTERNATIONAL COLLABORATION



USA
Sarah L. Codd, Joseph Seymour: *College of Engineering, Montana State University, Bozeman*
James E. McClure: *Virginia Tech*
Peter Kang: *University of Minnesota*
Saman Aryana: *University of Wyoming*
Douglas Durian: *University of Pennsylvania*
Catherine Spurin: *Stanford University*
Muhammad Sahimi: *University of Southern California*

CANADA
Danial Arab, Apostolos Kantzas: *University of Calgary*
Ian Frigaard: *University of British Columbia*

COLOMBIA
Daniel Barragán, Andrés Arango-Restrepo: *School of Chemistry, Faculty of Sciences, National University of Colombia*

ARGENTINA
Diego Kingston: *University of Buenos Aires*

BRAZIL
José Soares Andrade Jr., Hans J. Herrmann, Humberto de Andrade Carmona: *Universidade Federal do Ceara*
Fernando A. Oliveira: *University of Brasilia*

NORWAY
Magnus Aa. Gjennestad, Rune Hansen, Ailo Aasen, Asbjørn Solheim, Vegard Brøtan, Pierre Cerasi: *SINTEF*
Preben Vie, Geir Helgesen, Kenneth Knudsen: *Institute for Energy Technology, IFE*
Lars Folkow: *The Arctic University of Norway*
Bernt O. Hilmo: *Asplan Viak AS*
Marianne Øksnes Dalheim, Kristin Syverud: *RISE PFI AS*
Harald Berland, Olav Aursjø: *NORCE Norwegian Research center AS*
Thomas Ramstad: *Equinor Research Center, Trondheim*

DENMARK
Joachim Mathiesen: *Niels Bohr Institute, University of Copenhagen*

FINLAND
L. Laurson, Mikko Alava: *Department of Applied Physics, Aalto University, Espoo*

GERMANY
Rainer Helmig and Joachim Gross: *University of Stuttgart*
Andrzej Gorak: *TU Dort*
Steffen Schlüter: *Helmholtz Center for Environmental Research, Leipzig*

THE NETHERLANDS
Thijs J.H. Vlugt, Claire Chassagne, Othon Moultos: *Delft University of Technology*
Majid Hassanizadeh: *Multiscale Porous Media Laboratory, Utrecht University*
Edgar M. Blokhuis: *University of Leiden*
Steffen Berg: *Shell Research, Amsterdam*
Maja Rücker: *Eindhoven University of Technology*
Michel Versluis: *University of Twente*

BELGIUM
Tom Bultreys, Veerle Cnudde: *Gent University*

AUSTRIA
Sofia Kantorovich: *University of Vienna*

UK
Bjørnar Sandnes: *Energy Safety Research Institute, College of Engineering, Swansea University*
Fernando Bresme, Erich A. Müller: *Imperial College London*
Daan Frenkel, Matthew Mason: *University of Cambridge*
Robin Cleveland: *Oxford University*
Ran Holtzman: *Coventry University*

FRANCE
Sunniva Indrehus: *Pierre and Marie Curie University, Paris VI*
Alberto Rosso: *Laboratoire Physique Théorique et Modèles Statistiques (LPTMS), Université Paris-Saclay, Orsay*
Laurent Talon: *Laboratoire FAST, Université de Paris-Saclay, Orsay*
Renaud Toussaint, Monem Ayaz: *Institut de Physique du Globe de Strasbourg, CNRS, Université de Strasbourg*
Tanguy Le Borgne, Yves Méheust : *University of Rennes*
Jean-Marc Simon: *University of Bourgogne, CNRS*
Stéphane Santucci, Michael Bourgoin: *Ecole Normale Supérieure de Lyon, UMR CNRS, Lyon*
Wei Dong: *CNRS, Lyon*
Osvanny Ramos: *Department of Physics, Claude Bernard University, Lyon*
Jean-Noël Jaubert, Silvia Lasala: *Université de Lorraine*

SPAIN
Miguel Rubi, David Reguera, Jordi Ortín, Ramon Planet: *University of Barcelona*
Riccardo Rurali: *Theory and Simulation Department, Materials Science Institute of Barcelona (ICMAB–CSIC)*
María Barragán Garciá: *Department of Applied Physics, Complutense University of Madrid*
Juan José Hidalgo González, Marco Dentz: *Institute of Environmental Assessment and Water Research (IDAEA)*

