19 – 20 March 2026

Symposium in Honor of Professor Alex Hansen's 70th Birthday

Institut Henri Poincaré (IHP)
Sorbonne University
Paris, France

PoreLab
NTNU-UiO Porous Media Laboratory

Norwegian Centre of Excellence

Contents

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ah70-a-scientific-symposium-in-honor-of-the-70th-birthday-of-professor-alex-hansen/

Hansen's Legacy

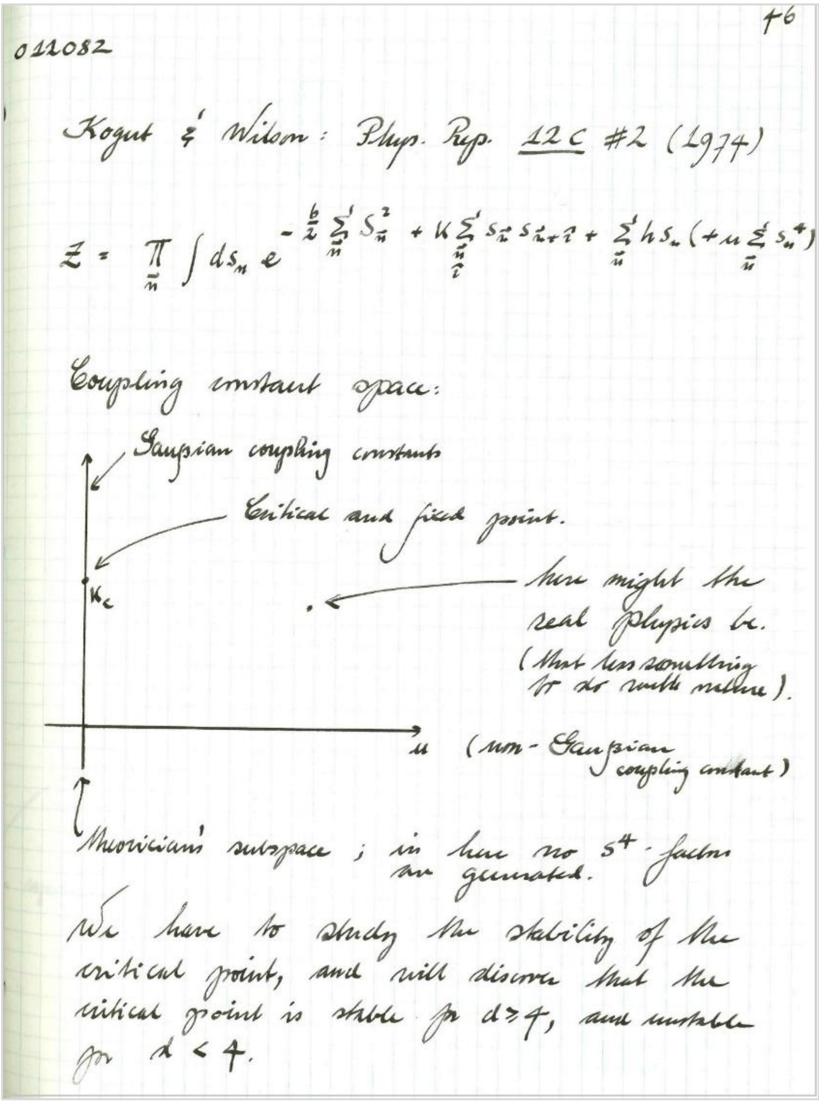
Alex Hansen has been a Professor of Theoretical Physics at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, since 1994. Since 2017, he has served as Director of PoreLab – the Porous Media Laboratory, a Centre of Excellence funded by the Research Council of Norway. PoreLab operates jointly between NTNU and the University of Oslo (porelab.no).

In 2024, Professor Hansen was awarded an ERC Advanced Grant (AGIPORE) from the European Research Council, dedicated to addressing the scaling-up problem in immiscible two-phase flow in porous media.

His research lies at the intersection of statistical mechanics and fluid mechanics.

Professor Hansen is a member of the Norwegian Academy of Science and Letters, the Royal Norwegian Society of Sciences and Letters, and the Norwegian Academy of Technological Sciences. He was awarded an honorary doctorate (Dr. h.c.) by the University of Rennes 1 in 2009, where he also completed his habilitation thesis in 1993.

He has chaired the Commission on Computational Physics and currently serves as Vice President of the International Union of Pure and Applied Physics (IUPAP). Professor Hansen earned his Ph.D. in Physics from Cornell University in 1986.



