Final Program

SIAM Conference on
Mathematical & Computational Issues in the Geosciences

March 11 – March 14, 2019
Houston Marriott Westchase
Houston, Texas, U.S.

Sponsored by the SIAM Activity Group on Geosciences

SIAM Activity Group on Geosciences provides an interactive environment wherein modelers concerned with problems of the geosciences can share their problems with algorithm developers, applied mathematicians, numerical analysts, and other scientists. Topics of interest include flow in porous media, multiphase flows, phase separation, wave propagation, combustion, channel flows, global and regional climate modeling, reactive flows, sedimentation and diagenesis, and rock fracturing.

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https://www.siam.org/conferences/CM/Main/GS19

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Conference Themes

Mathematical Models in the Geosciences

Atmospheric modeling: Meteorology, Urban climate

Biosphere modeling

Cryosphere and hydrosphere modeling: Glaciology, Hydrology and limnology, Oceanography, Sea ice and ice cap

Lithosphere and pedosphere modeling: Geochemistry, Geology and geophysics, Plate tectonics and earth dynamics, Soil science, Volcanoes and earthquakes

Climate: Climate system, Paleoclimate, Climate change

Energy resource modeling: Carbon sequestration, Geothermal energy, Hydrogen or compressed air storage, Methane hydrates, Nuclear waste disposal, Oil exploration and improved oil recovery, Shale gas and oil, Solar and wind energy, Thermo-chemical storage

Mathematical Methods

Mathematical modeling: Fundamental modeling and scale transitions, Advanced theories and non-standard models, Flow, reactions, transport and mechanical effects in complex media

Computational and mathematical methods: Algorithms and discretization methods, Solution methods for coupled systems, Error analysis and estimation, Linear and nonlinear solvers, Multiscale, upscaling, and model-reduction methods, Mathematical analysis methods, Optimization methods, Stochastic methods, Machine Learning, High-performance computing

Model data and parameters: Data assimilation, Data classification, big data, Model uncertainty, Model calibration, inverse problems, uncertainty reduction, Validation and verification, Design of experiments

SIAM Registration Desk

The SIAM registration desk is located in Westchase 3/4. It is open during the following hours

Sunday, March 10
5:00 p.m. - 8:00 p.m.

Monday, March 11
7:15 a.m. - 5:15 p.m.

Tuesday, March 12
8:00 a.m. - 5:15 p.m.

Wednesday, March 13
8:00 a.m. - 5:15 p.m.

Thursday, March 14
8:00 a.m. - 3:00 p.m.

Hotel Address

Houston Marriott Westchase
2900 Briarpark Drive
Houston, TX 77042, U.S.

Hotel Telephone Number

To reach an attendee or leave a message, call +1-713-978-7400. If the attendee is a hotel guest, the hotel operator can connect you with the attendee's room.

Hotel Check-in and Check-out Times

Check-in time is 3:00 p.m.
Check-out time is 12:00 p.m.

Child Care

Visit *www.care.com* for information on child care services. Care.com provides a web-based resource to connect individuals with vetted babysitters and nannies. Attendees are responsible for making their own child care arrangements.

Corporate Members and Affiliates

SIAM corporate members provide their employees with knowledge about, access to, and contacts in the applied mathematics and computational sciences community through their membership benefits. Corporate membership is more than just a bundle of tangible products and services; it is an expression of support for SIAM and its programs. SIAM is pleased to acknowledge its corporate members and sponsors. In recognition of their support, non-member attendees who are employed by the following organizations are entitled to the SIAM member registration rate.

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Exxon Mobil
IDA Center for Communications Research, La Jolla
IDA Institute for Defense Analyses, Princeton

IDA Institute for Defense Analyses, Bowie, Maryland

Lawrence Berkeley National Laboratory

Lawrence Livermore National Labs

Lockheed Martin Maritime Systems & Sensors

Los Alamos National Laboratory

Max-Planck-Institute

Mentor Graphics

National Institute of Standards and Technology (NIST)

National Security Agency

Oak Ridge National Laboratory

Sandia National Laboratories

Schlumberger

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U.S. Army Corps of Engineers, Engineer Research and Development Center

List current as of January 2019.