ITALY
Luciano Colombo: *University of Cagliari*

MOZAMBIQUE
Alberto Bila: *Eduardo Mondlane University (EMU). Maputo*

POLAND
Wojciech Debski: *Department of Theoretical Geophysics, Institute of Geophysics Polish Academy of Sciences, Warszawa*

ROMANIA
Mirela-Nicoleta Stoeac-Vladuti: *Art space director, META Spatiu, Timisoara*
Cosmin Haias, automation engineer and artist, *Timisoara*

UKRAINE
Natalya Kizilova: *Department of Theoretical and Applied Mechanics, Kharkov National university*

TURKEY
Talha Erdem: *Abdullah Gul University, Kayseri*
Levent Akyalçin: *Eskişehir Technical University, Eskişehir*

INDIA
Purusattam Ray: *Institute of Mathematical Sciences, Chennai*
S. B. Santra: *Indian Institute of technology, Guwahati*
Subhadeep Roy: *BITS Pilani, Hyderabad*

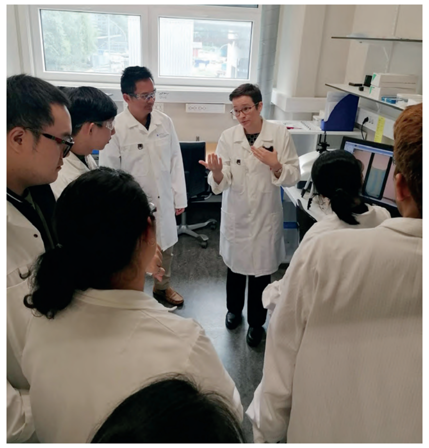
CHINA
Ye Xu: *School of Mechanical Engineering and Automation, Beihang University, Beijing*
Xin Wang: *Institute of Oceanography Instrumentation, Shandong Academy of Sciences, Qingdao*

JAPAN
Pieter Krüger: *Graduate School of Science and Engineering, Molecular Chirality Research Center, Chiba University, Chiba*
Koji Amezawa: *Institute of Multidisciplinary Research for advanced materials, Tohoku University*
Hironori Nakajima: *Department of Mechanical Engineering, Faculty of Engineering, Kyushu University*
Satoshi Nishimura: *Faculty of Engineering, Field Engineering for the Environment, Hokkaido University*
Yasuhiro Fukunaka: *Research Organization for Nano and Life Innovation, Waseda University, Shinjuku, Tokyo*

AUSTRALIA
Peter Daivis: *RMIT, Royal Melbourne Institute of Technology, Melbourne*
Benjy Marks: *University of Sydney*
Ryan Armstrong: *University of New South Wales*
Mark Knackstedt: *Australian National University, Department of Applied Mathematics, Canberra*

GUEST RESEARCHERS AT PORELAB

During the challenging period of COVID-19 and following restrictions on travels, PoreLab experienced a drastic drop in guest number. We had 64 visitors in 2019, 14 in 2020 and only 7 in 2021. As restrictions were gradually lifted, a gradually recovery began to take shape. The number bounced back in 2022 with 46 visitors. This trend continues into 2023 with 58 guests visiting PoreLab both at NTNU and UiO. This is a great privilege and pleasure for us to welcome at PoreLab guest researchers from diverse disciplines and communities. They bring with them a wealth of knowledge, experience and fresh perspectives that enrich our research activities. Hosting guest researchers not only broaden our academic horizons but also fosters collaboration and interdisciplinary exchange. Most of them gave lectures and workshops were organized when international delegations visited us.



On August 22nd, 2023, a delegation from Thailand came to visit PoreLab, alongside the Norwegian CCS Research Center, SINTEF and Equinor, to learn more about CCS (Carbone Capture Storage). The delegation included 17 representatives from Chiang Mai University, EGAT, the Electricity Generating Authority of Thailand, the Energy Regulatory Commission as well as the National Research Council of Thailand. At PoreLab, Carl Fredrik Berg, PI at PoreLab and Antje van der Net, associated member at PoreLab, gave a guided tour of the facilities at the Reservoir Laboratory of the Institute of Geoscience and Petroleum. There, our guests could observe convective flow of CO_2 enriched water at lab-scale.