Page 46 of my lecture notes from Kenneth G. Wilson's course on the renormalization group given at Cornell in the fall of 1982. The lecture is dated October 1, 1982, which was less than ten days before the Swedish Academy announced that he had won the Nobel prize in physics for the renormalization group. – Alex Hansen

Agenda

Thursday, 19 March 2026

8:30	Coffee and light bites
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FLUIDS AND FLOW

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9:50	Permeability of self-affine fractures and the critical barrier concept | Laurent Talon
10:10	Break
10:30	Mixed-wet percolation | Sitangshu B. Santra
10:50	Darcy's law for yield-stress fluids: a disordered systems perspective | Alberto Rosso
11:10	Multiphase porous flow in the dynamic fluid connectivity regime: Non-Darcian flow and accelerated solute dispersion | Joachim Mathiesen
11:30	Two-phase intermittent flow in capillary tubes: some bubbly thoughts | Federico Lanza
11:50	Melting and freezing in porous media | Eirik Grude Flekkøy
12:10	Lunch Break
13:30	Forced convection in two-phase core-annular flows | Paolo Botticini
13:50	Upscaling Multiphase Flow in Porous Media from Pore to Darcy Scale – A Space-Time Averaging Approach | Steffen Berg
14:10	Aging non-Newtonian suspensions for in-situ geobarriers in porous media | Saman Aryana
14:30	Stationary Regimes of Two-Phase Flow in Disordered Porous Media | José Soares de Andrade Junior
14:50	Break
15:30	From Non-linearity to Glassy Phase: Our Studies on Two-Phase Flow in Porous Media | Santanu Sinha
15:50	Disorder-induced non-linear growth of fingers during immiscible two-phase flow in porous media | Yves Méheust
16:10	Evolving porous media and transport at percolation threshold | Carl Fredrik Berg
16:30	Is the lung airway system an efficient transport system? | Marcel Filoche
16:50	Adjourn for the day
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Friday, 20 March 2026

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9:00	Welcome and openings remarks | Eirik G. Flekkøy

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FRACTURING AND BREAKING

9:30	Between Britanny and Norway, Fuse Models and Fracture, Statistical Physics and Geophysics, from Complex to PoreLab: following inspiring paths opened by Alex Hansen and friends | Renaud Toussaint
9:50	Record-Breaking Avalanches in Fiber Bundle Models | Ferenc Kun
10:10	From roughness to toughness: from curiosity-driven research to innovation in mechanical reliability | Laurent Ponson
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STRUCTURES OF CONNECTION

11:10	Marking 8 years of collaboration and dedication | Marie-Laure Olivier
11:30	POROUS MATTER: PoreLab's sci-art adventures in Romania | Marcel Moura
11:50	Alex Hansen, and the explosion of computational physics | Werner Krauth
12:10	Lunch Break
13:10	A Few Applications of Statistical Physics and Mathematics in Musical Analysis | Håkon Pedersen
13:30	Phase Separation and Genetic Resonance in Cell Dynamics | Mogens Høgh Jensen
13:50	Multiple Percolating Clusters | Hans Herrmann
14:10	Break
14:50	Janus Percolation in Anisotropic Limited-Degree Networks | Lucilla de Arcangelis
15:10	Shaping neutral atom beams by grid-based holography | Ingve Simonsen
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Stationary Regimes of Two-Phase Flow in Disordered Porous Media

José Soares de Andrade Junior[1]

[1] Departamento de Física, Universidade Federal do Ceará, Fortaleza, Brazil

Characteristic patterns in stationary two-phase flow of immiscible fluids in porous media emerge from the competition among viscous, capillary, and inertial forces. This interplay, besides setting the flow configurations and the statistics of phase velocity fluctuations, also governs macroscopic properties of the system, such as effective permeability and relative-permeability curves. To elucidate how pore-scale dynamics shape the macroscopic response, we perform direct numerical simulations of two immiscible fluids flowing through a two-dimensional disordered porous medium with periodic boundary conditions in both directions. Here, two-phase flows through the pore space under several different conditions are modeled and solved numerically using a Volume-of-Fluid (VoF) formalism, an adaptation of the Navier–Stokes equations for multiphase flow, as implemented in the Ansys Fluent™ software. We show that three dominant stationary regimes, namely bubble-like, striped, and mixed, delineate stability domains and transitions between patterns in a phase diagram defined by the Capillary number (Ca) and Reynolds number (Re). The results link mesoscopic (pore-scale) mass and momentum conservation to emergent macroscopic transport laws, providing a quantitative framework to characterize regime-dependent permeabilities and flow fluctuations.

Janus Percolation in Anisotropic Limited-Degree Networks

Lucilla de Arcangelis[1]

[1] Department of Mathematics and Physics, University of Campania "Luigi Vanvitelli", Caserta, Italy

Many real-world infrastructures, from sensor and road networks to power grids, are spatially embedded and anisotropic, with constraints on the maximum number of links each node can establish. Such systems can be represented as anisotropic limited-degree networks, in which each node forms at most q outgoing links preferentially oriented along a fixed direction. By increasing the node density at fixed q, we uncover a reentrant percolation transition: a giant strongly connected component emerges but unexpectedly disintegrates again at high densities. This counterintuitive behavior implies that adding nodes, normally expected to enhance robustness, can reduce mutual accessibility and weaken global connectivity.

The critical behavior displays two coexisting "faces": random-percolation scaling along the preferred direction and directed-percolation scaling transversely, therefore we name this phenomenon Janus percolation, in analogy with the dual-faced Roman god.