Funding Agencies

SIAM and the Conference Organizing Committee wish to extend their thanks and appreciation to the U.S. National Science Foundation and DOE Office of Advanced Scientific Computing Research for their support of this conference.

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Leading the applied mathematics community . . .

SIAM members save up to $140 on full registration for the 2019 SIAM Conference on Mathematical & Computational Issues in the Geosciences! Join your peers in supporting the premier professional society for applied mathematicians and computational scientists. SIAM members receive subscriptions to *SIAM Review*, *SIAM News* and *SIAM Unwrapped*, and enjoy substantial discounts on SIAM books, journal subscriptions, and conference registrations.

If you are not a SIAM member and paid the *Non-Member* rate to attend, you can apply the difference of $140 between what you paid and what a member paid towards a SIAM membership. Contact SIAM Customer Service for details or join at the conference registration desk.

If you are a SIAM member, it only costs $15 to join the SIAM Activity Group on the Geosciences (SIAG/GS). As a SIAG/GS member, you are eligible for an additional $15 discount on this conference, so if you paid the SIAM member rate to attend the conference, you might be eligible for a free SIAG/GS membership. Check at the registration desk.

Students who paid the *Student Non-Member* Rate will be automatically enrolled as SIAM Student Members. Please go to *my.siam.org* to update your education and contact information in your profile. If you attend a SIAM Academic Member Institution or are part of a SIAM Student Chapter you will be able to renew next year for free.

Join onsite at the registration desk, go to *https://www.siam.org/Membership/Join-SIAM* to join online or download an application form, or contact SIAM Customer Service:

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Standard Audio/Visual Set-Up in Meeting Rooms

SIAM does not provide computers for any speaker. When giving an electronic presentation, speakers must provide their own computers. SIAM is not responsible for the safety and security of speakers' computers.

A data (LCD) projector and screen will be provided in all technical session meeting rooms. The data projectors support both VGA and HDMI connections. Presenters requiring an alternate connection must provide their own adaptor.

Internet Access

The Houston Marriott Westchase offers wireless internet access to hotel guests in the public areas of the hotel at no additional charge. Complimentary wireless internet access in the meeting space and sleeping rooms is also available to SIAM attendees. In addition, a limited number of computers with internet access will be available during registration hours.

Registration Fee Includes

Admission to all technical sessions

Business Meeting (open to SIAG/GS members)

Coffee breaks daily

Room set-ups and audio/visual equipment

Welcome Reception

Poster Sessions

Job Postings

Please check at the SIAM registration desk regarding the availability of job postings or visit *https://jobs.siam.org/*.

Poster Participant Information

The poster sessions will take place during both coffee breaks on Tuesday, March 12. The morning coffee break is scheduled from 9:15 a.m. - 9:45 a.m.; the afternoon coffee break is scheduled from 4:20 p.m. - 4:50 p.m. Poster presenters should set-up their poster material on the 4' x 8' poster boards in Grand Ballroom A after 4:20 p.m. on Monday, March 11. All materials must be posted by 9:15 a.m. on Tuesday, March 12, the official start time of the session. Posters will remain on display through Thursday, March 14. **Posters must be removed by 10:00 a.m. on Thursday, March 14.**

SIAM Books and Journals

SIAM books are available for purchase onsite along with complimentary copies of journals. Titles of particular interest include Fornberg & Flyer: A Primer on Radial Basis Functions with Applications to the Geosciences; Asch: Data Assimilation: Methods, Algorithms, and Applications; and Tenorio: An Introduction to Data Analysis and Uncertainty Quantification for Inverse Problems. All SIAM books are offered at discounted prices. Acquisitions editor Paula Callaghan will be at the booth so please feel free to stop by if you have a book idea you'd like to discuss. The books booth will be staffed from 9:00 a.m. - 5:00 p.m. Monday through Wednesday and 9:00 a.m. - 12:30 p.m. on Thursday.

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A space for emergency contact information is provided on the back of your name badge. Help us help you in the event of an emergency!