On February 16th, 2023 was organized a meeting connected to the project "Ultrasound-mediated Transport of Nanoparticle in Tissue" with the project's partners. The participants discussed the mechanism for enhanced drug delivery, for instance by acoustic streaming. From left to right: Magnus A. Gjennestad (SINTEF Energy AS), Rune Hansen (Department of Circulation and Medical Imaging, NTNU), Bjørn A. Angelsen (Department of Circulation and Medical Imaging, NTNU), Signe Kjelstrup (PoreLab, department of Chemistry, NTNU), Robin O. Cleveland (Institute of Biomedical Engineering, University of Oxford, UK), Natalya Kizilova (Department of Theoretical and Applied Mechanics, Kharkov National University, Ukraine), Catharina de Lange Davies (PoreLab, Department of Physics, NTNU), Caroline Einen (PoreLab, Department of Physics, NTNU) and Sebastian Price (PoreLab, Department of Chemistry, NTNU)

As part of the POROUS MATTER project, Florin Drăgan, rector for the Polytechnic University of Timisoara in Romania, visited both PoreLab at the University of Oslo and PoreLab at NTNU during the last week of February 2023. During his stay in Trondheim, he met NTNU's rector, Professor Anne Borg. Professor Emerita Signe Kjelstrup, former PI at PoreLab, accompanied him during this visit (on the right)