These findings demonstrate that anisotropy and degree limitation can jointly induce a novel reentrant connectivity with mixed universality that bridges the universality classes of random and directed percolation, providing fresh insight into how structural constraints shape connectivity and resilience in spatial networks.

Aging non-Newtonian suspensions for in-situ geobarriers in porous media

Saman Aryana[1,2]

[1] Department of Chemical & Biomedical Engineering, University of Wyoming, Laramie, WY, USA
[2] PoreLab, Department of Physics, Norwegian University of Science and Technology, Trondheim, Norway

Leakage risk remains a key barrier for large-scale subsurface hydrogen storage. This talk presents aging, non-Newtonian Laponite suspensions as injectable materials that evolve from pumpable fluids into solid-like, pressure-bearing geobarriers within porous media. I will summarize how composition and aging state control injectability and barrier formation, and then highlight pore-network experiments and high-pressure tests demonstrating that appropriately formulated suspensions can form robust barriers with high resistance to hydrogen breakthrough.

Evolving porous media and transport at percolation threshold

Carl Fredrik Berg[1]

[1] PoreLab, Department of Geosciences, Norwegian University of Science and Technology, Trondheim, Norway

Dissolution and precipitation change the pore structure of porous media, e.g., during salt precipitation close to injectors during CO_2 sequestration. In this talk we will present results from recent studies on the transport properties of networks close to the percolation threshold. The first part of the talk will present how the critical exponent that characterize the power-law behavior of conductivity near the percolation threshold can be related to exponents that describe the morphology of percolation clusters. In the second part of the talk, we investigate how these morphological exponents vary under different evolutions towards the percolation threshold. We will consider networks that change according to different sets of rules alluding to different processes of pore space changes, such as clogging or precipitation. Investigating behavior close to the percolation threshold results in a new proof for the bound of the critical exponent for conductivity.

Upscaling Multiphase Flow in Porous Media from Pore to Darcy Scale – A Space-Time Averaging Approach

Steffen Berg [1,2]

[1] Shell Global Solutions International B.V., Amsterdam, The Netherlands
[2] PoreLab, Department of Physics, Norwegian University of Science and Technology, Trondheim, Norway

Porous media are central to human existence in many different aspects, fulfilling key functions in terms of mechanical stability and fluid transport, ranging from food to water to energy and lastly include biological processes in nature and the human body. In many cases that involves the transport of multiple fluid phases (gases, liquids) for instance in applications in geosciences in the subsurface (underground storage of CO_2 and hydrogen, hydrocarbon recovery), but also transport in gas diffusion layers in fuel cells, chemical catalysis, embolism in plants, and in building materials. In these applications fluid transport is typically described at the continuum mechanics level by Darcy's law for single-phase flow and a phenomenological extension to multiphase flow. The latter is a pragmatic engineering approach, the correctness of which is a priori not guaranteed, and which leads to a number of practical and also conceptual problems such as capillary pressure hysteresis.

Significant progress in pore scale imaging and modelling over the past decade has improved our conceptual understanding of fundamental processes in multiphase flow. This has led to the development of new theoretical concepts largely solving some of the biggest unresolved problems. This presentation will take you on a journey from resolving capillary pressure hysteresis considering fluid topology to deriving the 2-phase Darcy equations in the capillary-dominated flow regime using a space-time averaging approach.

More general frameworks are currently being developed. They provide a much deeper understanding and a more holistic framework that will eventually capture all possible flow regimes. As they are deeply rooted in non-equilibrium and statistical thermodynamics, they naturally allow integration of more driving forces such as temperature and concentration gradients which are relevant for energy applications.

Forced convection in two-phase core-annular flows

Paolo Botticini[1]

[1] Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Brescia, Italy

Predicting the temperature distribution in laminar two-phase flows is essential in a wide range of engineering applications, like heat dissipation of electronic equipment and thermal design of biological reactors. Motivated by this, we extend the classical Graetz problem, studying the heat transfer between two flowing phases in a core-annular flow configuration. Using a rigorous two-scale asymptotic analysis, we derived two coupled one-dimensional advection–diffusion heat-transfer equations (one for each phase) embedding the effects of advection, diffusion (both axial and transverse) and viscous dissipation. Specifically, the heat-transfer mechanisms are described through effective velocity and effective diffusion coefficients, while the interaction between the phases is accounted for via ad hoc coupling and source terms, respectively. The dynamics of the problem is controlled by seven dimensionless groups: the Péclet and Brinkman numbers, the heat flux, the viscosity, thermal diffusivity and thermal conductivity ratios, and the volume fraction. Our analysis reveals the existence of two main regimes, depending on the disparity in thermal conductivity between the phases. When the conductivity ratio is of order one, the problem is strongly coupled; otherwise, the phases are thermally decoupled. Interestingly, we investigate the evolution of the heat-transfer coefficient in the thin-film limit, shedding light on the most common assumptions underlying extensively used models in the context of film flows. Finally, we derived closed-form scaling laws for the Nusselt number clarifying the impact of the phases topology on heat-transfer dynamics. Since our model has been derived by first principles, we hope that it will improve the understanding of two-phase forced convection.

