Rainer Helmig - From multi-physics, multi-scale modelling and model reduction, via risk assessment and robust design towards the science/policy interface

The characterization and selection of suitable sites for the storage of CO_2 or green gases is becoming increasingly important in the necessary energy transition. On the one hand, the most suitable sites have to be identified by experts, on the other hand, the problem of public acceptance will have to be solved for each individual site. Therefore, both aspects -best site and public acceptance- in an integrated approach of natural/engineering sciences with social sciences should be the appropriate solution approach. In this context, participatory modeling represents a method that incorporates the concerns of various expert groups, industry, and other stakeholders to investigate risks. The central aspect of participatory modeling is disclosure of the modeling process to non-experts. A participatory modeling approach makes it possible to translate scientific and technical results and how they are arrived at into the policy and management process.
I would like to report on my experiences as a participant in the "Fracking Round table", as a consultant in the development of nuclear repositories in Switzerland as well as from CCS projects and discuss with you what is needed in the field of education to communicate complex scientific results to a broad public in a transparent and credible way. The question is, what is and how we get a good **science/policy interface?**

Lars Ottemöller - Intraplate earthquake swarms: Nature and causes

Earthquake swarms are observed in various tectonic environments such as plate boundaries and volcanoes, and are often associated with migration of fluids. However, they also occur in intraplate areas that are located away from plate boundaries and tectonically less active. This presentation will focus on earthquake swarm activity in three different intraplate regions: New Madrid (USA), Palghar (India) and Nordland (Norway). The examples will be used to demonstrate how seismic monitoring is used to detect and characterize seismic activity. The main physical cause for earthquakes is tectonic stress, but in these three cases fluids and hydrological load are considered to play a triggering role, evidence and models for this will be presented.

Jan Martin Nordbotten - The FluidFlower International Forecasting and Validation Study

Validating the security of carbon storage on centurial timescales is inherently challenging, as industrial storage operations are only a few decades old, and natural analogues contain few transferrable datasets. As such, the accuracy of modeling and simulation capabilities is poorly understood.

To address this shortcoming, we constructed a room-scale model (with spatial dimensions of about 1:1000 relative to field scale) of a carbon storage project, including representative geological complexity. At this scale, the active period of CO_2 storage is in the order of hours, while the long-term dynamics happen within days. By defining the experiment as ground truth, we were able to conduct an international double-blind forecasting and validation study, with the participation of leading international academic research groups.

This talk firstly presents the experimental results, including the development of new algorithms for image analysis of flow and transport in porous media. Thereafter, we summarize the numerical modeling conducted by the international participants. Finally, we detail qualitative and quantitative analysis both of forecasted spatial maps, as well as pre-defined metrics determining efficacy and security of carbon storage. This allows us to provide an assessment both of the validity of numerical simulation software for modeling carbon storage, as well as the forecasting capabilities of the carbon storage community.

Eirik Keilegavlen – Crash course in PorePy

Fractures and faults play an important role in processes in the subsurface. Networks of fractures may provide major conduits for fluid flow which have a dominating effect on the transport of, say, energy or pollutants. Fractures can also form low-permeable barriers that impede transport processes. Moreover, fracture deformation, under a combination of mechanical, hydraulic, and thermal forces, is associated with seismic activity and alteration of fracture flow properties, both of which can have a significant impact on subsurface engineering operations.

The critical role played by fractures in these processes makes it important that numerical simulation models adequately resolve the interaction between fractures. The simulation tool PorePy (https://github.com/pmgbergen/porepy/), written in Python and developed and maintained at the Department of Mathematics, University of Bergen, explicitly targets multiphysics processes in fractured porous media. In PorePy, fractures are explicitly represented in the simulation models and resolved by the computational grid. This gives high resolution in the representation of processes within fractures and thus enables the study of the, often complex, interaction between multiphysics processes and fractures and fracture networks.

In this short course, we will give a brief introduction to the main features of PorePy and their usage. We will cover mesh construction, modeling of processes by combining conservation principles and constitutive relations, and simulations. The focus will be on simulation of fluid flow and transport, where we will cover how to set up a model, define parameters for rock and fractures, and how to run simulations and visualize results. If time permits, we may also touch upon mechanical deformation of fractures and the surrounding rock mass. The course will be based on short introductory presentations followed by exercises that illustrate the usage of PorePy.

The course will assume basic familiarity with mathematical models for subsurface processes (e.g., Darcy's law, conservation principles) but requires little experience in numerical modeling. The course material will contain code examples that should be sufficient to complete the exercises but having basic experience in programming (ideally in Python, but other languages will also be helpful) will still be an advantage.