NAME	POSITION	AFFILIATION	PERIOD
Per Arne Rikvold	Professor Emeritus	Florida State University, USA	06.08.20 - current
Natalya Kizilova	Professor	Kharkov National niversity, Ukraine	01.04.22 – 01.04.24
Daan Frenkel	Professor Emeritus	University of Cambridge, UK	01.01.23 – 12.02.23
Bertrand Lacroix-A-Chez Toine	Research Associate	King's College in London, UK	16.01.23
Robin O. Cleveland	Professor	Institute of Biomedical Engineering, University of Oxford, UK	16.02.23
Florin Drăgan	Rector	Polytechnic University of Timisoara, Romania	23.02.23 – 01.03.23
Liviu Marşavina	Professor, vice rector	Polytechnic university of Timisoara, Romania	23.02.23 – 04.03.23
Mirela Stoeac Vlăduți	Art Gallery Director	META Spatiu, Timisoara, Romania	23.02.23 – 04.03.23
Maria Castellaños	Postdoc	Oslo Metropolitan University, Oslo, Norway	23.02.23 – 04.03.23
Floriama Cândea	Artist	META Spatiu, Timisoara, Romania	23.02.23 – 04.03.23
Ryan Armstrong	Professor	University of New South Wales, Australia	16.03.23 – 15.04.23
Daan Frenkel	Professor Emeritus	University of Cambridge, UK	20.03.23 – 20.04.23
Albert-László Barabási	Professor	Northeastern University, Boston, USA	22.03.23
Pranay Shrestha	PhD candidate	University of Toronto, Canada	11.04.23 – 16.06.23
Subhadeep Roy	Assistant Professor	Birla Institute of Technology and Science, Hyderabad, India	29.04.23 – 05.05.23
Steffen Berg	Principal Science expert	Shell Global Solutions, the Netherlands	30.04.23 – 04.05.23
Ryan Armstrong	Professor	University of New South Wales, Australia	30.04.23 – 04.05.23
Maja Rücker	Assistant Professor	Eindhoven University of Technology, The Netherlands	30.04.23 – 04.05.23
Saman Aryana	Associate Professor	University of Wyoming, USA	30.04.23 – 05.05.23
James McClure	Research As. Professor	Virginia Tech, USA	30.04.23 – 12.05.23
Rosangela B. Z. Lopes Moreno	Professor	University of Campinas, Unicamp, Portugal	10.05.23
Daan Frenkel	Professor Emeritus	University of Cambridge, UK	25.05.23 – 29.05.23
Stéphane Santucci	Researcher	ENS, Lyon, France	12.06.23 – 17.06.23
Sarah Perez	PhD candidate	University of Pau, France	11.08.23
Daan Frenkel	Professor Emeritus	University of Cambridge, UK	19.08.23 – 30.08.23
Chatchawan Chaichana	Assistant Professor	CCS Frontier Research Group, Chiang Mai University, Thailand	22.08.23
Nakorn Tippayawong	Professor	CCS Frontier Research Group, Chiang Mai University, Thailand	22.08.23
Suparit Tangparitkul	Assistant Professor	CCS Frontier Research Group, Chiang Mai University, Thailand	22.08.23
Natthanan Promsuk	Assistant Professor	CCS Frontier Research Group, Chiang Mai University, Thailand	22.08.23
Tadsuda Taksavasu	Lecturer	CCS Frontier Research Group, Chiang Mai University, Thailand	22.08.23
Khomchan Promneewat	Software developer	CCS Frontier Research Group, Chiang Mai University, Thailand	22.08.23
Chanchana Thanachayanont	Principal researcher	Thailand national metal and materials technology center (MTEC)	22.08.23
Sirikarn Wisetsuwannaphum	Researcher	Thailand national metal and materials technology center (MTEC)	22.08.23
Apiradee Suwannathong	Geologist	Department of Mineral Fuels, Ministry of Energy, Thailand	22.08.23
Natchana Boonchaluay		Department of Mineral Fuels, Ministry of Energy, Thailand	22.08.23
Tawan Sanya		Electricity Generating Authority of Thailand (EGAT)	22.08.23
Pongvipa Lohsomboon		Thailand Science Research and Innovation (TSRI)	22.08.23
Surachai Vangrattanachai	Senior sales executive	SCG CEMENT CO.,LTD, Thailand	22.08.23
Manow Piyaworapaiboon	Researcher	SCG CEMENT CO.,LTD, Thailand	22.08.23
Sumate Pettong	Innovation manager	Dexon Technology PCL, Thailand	22.08.23
Nawarat Khamsri	Marketing manager	Dexon Technology PCL, Thailand	22.08.23
Felix Schloms	Erasmus Master student	University of Stuttgart, Germany	01.09.23 – 31.12.23
Daan Frenkel	Professor Emeritus	University of Cambridge, UK	29.09.23 – 17.10.23
Rafał Bielas	Researcher	Adam Mickiewicz University, Poznan, Poland	02.10.23 – 10.10.23
Miguel Rubi	Professor	University of Barcelona, Spain	09.10.23 - 14.10.23
Simone Wiegand	Professor	Institute of Biological Information Processing, Germany	19.10.23
Johannes Landesfeind	Associate Professor	Dept. of Engineering and Sciences, University of Agder, Norway	19.10.23
Joachim Mathiesen	Professor	Niels-Bohr-Institute, Copenhagen, Denmark	27.10.23
Daan Frenkel	Professor Emeritus	University of Cambridge, UK	27.10.23 – 05.11.23
Jean-Marc Simon	Associate Professor	Université de Bourgogne, France	29.10.23 – 03.11.23
Laurent Talon	Researcher	FAST at CNRS/University Paris-Saclay	01.11.23 – 05.11.23
Alberto Rosso	Directeur de recherche	LPTMS at CNRS/University Paris-Saclay	01.11.23 – 05.11.23
Rainer Helmig	Professor	University of Stuttgart, Germany	03.11.23
Majid Hassanizadeh	Professor	Faculty of geosciences, Utrecht University, The Netherlands	05.11.23 – 10.11.23
Douglas Durian	Professor	Department of Physics and Astronomy, U. of Pennsylvania, USA	06.11.23 – 10.11.23
Daan Frenkel	Professor Emeritus	University of Cambridge, UK	18.11.23 – 03.12.23
José Soares de Andrade Junior	Professor	Universidade Federal do Céara, Fortaleza, Brazil	05.12.23 - 16.12.23
Humberto de A. Carmona	Professor	Universidade Federal do Céara, Fortaleza, Brazil	05.12.23 – 16.12.23

PORELAB LECTURE SERIES LIST OF LECTURES

The PoreLab lecture series are organized alternating with the Porous Media Tea Time Talks (#PorousMediaTTT) and the Thursday's talk. The series are held simultaneously in Oslo (UiO) and Trondheim (NTNU). The PoreLab lecture series are now almost always given by external lecturers. The development of video conferencing during the pandemic allowed us to broaden our pool of lecturers and we noticed a boost in attendance.