[1] P. Botticini, D. Picchi and P. Poesio, *Forced convection in two-phase core-annular flows,* Journal of Fluid Mechanics, 1011 (2025).
DOI: https://doi.org/10.1017/jfm.2025.360

Unveiling Dynamics in Porous Media Through 4D Imaging

Dag Werner Breiby[1]

[1] Department of Physics, Norwegian University of Science and Technology, Trondheim, Norway

Modern X-ray tomography has transformed the field of porous media research by revealing the internal structure of opaque materials in unprecedented detail. I will present recent experimental advances in 4D imaging that expose the dynamic interplay between structure, multiphase flow, and phase transitions at the pore scale.

Is the lung airway system an efficient transport system?

Marcel Filoche[1]

[1] Institut Langevin, École Supérieure de Physique et Chimie Industrielles (ESPCI), Université PSL, CNRS, Paris, France

The lung airway system can be viewed as a highly hierarchical network of interconnected conduits organized in a branching, tree-like architecture. Although it shares several features with porous media, its specific scaling laws and asymmetric branching geometry endow it with distinctive transport properties for gases, fluids, and suspended particles across a wide range of length and time scales. In this talk, we present an overview of these transport mechanisms, with particular emphasis on the coupling between airway geometry, flow regimes, and transport efficiency. We show how this multiscale organization confers remarkable robustness and redundancy to pulmonary gas exchange under physiological variability. At the same time, these same structural and dynamical features pose substantial challenges for the accurate diagnosis of lung diseases and for the targeted delivery of therapeutic agents.

Melting and freezing in porous media

Eirik Grude Flekkøy[1]

[1] PoreLab, Department of Physics, University of Oslo, Oslo, Norway

Water in small (nanometer sized) pores have a freezing point that may be depressed by several 10's of degrees K. This is due to the Gibbs-Thomson effect, which predicts a freezing point that decreases with decreasing pore size. This implies that a heat front propagating through a frozen porous medium with a range of pore sizes, will only melt a subset of the pores as thermal energy bypasses the other pores. Such melting fronts thus become significantly more smeared out than in a medium with constant or large pore sizes. Quantitatively, such fronts are described as a superdiffusive process (the diffusion exponent is >1/2), and, in some cases, even as hyperballistic spreading process (the diffusion exponent is >1).
Moreover, freezing and melting cycles may exhibit significant hysteresis effects as the free energy associated with the ice-water interface creates nucleation barriers. The most significant aspect of this is the possibility of forming solid ice that is superheated relative to the depressed freezing point.

Klein's paradox and its resolution

Alex Hansen[1]

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The Klein paradox concerns what happens if a particle is scattered by a very strong electric field. If this field is strong enough, the reflection coefficient apparently grows larger than unity [1]. This was first pointed out by Klein in a 1929 paper [2]. The paradox has been lingering on for almost 100 years now, with a surge of interest over the last 20 years due to the paradox appearing under certain circumstances in graphene [3].

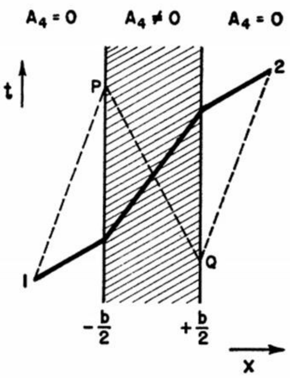

FIG. 1. If two points 1, 2 are separated by a high potential barrier, there are two paths which make action an extremum. One (solid line) represents passage of a fast electron. The other (dotted line) has a section reversed in time and is interpreted as the effective penetration of the barrier by a slow electron by means of a pair production at Q and annihilation at P, section PQ representing the motion of the positron.

My first paper "Klein's paradox and its resolution" [4] was built on an obscure remark in one of Feynman's papers [5]. He considers a *classical* particle that hits a box potential, and he shows that if the potential is high enough, there is a classical solution where the particle gets through the potential. But the particle will inside the potential move *backwards* in time, see Figure 1, copied from Reference [5]. My Cand. Real. (= MSc) advisor, Finn Ravndal, had the feeling that this observation could clarify the Klein paradox. And indeed, it did. Finn then proceeded to work out the field theoretical implications.

I will sketch the contents of this paper together with a number of unpublished results including a renormalization group procedure to calculate the reflection and transmission coefficients for more complicated barriers than just steps and boxes.

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[1] N. Dombey and A. Calogeracos, *Seventy years of the Klein paradox*, Physics Reports, 315, 41 (1999).
[2] O. Klein, *Die Reflexion von Elektronen an einem Potentialsprung nach der relativistischen Dynamik von Dirac*, Zeitschrift für Physik, **53**, 157 (1929).
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[5] R. P. Feynman, *A relativistic cut-off for classical electrodynamics*, Phys. Rev. **74**, 939 (1948).