Comments?

Comments about SIAM meetings are encouraged! Please send to:

Cynthia Phillips, SIAM Vice President for Programs (vpp@siam.org).

Get-togethers

Sunday, March 10

Welcome Reception

6:00 p.m. - 8:00 p.m.

Grand Foyer

Tuesday, March 12

Poster Sessions

9:15 a.m. - 9:45 a.m. and
4:20 p.m. - 4:50 p.m.

Grand Ballroom D

Business Meeting (open to SIAG/GS members)

Monday, March 11

6:15 p.m. - 7:15 p.m.

Grand Ballroom EFGH

Complimentary beer and wine will be served.

Statement on Inclusiveness

As a professional society, SIAM is committed to providing an inclusive climate that encourages the open expression and exchange of ideas, that is free from all forms of discrimination, harassment, and retaliation, and that is welcoming and comfortable to all members and to those who participate in its activities. In pursuit of that commitment, SIAM is dedicated to the philosophy of equality of opportunity and treatment for all participants regardless of gender, gender identity or expression, sexual orientation, race, color, national or ethnic origin, religion or religious belief, age, marital status, disabilities, veteran status, field of expertise, or any other reason not related to scientific merit. This philosophy extends from SIAM conferences, to its publications, and to its governing structures and bodies. We expect all members of SIAM and participants in SIAM activities to work towards this commitment.

Please Note

SIAM is not responsible for the safety and security of attendees' computers. Do not leave your laptop computers unattended. Please remember to turn off your cell phones, tablets, etc. during sessions.

Recording of Presentations

Audio and video recording of presentations at SIAM meetings is prohibited without the written permission of the presenter and SIAM.

Social Media

SIAM is promoting the use of social media, such as Facebook and Twitter, to enhance scientific discussion at its meetings and enable attendees to connect with each other prior to, during and after conferences. If you are tweeting about a conference, please use the designated hashtag to enable other attendees to keep up with the Twitter conversation and to allow better archiving of our conference discussions. The hashtag for this meeting is #SIAMGS19. SIAM's Twitter handle is @ TheSIAMNews.

Changes to the Printed Program

The printed program was current at the time of printing, however, please review the online program schedule (*http://meetings.siam.org/program.cfm?CONFCODE=GS19*) or use the mobile app for up-to-date information.

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To enhance your conference experience, we're providing a state-of-the-art mobile app to give you important conference information right at your fingertips. With this TripBuilder EventMobile™ app, you can:

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You can also visit *www.tripbuildermedia.com/apps/siamevents*

Invited Plenary Speakers

*** All Invited Plenary Presentations will take place in Grand Ballroom EFGH ***

Monday, March 11

8:30 a.m. - 9:15 a.m.

IP1 Numerical Models for Earthquake Ground Motion

Alfio Quarteroni, *Politecnico di Milano, Italy*

1:20 p.m. - 2:05 p.m.

IP2 Homogenization Approach for Modeling of Reactive Transport in Porous Media

Gregoire Allaire, *Ecole Polytechnique, France*

Tuesday, March 12

1:20 p.m. - 2:05 p.m.

IP3 Challenges in Recovering Deep Low-Wavenumber Updates in Full Waveform Inversion

Anatoly Baumstein, *ExxonMobil Upstream Research Company, U.S.*

Wednesday, March 13

8:30 a.m. - 9:15 a.m.

IP4 Sea Ice Model Complexity

Elizabeth Hunke, *Los Alamos National Laboratory, U.S.*

Thursday, March 14

8:30 a.m. - 9:15 a.m.

IP5 Multicomponent Elastic Imaging: New Insights from the Old Equations

Yunyue Elita Li, *National University of Singapore, Singapore*

1:20 p.m. - 2:05 p.m.

IP6 Learning from Sparse Observations: The Global Ocean State and Parameter Estimation Problem

Patrick Heimbach, *University of Texas at Austin, U.S.*

Prize Lectures

*** The Prize Lectures will take place in Grand Ballroom EFGH ***

Tuesday, March 12

8:30 a.m. – 9:15 a.m.