GUEST LECTURES 2023:

DATE	NAME, AFFILIATION	TITLE
Feb. 27	Mirela Vladuti, Art Center Manager for META Spatiu, Timisoara, Romania	*Art collaboration project with PoreLab*
March 29	Dr. Tomás Aquino, researcher, Institute for Environmental Assessment and Water Research (IDAEA), Spain	*Mixing, delay, and restart — Fluid-solid reaction efficiency in incompletely-mixed porous media*
March 31	Maciej Lisicki, Associate Professor, Institute of Theoretical Physics, Faculty of Physics University of Warsaw, Poland	*Elastohydrodynamics of microscale swimming*
April 12	Professor Shervin Bagheri, KTH Royal Institute of Technology, Sweden	*Liquid-infused materials and surfaces*
April 19	Dr. Mathieu Souzy, Research Associate, INRAE (French National Research Institute for Agriculture, Food and Environment)	*Dispersion and stretching in 3D porous media*
April 26	Dr. Tom Bultreys, assistant professor, Ghent University and recipient for the Interpore-PoreLab award for young researchers 2019	*New developments in micro-CT-based imaging of flow in porous media: 3D X-ray micro-velocimetry and to pore-to-core imaging experiments*
May 3	Associate Professor Daniel Lester, RMIT University, Australia	*Fluid Mixing in Porous Media Flows of Arbitrary Complexity*
May 10	Professor Salvatore Torquato, Princeton University, USA	*Microstructure-Dependent Predictions of the Transport Properties of Porous Media*
May 10	Professor Rosangela Barros Zanoni Lopes Moreno, School of Mechanical Engineering, University of CAMPINAS, Unicamp, Brazil	*Petroleum at Unicamp, LABORE Research Group, and Opportunities for Collaboration*
May 31	Professor Majid Hassanizadeh, Utrecht University, Netherlands	*Two-phase flow in industrial porous media; Experiments, theory, and modelling*
June 7	Dr. Bauyrzhan Primkulov, Massachusetts Institute of Technology, USA	*Moving contact lines over imperfect surfaces: from stick-slip to steady-sliding*
Sept. 27	Prof. Bjørnar Sandnes, Swansea University, UK	*Viscously stable frictional fingers*
Oct. 11	Dr. Olivier Vincent, Permanent Research Scientist at CNRS, Institut Lumière Matière, Lyon, France	*Water and solutions in nanoporous media: capillarity, osmosis and phase change*
Oct. 13	Prof. Miguel Rubi, Department of Fundamental Physics, University of Barcelona, Spain	*Non-equilibrium thermodynamics of active particles self-assembly*
Oct. 25	Professor Eirik G. Flekkøy, Department of Physics, University of Oslo, Norway	*Cavitation dynamics in creeping flow*
Oct. 31	Professor Jean-Marc Simon, Université de Bourgogne, France	*Application of nano-thermodynamics to the analysis of 2D images. From molecular simulation to the analysis of optical microscopic images of colloidal particles*
Nov. 2	Marcello De Donno, Institute of Scientific Computing, TU Dresden, Germany	*Amplitude phase-field crystal model for complex lattices*
Nov. 14	Dr. Marco De Paoli, University of Twente, The Netherlands, and TU Wien, Austria	*Multiscale modelling of convective mixing in confined porous media*
Nov. 15	Professor Ian Frigaard, University of British Columbia, Vancouver, Canada	*Handling Uncertainty in the Squeeze Cementing Process*
Nov. 22	Associate Professor Cecilia Leal, University of Illinois, Urbana-Champaign, USA	*Structural complexity of lipid nanoparticles: implications for efficient gene delivery*
Nov. 23	Professor Berend Smit, Chemical Engineering at the School of Basic Sciences, EPFL, Switzerland	*Big Data in Nanoporous Materials: Science beyond Understanding*
Nov. 29	Prof. Marcel Filoche, ESPCI Paris, Université Paris Sciences et Lettres, France:	*Heterogeneous delivery of surfactant into the pulmonary airway system*
Dec. 1	Associate Professor Irene Rocchi, Department of Environmental and Resource Engineering, Technical University of Denmark	*Investigating swelling across scales*
Dec. 6	Dr.-Ing. habil. Abdolreza Kharaghani, Otto von Guericke University Magdeburg, Germany	*Scale transition from discrete to continuum models for the drying of capillary porous media*
Dec. 13	Prof. José S. Andrade Jr. , Universidade Federal do Ceará (UFC), Fortaleza, Brazil	*Itinerant conductance in fuse-antifuse networks*
Dec. 14	Dr. Bérénice Vallier, University of Strasbourg, France	*Influence of pumping strategies on the induced seismicity from pressure disturbances on faults during well injections*