Multiple Percolating Clusters

Hans Herrmann[1,2]

[1] Departamento de Física, Universidade Federal do Ceará, Fortaleza, Brazil
[2] Laboratoire Physique et Mécanique des Milieux Hétérogènes (PMMH), École Supérieure de Physique et de Chimie Industrielles de la ville de Paris (ESPCI), Paris, France

Inspired by the formation of bigels, we developed a bond percolation model that yields multiple percolating clusters in three dimensions not only at the critical point, but also above it. Our simulations suggest that, in the thermodynamic limit, there is no upper limit to the number of percolating clusters. We show that in finite systems the maximum number of percolating clusters that can be obtained grows logarithmically with the lattice size. For equal initial densities in the thermodynamic limit, all clusters percolate at the same threshold and exhibit critical exponents consistent with the critical exponents of standard percolation. The threshold depends linearly on the initial density of species and the maximum and minimum initial densities decay exponentially with the maximal number of spanning clusters. We also study a percolation model in which we occupy bonds randomly and each time a spanning cluster appears we remove it. The maximum number n_max of spanning clusters one can harvest in this way grows with the system size like a power-law with exponent d-d_f. Also, the variance of n_max and the size distribution of the remaining finite clusters grow like power-laws.

Phase Separation and Genetic Resonance in Cell Dynamics

Mogens Høgh Jensen[1]

[1] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

When cells are damaged or stressed, they often respond by oscillating protein densities. We show that liquid-liquid phase separations lead to condensates of repair proteins around damage sites which occur in an oscillating fashion thus preventing Oswald ripening. The period of oscillations provides an optimal time scale for the repair mechanism [1]. By applying an external periodic protein signal, the internal oscillation can lock to the external signal and thus controls the genes [2]. The locking occurs when the ratio between the two frequencies is a rational number leading to Arnold tongues. If tongues overlap, chaotic dynamics may appear [2]. When the cells are not stressed and again applying an external periodic protein signal, we obtain non-linear resonance phenomena in the genetic response [3]. The findings are supported by experimental data from our collaborative groups at Harvard Medical School and Taipei.

[1] M.S. Heltberg, A. Lucchetti, F.-S. Hsieh, D.P.M. Nguyen, S.-h.Chen and Mogens H. Jensen, "Enhanced DNA repair through droplet formation and p53 oscillations", *Cell* 185, 4394–4408 (2022).

[2] A. Jimenez, A. Lucchetti, M.S. Heltberg, L. Moretto, C. Sanchez, A. Jambhekar, G. Lahav and M.H. Jensen, "Entrainment and multi-stability of the p53 oscillator in human cells", *Cell Systems* 15, 956-968 (2024).

[3] M.S. Heltberg, A. Jimenez, G. Lahav and M.H. Jensen, "Genetic Resonance in the p53 Signaling Network", *Cell Systems* March (2026).

Alex Hansen, and the explosion of computational physics

Werner Krauth[1,2]

[1] Laboratoire de Physique, École Normale Supérieure, Paris, France
[2] Department of Physics, University of Oxford, Oxford, UK

I discuss an explosion of work and lasting influence of Alex Hansen in computational physics, including long-lived influences of K. G. Wilson onto both of us, from accelerated Markov-chain sampling to the renormalization group, and leading up to very recent work.

Record-Breaking Avalanches in Fiber Bundle Models

Ferenc Kun[1]

[1] Department of Theoretical Physics, University of Debrecen, Debrecen, Hungary

Fiber bundle models have long served as a paradigmatic framework for exploring the statistical and dynamical properties of fracture processes in heterogeneous materials. One of the most important outcomes of this line of research - pioneered and significantly advanced by Alex Hansen - is the identification of precursory features that may act as signatures of impending catastrophic failure in loaded systems. Here we focus on record-breaking fracture avalanches in a fiber bundle model, defined as cracking events whose size exceeds that of all previous avalanches. We demonstrate that the statistics and temporal evolution of these extreme events provide a promising predictive tool. In particular, the record avalanche with the longest lifetime emerges as a clear indicator of the transition to an accelerated damage regime preceding global failure. These results suggest that record-based observables capture essential aspects of the approach to failure and may offer a robust way to characterize critical dynamics in fracture processes.

Two-phase intermittent flow in capillary tubes: some bubbly thoughts

Federico Lanza[1]

[1] PoreLab, Department of Physics, University of Oslo, Oslo, Norway

Bubbles and droplets motion in capillary tubes is commonly employed as a simplified model for studying two-phase transport at the pore scale. While this geometry is a strong idealization of real porous media, it nonetheless provides useful insight into the underlying hydrodynamic mechanisms. In my talk, I will provide a review of two related works I've been involved, directly and indirectly, with Alex. First, an analytical work on two-phase non-Newtonian system consisting droplets of yield stress fluid is presented. Second, an experiment of bubble trains in a straight tube is discussed, aimed at testing some predictions of a recent theoretical work.