SP1 SIAG/GS Career Prize Lecture -

Large-scale Bayesian Inversion for Geoscience Problems

Omar Ghattas, *University of Texas at Austin, U.S.*

Wednesday, March 13

1:20 p.m. – 2:05 p.m.

SP2 SIAG/GS Early Career Prize Lecture -

Multi-scale Simulation of Porous Media Flow: Obstacles, Opportunities and Open-source

Olav Møyner, *SINTEF Digital, Norway*

Minitutorials

*** All Minitutorials will take place in Grand Ballroom EFGH ***

Monday, March 11

2:15 p.m. – 4:20 p.m.

MT1 Probabilistic Modeling and Computations with Polynomial Chaos for Heterogeneous Multiscale Environments

Organizer and Speaker: **Roger Ghanem**, *University of Southern California, U.S.*

7:30 p.m. – 9:30 p.m.

MT2 Phase Transitions in Porous Media

Organizer and Speaker: **Malgorzata Peszynska**, *Oregon State University, U.S.*

Tuesday, March 12

4:50 p.m. – 6:55 p.m.

MT3 Data-Driven Discovery for Geophysical Systems: Integrating Machine Learning and Dynamical Systems for Learning Multiscale Physics Systems

Organizer and Speaker: **Nathan Kutz**, *University of Washington, U.S.*

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SIAM Activity Group on Geosciences (SIAG/GS)

https://www.siam.org/membership/Activity-Groups/detail/geosciences

A great way to get involved!
Collaborate and interact with mathematicians and applied scientists whose work involves geosciences.

ACTIVITIES INCLUDE

- Special Sessions at SIAM meetings
- Biennial conference
- SIAG/GS Career Prize
- SIAG/GS Junior Scientist Prize
- SIAG/GS Wiki

BENEFITS OF SIAG/GS MEMBERSHIP

- Listing in the SIAG's online membership directory
- Additional $15 discount on registration at the SIAM Conference on the Mathematical and Computational Issues in the Geosciences
- Electronic communications about recent developments in your specialty
- Eligibility for candidacy for SIAG/GS office
- Participation in the selection of SIAG/GS officers

ELIGIBILITY

- Be a current SIAM member

COST

- $15 per year
- Student members can join two activity groups for free!

2019-20 SIAG/GS OFFICERS

Chair:	Béatrice Rivière, Rice University
Vice-Chair:	Marc Hesse, University of Texas at Austin
Program Director:	Youssef M. Marzouk, Massachusetts Institute of Technology
Secretary:	Inga Berre, University of Bergen

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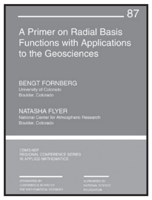
SIAM:	siam.org/joinsiam

Books from SIAM

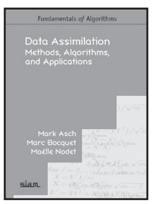


A Primer on Radial Basis Functions with Applications to the Geosciences

Bengt Fornberg and Natasha Flyer

Adapted from a series of lectures given by the authors, this monograph focuses on radial basis functions (RBFs), a powerful numerical methodology for solving PDEs to high accuracy in any number of dimensions. This method applies to problems across a wide range of PDEs arising in fluid mechanics, wave motions, astro- and geosciences, mathematical biology, and other areas and has lately been shown to compete successfully against the very best previous approaches on some large benchmark problems. Using examples and heuristic explanations to create a practical and intuitive perspective, the authors address how, when, and why RBF-based methods work.

2015 / x + 225 pages / Softcover / 978-1-611974-02-7
List $79.00 / Member $55.30 / **CB87**

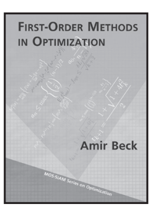


Data Assimilation: Methods, Algorithms, and Applications

Mark Asch, Marc Bocquet, and Maëlle Nodet

Readers will find a comprehensive guide that is accessible to nonexperts; numerous examples and diverse applications from a broad range of domains, including geophysics and geophysical flows, environmental acoustics, medical imaging, mechanical and biomedical engineering, economics and finance, and traffic control and urban planning; and the latest methods for advanced data assimilation, combining variational and statistical approaches.