FUNDING IN 2023

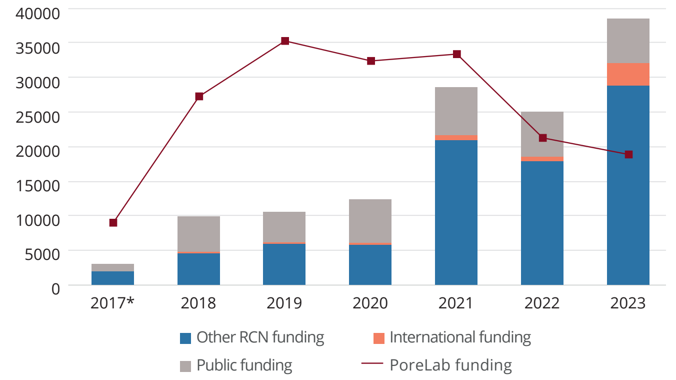
FUNDING (kNOK)	AMOUNT	PERCENTAGE
The Research Council	8 803	46%
NTNU	4 063	21%
University of Oslo	6 075	32%
TOTAL	18 941	100%

PoreLab funding represents the resources that are made available in order to implement the Center and cover the Center's costs. PoreLab will receive a total funding from the Research Council of Norway (RCN) of 148,1 MNOK over 10 years from 2017 to 2027. NTNU and UiO contribute on the same period with a total funding of 126,3 MNOK with respectively 72 MNOK for NTNU (57%) and 54,3 MNOK for UiO (43%).

PoreLab funding varies every year depending on the activities of the Center. RCN funding combined with NTNU and UiO contributions will sum up to 274,4 MNOK for the entire 10-year period, representing an average of 27,4 MNOK per year.

As part of the CoE agreement with the RCN, researchers at PoreLab are encouraged to develop additional externally funded projects (see "Heading for the future, our new projects" in PoreLab annual reports). These additional projects developed under the umbrella of PoreLab can be funded by the RCN, EU, industries, as well as universities internal funds and other sources. The graph on the right represents the funding in kNOK per year per source. "International funding" is primarily funding coming from the European Commission. "Public funding" is essentially internal funding from NTNU and UiO.

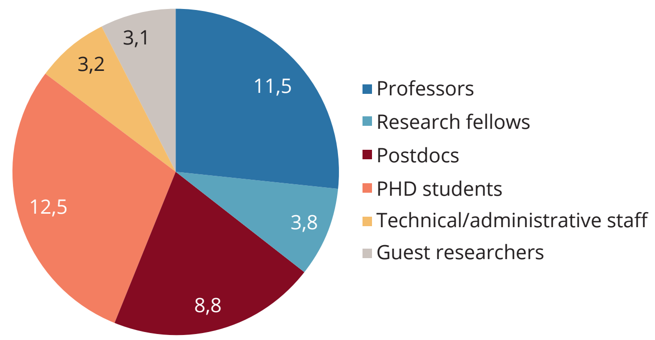
It is worth noticing two important results: 1) The amount of funding coming from additional externally funded projects just keep growing reaching a staggering 39 MNOK in 2023 and 2) 2022 was a pivotal year when the funding coming from additional projects exceeds for the first time PoreLab funding.