Multiphase porous flow in the dynamic fluid connectivity regime: Non-Darcian flow and accelerated solute dispersion

Joachim Mathiesen[1,2]

[1] Niels Bohr Institute, University of Copenhagen, Denmark
[2] NJORD Centre for Studies of the Physics of the Earth, University of Oslo, Oslo, Norway

My many discussions with Alex have always been an inspiration, particularly my discussions on the complex behavior of multiphase flow. Interactions between fluid flow and capillary forces create continuously evolving flow pathways, yet their impact on solute dispersion remains poorly understood. From numerics, we show that the repeated opening and closing of flow paths significantly enhances solute spreading compared to single-phase flow. We quantify this behavior by linking the dispersion coefficient to the Bond number, which captures the balance between driving forces and surface tension. These results identify key controls on solute dispersion and provide new insight into transport processes in porous geological systems.

Disorder-induced non-linear growth of fingers during immiscible two-phase flow in porous media

Yves Meheust[1]

[1] Geosciences Rennes, University of Rennes, CNRS, France

Immiscible two-phase flow in porous media produces different types of patterns depending on the capillary number *Ca* and viscosity ratio *M*. At high *Ca*, viscous instability of the fluid–fluid interface occurs when the displaced fluid is the more viscous, and leads to viscous fingering, which is believed to exhibit the same growth behavior as the viscously-unstable fingers observed in Hele–Shaw cells by Saffman and Taylor in their similar study [1], or as diffusion-limited aggregates (DLA). In such Laplacian growth processes, the interface velocity depends linearly on the local gradient of the physical field that drives the growth process (for two-phase flow, the pressure field). However, a non-linear power-law dependence between the flow rate and the global pressure drop, reminiscent of what has also been observed for steady-state two-phase flow in porous media, was evidenced experimentally for the growth of viscously-unstable drainage fingers in two-dimensional porous media, 20 years ago [2,3]. More recently we revisited this flow regime using dynamic pore-network modeling, and explored the non-linearity in the growth properties. We characterized the previously unstudied dependencies of the statistical finger width and non-linear growth law's exponent on Ca [2], and discussed quantitatively, based on theoretical arguments, how disorder in the capillary barriers controls the growth process' non-linearity [2], and why the flow regime crosses over to Laplacian growth at sufficiently high Ca. In addition, the statistical properties of the fingering patterns were compared to those of Saffman–Taylor fingers, DLA growth patterns, and the results from the aforementioned previous experimental study.

<u>References</u>

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POROUS MATTER: PoreLab's sci-art adventures in Romania

Marcel Moura[1]

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

In this talk I will show how Alex's attention to an unconventional message in his mailbox led to a very interesting scientific and artistic collaboration between Norway and Romania. This is the story of the project "POROUS MATTER: Void fractions in materials, ideas and society", a collaboration between the META Spațiu contemporary art gallery and the Polytechnic University of Timisoara (both in Romania) and PoreLab in Norway.

Marking 8 years of collaboration and dedication

Marie-Laure Olivier[1]

[1] PoreLab, Department of Physics, Norwegian University of Science and Technology, Trondheim, Norway

PoreLab, short for "Porous Media Laboratory", has flourished over the past eight years under the Center of Excellence (CoE) scheme, funded by the Research Council of Norway (RCN), the Norwegian University of Science and Technology (NTNU), and the University of Oslo (UiO).

In this presentation, I will provide an overview of PoreLab's mission, organizational structure, management, and its key achievements in terms of publications, collaborations, networking, staffing strategy, and the development of new projects supported by additional funding.

PoreLab can justly take pride in its accomplishments, but what a journey it has been! I will revisit the main challenges that Alex and the leadership team had to overcome to bring us to the strong position we occupy today. I will also share insights from my own experience of this journey.

A Few Applications of Statistical Physics and Mathematics in Musical Analysis

Håkon Pedersen[1]

[1] SINTEF Energy AS, Trondheim, Norway

Mathematics and physics have always inspired the arts and vice versa. It is well known among both physicists, mathematicians, and musical analysts that mathematical structure and physics lend themselves very well to describing a number of aspects of music like harmony, pitch, timbre, rhythm, and form.

Physical descriptions based on wave mechanics have often been applied in explaining sound characteristics of different instruments and harmony, while both abstract algebra, category theory, and geometry have seen applications in analysis of musical structure and functional analysis (the one based on notes, not on functionals). A classical example of this is given by Leonhard Euler himself and his description of the *tonne*tz-lattice at the beginning of the 17th century, while the orbifold structure of musical chords is an example of a more recent discovery.

In the last century, researchers in the field have often found it useful to model music as a stream of information. This has turned out to be a fruitful endeavor, as it has opened the doors for using information theory, signal analysis, and statistical inference in musical analysis. Examples include the emergence of twelve-tone equal temperament from a simple "Bayesian" statistical mechanics model based on the Shannon entropy, and the usage of Fisher information in separating music from noise. In this talk, I will present some historical background of mathematical modelling in music, applications of statistical physics, and a short outlook on the field.

It is worth remarking that the purpose of this research, or this talk for that matter, is not simply to "dissect the proverbial frog" that is music itself to make it fit for further mass production, automation, and consumption (which has been a fear of music theorists in particular). One could instead find comfort in the fascinating fact that something as integral to human society and culture as music, with a deep complexity in its structure historically borne from artistic expression, allows itself to be so readily described in the language of math and physics.