2017 / xviii + 306 pages / Softcover / 978-1-611974-53-9
List $84.00 / Member $58.80 / **FA11**

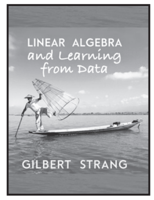


First-Order Methods in Optimization

Amir Beck

The primary goal of this book is to provide a self-contained, comprehensive study of the main first-order methods that are frequently used in solving large-scale problems. First-order methods exploit information on values and gradients/subgradients (but not Hessians) of the functions composing the model under consideration. With the increase in the number of applications that can be modeled as large or even huge-scale optimization problems, there has been a revived interest in using simple methods that require low iteration cost as well as low memory storage.

2017 / x + 484 pages / Softcover / 978-1-611974-98-0
List $97.00 / Member $67.90 / **MO25**

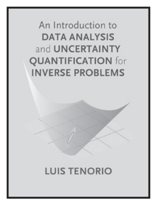


Linear Algebra and Learning from Data

Gilbert Strang

This is a textbook to help readers understand the steps that lead to deep learning. Linear algebra comes first—especially singular values, least squares, and matrix factorizations. Often the goal is a low rank approximation A = CR (column-row) to a large matrix of data—to see its most important part. This uses the full array of applied linear algebra, including randomization for very large matrices.

2019 / XVI + 432 pages / Hardcover / 978-0-692196-38-0
List $95.00 / Member $66.50 / **WC0016**

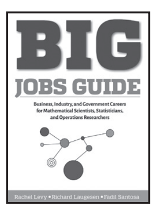


An Introduction to Data Analysis and Uncertainty Quantification for Inverse Problems

Luis Tenorio

Inverse problems are found in many applications, such as medical imaging, engineering, astronomy, and geophysics, among others. To solve an inverse problem is to recover an object from noisy, usually indirect observations. Solutions to inverse problems are subject to many potential sources of error introduced by approximate mathematical models, regularization methods, numerical approximations for efficient computations, noisy data, and limitations in the number of observations; thus it is important to include an assessment of the uncertainties as part of the solution. Such assessment is interdisciplinary by nature, as it requires, in addition to knowledge of the particular application, methods from applied mathematics, probability, and statistics.

2017 / x + 269 pages / Softcover / 978-1-611974-91-1
List $69.00 / Member $48.30 / **MN03**



BIG Jobs Guide: Business, Industry, and Government Careers for Mathematical Scientists, Statisticians, and Operations Researchers

Rachel Levy, Richard Laugesen, and Fadil Santosa

Jobs using mathematics, statistics, and operations research are projected to grow by almost 30% over the next decade. BIG Jobs Guide helps job seekers at every stage of their careers in these fields explore opportunities in business, industry, and government (BIG) by providing insight on topics such as what skills to offer employers, how to write a high-impact resumé, where to find a rewarding internship, and what kinds of jobs are out there.

2018 / xii + 141 pages / Softcover / 978-1-611975-28-4
List $25.00 / Member $17.50 / Student $15.00 / **OT158**

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Sunday, March 10

Registration

5:00 p.m.-8:00 p.m.

Room: Westchase 3/4

Welcome Reception

6:00 p.m.-8:00 p.m.

Room: Grand Foyer

Monday, March 11

Registration

7:15 a.m.-5:15 p.m.

Room: Westchase 3/4

Welcome and Introductory Remarks

8:15 a.m.-8:30 a.m.

Room: Grand Ballroom EFGH

Monday, March 11

IP1

Numerical Models for Earthquake Ground Motion

8:30 a.m.-9:15 a.m.