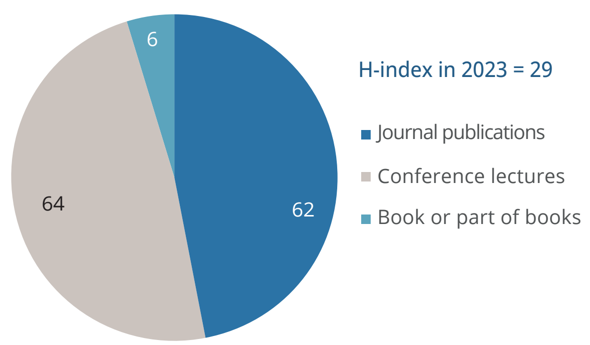
FACTS AND FIGURES

PORELAB STAFF categorized by position

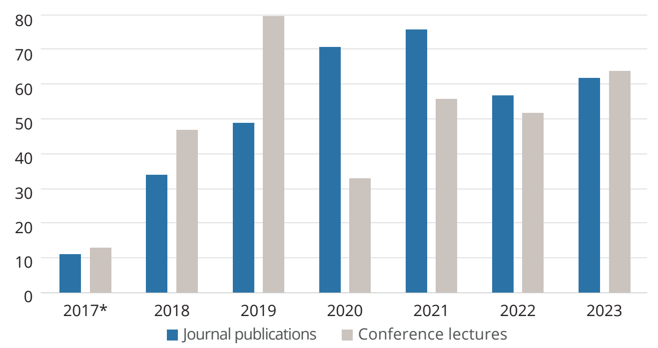
PoreLab equals 42,8 man-years in 2023
The pie chart on the right shows the categorization of our staff by position



PUBLICATIONS in 2023



PUBLICATIONS since 2017



*Publications over 4,5 months since PoreLab started on 15.08.2017

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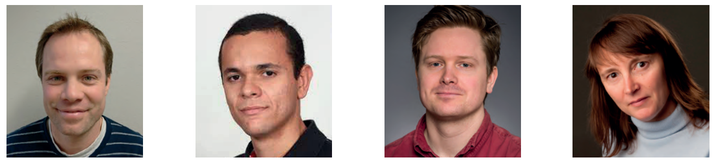

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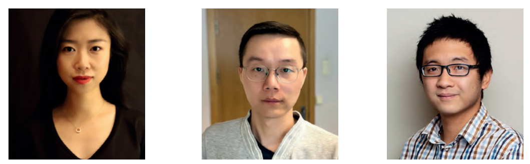

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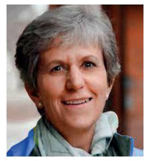
Ursula Gibson
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Department of Physics,
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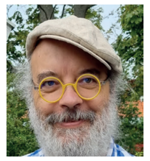
Renaud Toussaint
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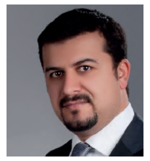
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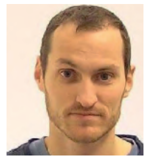
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Steinar Nordal
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NTNU


Astrid de Wijn
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Department of Mechanical
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Anders Lervik
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Department of Chemistry,
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Antje van der Net
Associate Professor,
Department of Geoscience
and Petroleum,
NTNU


Roberto Troncoso
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Department of Mechanical
and Industrial Engineering,
NTNU


François Renard
Professor,
Department of Physics,
UiO

PUBLICATIONS 2023

The following lists journal publications, books, reports, conference lectures and academic presentations generated in 2023

JOURNAL PUBLICATIONS

Aasen, Ailo; Wilhelmsen, Øivind; Hammer, Morten; Reguera, David.
Free energy of critical droplets - From the binodal to the spinodal. *Journal of Chemical Physics* 2023; Volume 158.(11) ENERGISINT NTNU

Angga, I Gusti Agung Gede; Bergmo, Per Eirik Strand; Berg, Carl Fredrik.
Joint well-placement and well-control optimization for energy-efficient water flooding of oil fields. *Geoenergy Science and Engineering* 2023; Volume 230. SINTEF NTNU

Bachelet, V.; Mangeney, A.; Toussaint, Renaud; de Rosny, Rosny; Arran, M.I.; Farin, M.; Hibert, C..
Acoustic Emissions of Nearly Steady and Uniform Granular Flows: A Proxy for Flow Dynamics and Velocity Fluctuations. *Journal of Geophysical Research (JGR): Earth Surface* 2023; Volume 128.(4) UiO

Ben-Zeev, Shahar; Goren, Liran; Toussaint, Renaud; Aharonov, Einat.
Drainage explains soil liquefaction beyond the earthquake near-field. *Nature Communications* 2023; Volume 14.(1) UiO