From roughness to toughness: from curiosity-driven research to innovation in mechanical reliability

Laurent Ponson[1,2]

[1] Institut Jean le Rond d'Alembert, CNRS - Sorbonne Université, Paris, France
[2] Tortoise, Paris, France

The study of the scaling properties of fracture surfaces has been a long scientific journey pioneered by Pr Alex Hansen and coworkers in the 90's. In this presentation, I will tell the on-going journey of an engineering technique that is the fruit of this line of research: statistical fractography, a multi-material engineering technique, halfway between data science and fracture mechanics, that provides the fracture properties of materials from the analysis of their fracture surfaces.

I will discuss through industrial examples the application of this technique to the determination of the root causes of the failure of components in the energy and the transport sector. I will also discuss its application to material characterization, as it provides a new route for measuring the crack growth resistance of materials, without having to resort to standard destructive tests. Applied to millimetric fractured specimens, it constitutes a helpful technique to assess the mechanical health of in-service components through mechanical biopsy, a methodology that is now used at a large scale to ensure the mechanical integrity of the French railway network or the penstocks of the Alpes and the Pyrenees.

Finally, I will discuss how this technique is now closing the loop to help scientists in their quest to understand how materials break, as it is now used to reveal the fundamental mechanisms governing the crack growth resistance of solids, from which stronger and more durable materials might emerge in the future.

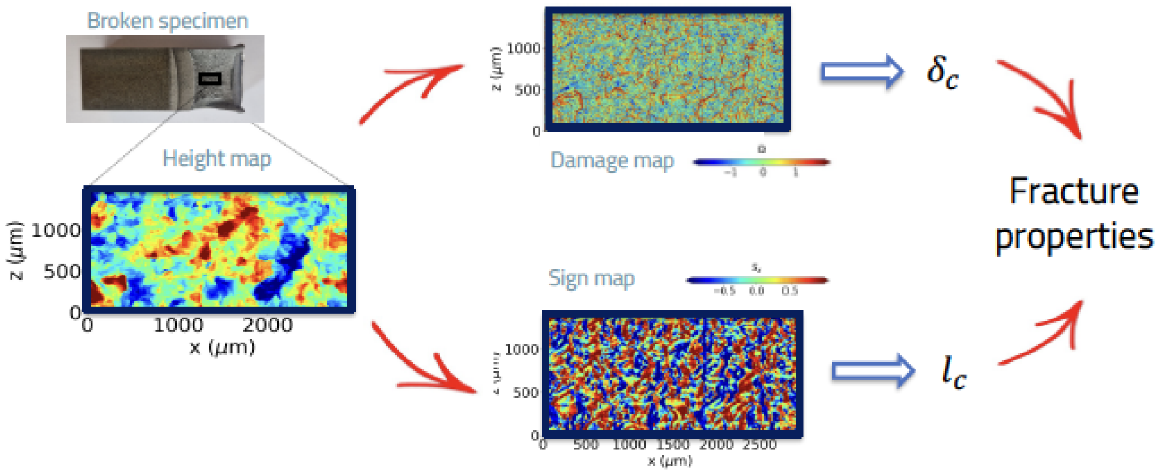

Figure. *The fracture properties of materials can be inferred from the statistical analysis of fracture surfaces without having to resort to destructive mechanical tests, using an approach that results from academic research pioneered by Pr. Alex Hansen on the scale invariance of the roughness of cracks.*

Darcy's law for yield-stress fluids: a disordered systems perspective

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The flow of yield-stress fluids through porous media is a problem of major importance in fluid dynamics and geophysics. While Darcy's law provides a simple and robust description for Newtonian fluids, its extension to yield-stress fluids is far from straightforward. In this case, the onset of flow depends on a complex interplay between the fluid's constitutive law and the heterogeneity of the pore space. I will show how this seemingly classical hydrodynamic problem can be reformulated as an exceptionally challenging problem in the physics of disordered systems.