The course material will be in the form of Jupyter notebooks that run in a Docker container. Since we will not have the time or manpower to provide installation support during the course, it is a prerequisite that all participants prior to the course have installed Docker Desktop and downloaded a Docker image (link to be provided) which contains the course material.

Jakub Both & Martin Fernø - Experiments involving flow in fractured medium: Interface between modelling and experiments

The existence of fractures in porous media has a strong impact on the characteristics of the flow behavior. In geological rocks, fractures occur both naturally as well as intentionally induced as in geothermal applications. Thus, accurate modeling and simulation of flow and transport in fractured media is vital for many industrial applications.

This talk discusses important flow phenomena for studies of multiphase flow in fractured porous media, illustrated by physical data. Next, mixed-dimensional models are discussed in the context of modeling flow in fractured media. The high aspect ratio of the fracture width as compared to their remaining dimensions allows for representing them as lower-dimensional manifolds. By combining mass conservation and Darcy's law on each subdomain and mass transfer between domains, underlying equidimensional models can be conveniently replaced. Yet, despite the large interest in mixed-dimensional models for flow in fractured media, direct comparisons to high-quality lab experiments have been missing.

Jakub Both - Iterative solvers: how to solve coupled PDEs with a link to applications

Multiphysics problems, described as systems of partial differential equations (PDEs), with strong couplings arise in various disciplines. Prominent examples are coupled flow and transport or flow and deformation in porous media. Since the development of tailored solver strategies for single-physics problems has seen great developments, partitioned approaches appear as attractive strategies, merely successively solving the smaller subproblems to eventually solve the overall coupled problem.

In this lecture, we will discuss possibilities to use partitioned schemes to solve such coupled PDEs, using flow in deformable porous media as our prime example. We focus on the concept of a problem's coupling strength; how to utilize knowledge about the origin of resulting algebraic systems, i.e., their PDE representation, to devise robust partitioned methods; how to integrate partitioned approaches in nonlinear problems; and how to include a simple but effective idea of preconditioning both for linear and nonlinear problems. Overall, the lecture will equip us with a general workflow useful for various coupled problems.

Volker Oye - Monitoring of Induced Seismicity

Induced seismicity is commonly associated with observations of earthquakes that occur in some relation to human activities changing locally the stress field of the earth. This is often observed in mining operations, oil and gas production, hydraulic fracturing for shale gas or enhanced geothermal systems, load changes at dams and also injection of large fluids like production waters or large-scale geological CO_2 storage. Most of the time, the size or magnitude of the induced seismicity is limited to being below about magnitude 2, and as such not felt at all by the population. However, in a few cases, very large earthquakes have been induced, like e.g. at three events at Gazli (all M7, Uzbekistan), Wilmington (M6.3, USA), Lacq (M4.2, France) and Ekofisk (M4.1, Norway) hydrocarbon fields, or after the first filling of the Koyna water reservoir in India (M 6.6).

In this lecture we will learn about a few examples of large earthquakes that were induced by human activity, and we will go through the relation between the build-up of stress fields that ultimately lead towards failure of the rock. As analogue, we will learn about laboratory-scale acoustic emission experiments and the characterization of different types of seismicity. This knowledge can then be transferred to better understand induced seismicity during hydraulic stimulation projects and large-scale gas storage projects. We will show two examples, one from an enhanced geothermal system where new fractures are generated due to high fluid pressure injection, and another example from industrial-scale CO2 storage operations, with low injection pressures (far below fracture pressure). The methods to detect, locate and characterize seismicity are scale-independent and can in principle be applied equally well at lab-scale as at field scale. Successful monitoring of induced seismicity will assist in safe subsurface energy management, including storage of hydrogen and CO2.

Sarah Gasda - Modeling and simulation approaches for offshore CO2 storage

The Norwegian continental shelf is quickly becoming one of the most attractive targets for commercial-scale CO2 storage of European emissions. Several large regional aquifers in the Norwegian North Sea have substantial theoretical storage potential, enough for massive scale-up of storage operations to meet expected demand from Europe. Development of new storage sites will likely be connected by common infrastructure, requiring careful assessment of injectivity and capacity of large, interconnected regions. Important risks include anomalous migration, poor trapping efficiency, fault leakage, and pressure interference. Simulation technology needs to tackle multiscale coupled processes at very large scales within substantial geologic uncertainty. These requirements put pressure on simulators to be fast and scalable, while still resolving the salient processes with reasonable accuracy.