Berg, Carl Fredrik; Sahimi, Muhammad.
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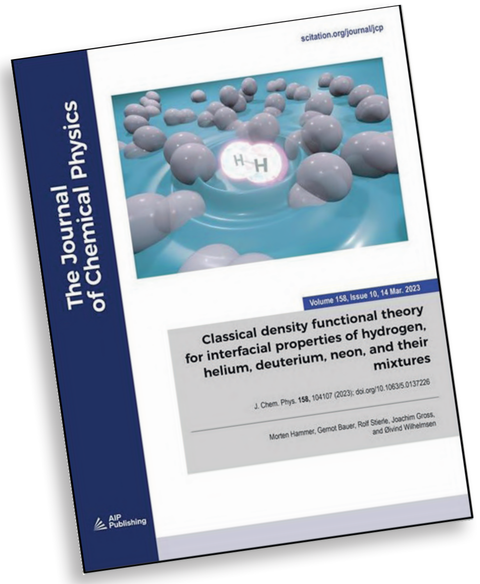

Congratulations to Morten Hammer, Øivind Wilhelmsen and their partners from the University of Stuttgart. Their paper on "Classical density functional theory for interfacial properties of hydrogen, helium, deuterium, neon, and their mixtures" was selected as ***cover*** *for the Journal of Chemical Physics on March 8th, 2023, and promoted as part of a* ***Featured collection****.*

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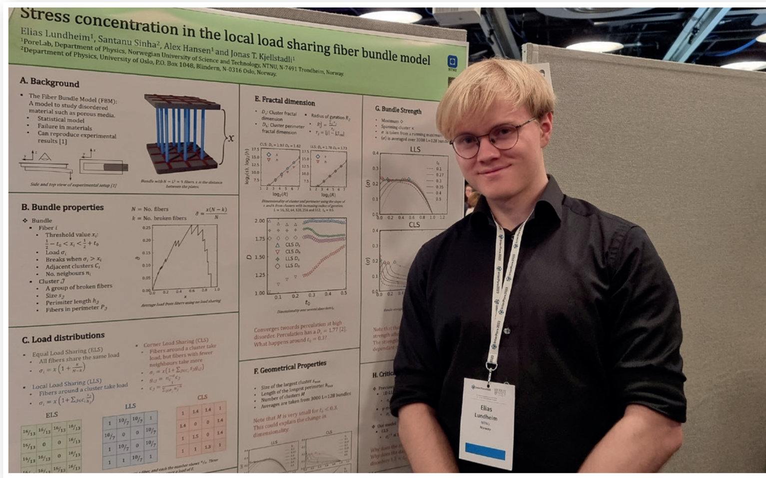

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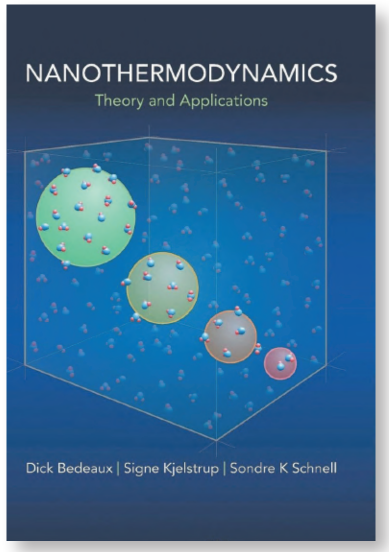
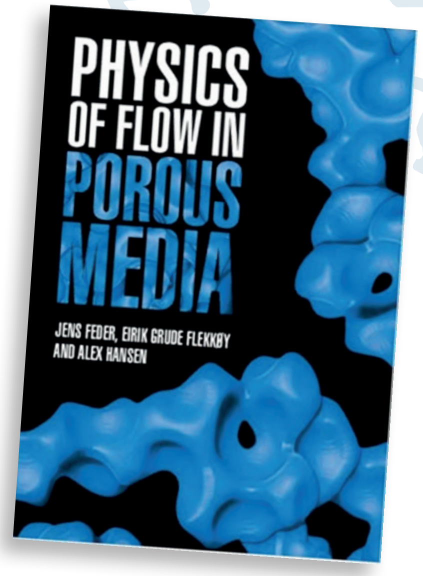


The present book by Bedeaux, Kjelstrup, and Schnell introduces this important subject by expounding Hill's theory in great details. Being leading scientists themselves working on thermodynamics of surface and interface, the authors combined their own expertise with Hill's seminal work into a modernized version of thermodynamics.

— Hong Qian

Olga Jung Wan Professor of Applied Mathematics
University of Washington



The book entitled "Physics of Flow in Porous Media" from Jens Feder, Eirik G. Flekkøy and Alex Hansen published in September 2022, is now being translated into Chinese.

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