Mixed-wet percolation

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Inspired by the two-phase flow of immiscible fluids in a mixed-wet porous medium, the mixed-wet percolation (MWP) model is developed. To develop the model, both the primal and its dual lattices are considered. The sites of the primal lattice are occupied with probability p and remain unoccupied with probability $1 - p$. The occupied and unoccupied sites represent grains of different wettability. The links of the dual lattice, appearing between two adjacent occupied-unoccupied sites of the primal lattice, are occupied by bonds. We study the properties of bond clusters composed of perimeter loops via knots in the dual lattice of the square, triangular and honeycomb lattices. The MWP is symmetric about $p = 1/2$, as for $p \ll 1/2$ perimeter loops appear around the occupied sites, and for $p \gg 1/2$ they appear around the unoccupied sites. Thus, two critical thresholds are expected to occur at p_c and $1 - p_c$. The spanning of perimeter bond clusters is checked on the dual lattices. For the dual square lattice (DSL), the critical thresholds are $p_c = 0.40725$ and $1 - p_c = 0.59275$, and for the dual triangular lattice (DTL), they are $p_c = 0.30295$ and $1 - p_c = 0.69705$, whereas for the dual honeycomb lattice (DHL), both appear at $p_c = 1 - p_c = 1/2$. The bond clusters are determined by employing a burning algorithm on the dual lattice. Cluster properties are studied around one of the thresholds. The critical exponents of MWP on DSL and DTL are found to be identical to those of ordinary percolation (OP), whereas on DHL, they are identical to those of the percolation hull [1, 2]. Since the bond clusters on the dual lattice are composed of perimeter loops, the MWP is expected to be in the universality class of the hull percolation, as in the case of DHL. However, MWP on DSL and DTL belongs to ordinary percolation. The perimeter bond clusters on these lattices bear the properties of percolation clusters, as the bond clusters have the same morphology as the percolation clusters. More interestingly, the clusters defined by the knots on DSL and DTL also exhibit percolation [3].

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Shaping neutral atom beams by grid-based holography

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Photo lithography is the default method for the production of integrated circuits in the semiconductor industry. Here incident light is shaped by optical elements to form a pattern that is projected onto photoresist that, after development, will display the wanted pattern. However, this method is starting to face a roadblock whenever decreasing structures are being fabricated. This is due to the increasing energy of low-wavelength photons used and the resulting ionization of the photo-resist. An alternative method is to use atom lithography since an atom beam has significantly less energy than light for the same wavelength. In this talk, a method for shaping an atom beam will be presented which is one of the critical steps for making atom lithography a reality. The method is centered around grid-based holography. Based on wave theory, we present the working principle of the method and discuss some of the features of the patterns that it can produce.

From Non-linearity to Glassy Phase: Our Studies on Two-Phase Flow in Porous Media

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Multiphase flow in porous media spans a wide spectrum of natural processes and industrial applications. Its behavior often deviates from the linear Darcy law, exhibiting distinct flow regimes that depend on key parameters such as capillary number and viscosity ratio. Over the past sixteen years, I have had the opportunity to work closely with Professor Alex Hansen on foundational aspects of porous media flow, particularly on upscaling, theoretical frameworks, and computational modeling.

This talk will provide an overview of our past and ongoing investigations. Key themes will include the emergence of power-law nonlinearities in flow rates observed in both viscous fingering and steady-state flow, the influence of fluid compressibility, the development of pore-network models, and our recent exploration of a glassy dynamical phase in two-phase flow systems.

Permeability of self-affine fractures and the critical barrier concept

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In many low-permeability geological formations, fluid flow occurs primarily through fracture networks. Reliable modeling of the hydromechanical behavior of such fractures is therefore essential. Here, we focus on fractures with self-affine correlations, for which most existing models fail to accurately predict effective permeability once contact areas are present.

We introduce a model based on a generalized bottleneck concept, enabling the prediction of permeability in self-affine rough channels (1D fractures) and 2D fractures across the full range of possible apertures. In 1D rough fractures, as the two walls come into contact, permeability becomes increasingly controlled by the region of minimum aperture—the classic bottleneck effect. In 2D fractures, however, the position of the minimum aperture is less critical, as flow can easily bypass low-permeability regions.

To extend this concept, we define the *most restrictive barrier path* as the barrier with the lowest average permeability. Through numerical simulations, we identify three permeability scaling regimes, which we explain by introducing additional critical barriers ranked by their restrictive impact.

Between Britanny and Norway, Fuse Models and Fracture, Statistical Physics and Geophysics, from Complex to PoreLab: following inspiring paths opened by Alex Hansen and friends

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Understanding fracture in disordered media is a scientific challenge with many consequences in human-built materials and in natural materials such as rocks. An important question is to examine how microcracks and defects interact mechanically, and can lead to distributed diffuse damage, abrupt failure propagating from neighbor to neighbor, or collective progressive localization.
Scrutinizing how complexity emerges from simple models of simple interacting elements, with a salt of controlled disorder, is a fruitful method inspired by Alex essential works on the topic. A few examples will be explored, with works carried out in French Brittany or in Norway. Some of these examples were carried out together with Alex. These interactions along the way took place in very stimulating and inspiring collaborating environments emerging as Complex and PoreLab.

Extrapolating into no man's land of a fluids phase diagram

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Fluids in porous media and confined spaces are central to PoreLab. They often reside in metastable states that are difficult to access using traditional experiments. In addition, fluid phase diagrams contain regions where the fluid is thermodynamically unstable, yet such states are essential for describing interfacial phenomena. However, even the most accurate equations of state yield non-physical predictions in these unstable regions.

In this presentation, we show that information from stable states, combined with a simple extrapolation strategy, can be used to reconstruct the full thermodynamic behavior of fluids in both metastable and unstable regions of the phase diagram. The approach is critically examined by comparing to results from molecular simulations. Furthermore, we demonstrate the feasibility and accuracy of the method by accurately reproducing surface tensions for a range of real fluids, including water, CO_2, and ammonia.

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