Room: Grand Ballroom EFGH

Chair: Sorin Pop, Hasselt University, Belgium

Physics-based numerical simulations provide a powerful tool to study the ground motion induced by earthquakes in regions threatened by seismic hazards. They can be used to better understand the physics of earthquakes, improve the design of site-specific structures, and enhance seismic risk maps. The distinguishing features of a numerical method designed for seismic wave propagation are: accuracy, geometric flexibility and parallel scalability. High-order methods ensure low dissipation and dispersion errors. Geometric flexibility allows complicated geometries and sharp discontinuities of the mechanical properties to be addressed. Finally, since earthquake models are typically posed on domains that are very large compared to the wavelengths of interest, scalability allows to efficiently solve the resulting algebraic systems featuring several millions of unknowns. In this talk we present a spectral element discontinuous Galerkin method on hybrid (non-conforming) grids for the numerical solution of three-dimensional wave propagation problems in heterogeneous media. We analyze the stability and the theoretical properties of the scheme and present some simulations of large-scale seismic events in complex media: from far-field to near-field including soil-structure interaction effects. Our numerical results have been obtained using the open-source numerical code SPEED (https://speed.mox.polimi.it).

Alfio Quarteroni
Politecnico di Milano, Italy

Coffee Break

9:15 a.m.-9:45 a.m.

Room: Grand Ballroom D

Monday, March 11

MS1

Advanced Models and Methods for Underground Flows in Complex Geometries with Applications - Part I of II

9:45 a.m.-11:50 a.m.

Room: Westchase 1/2

For Part 2 see MS28

A wide range of applications, such as exploitation of subsurface resources or geological waste disposal, requires accurate description of flows in underground basins. The subsoil is a porous medium, typically crossed by intricate networks of fractures and with an intrinsic multiscale nature, where complex physical phenomena, like solute transport, single and multi-phase flows, take place. Unconventional mathematical models and numerical schemes, able to deal with such challenges are thus crucial for effective and reliable predictions. Examples are robust meshing strategies, non-conforming or polygonal discretization methods, reduced order models, coupling strategies for mixed-dimensional problems. This minisymposium is aimed at collecting the most recent methods and models based on non-standard approximation strategies in complex domains for simulating underground flows and related applications.

Organizer: Alessio Fumagalli
University of Bergen, Norway

Organizer: Anna Scotti
Politecnico di Milano, Italy

Organizer: Stefano Scialo
Politecnico di Torino, Italy

9:45-10:05 Modeling the Flow in Complex Fracture Networks in Porous Materials via an Optimization Approach on Non Conforming Meshes

Stefano Scialo, Stefano Berrone, and Sandra Pieraccini, Politecnico di Torino, Italy

10:10-10:30 Local and Semi-local Modeling and Discretization Principles for Fractured Porous Media

Jan M. Nordbotten, University of Bergen, Norway

continued in next column

10:35-10:55 Face-based Discretization of Two-phase Discrete Fracture Matrix Models with Interface Solver

Joubine Aghili, Inria Sophia Antipolis, France; Konstantin Brenner, Université de Nice, France; Roland Masson, Université de Nice, Sophia Antipolis, France; Julian Hennicker, Université de Genève, Switzerland; Laurent Trenty, ANDRA, France

11:00-11:20 Block Preconditioners for Mixed-dimensional Flow Problems in Fractured Porous Media

Ana Budiša, University of Bergen, Norway; Xiaozhe Hu, Tufts University, U.S.

11:25-11:45 Unified Formulation for Polytopic Discontinuous Galerkin Approximation of Flows in Fractured Porous Media

Chiara Facciolà, Marco Verani, and Paola F. Antonietti, Politecnico di Milano, Italy

Monday, March 11

MS2

Advances in Hybrid Numerical Methods for Porous Media Applications

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom A

Many natural and technological processes involve flow and reactive transport in porous media. In order to precisely approximate the respective mathematical models, there is a need for (high order) accurate, locally conservative, and efficient numerical schemes. These schemes should also be able to deal with multiscale modeling and/or adaptive local mesh refinement. In the last years, there have been significant new developments in the areas of hybrid(izable) discontinuous Galerkin, mixed hybrid finite element, and other skeletal methods. To this end, the formulation, implementation, application, and analysis of modern discretization techniques are reviewed in this minisymposium. The speakers will discuss theoretical and computational approximation issues of parabolic, elliptic, and hyperbolic PDEs for applications to single and multiphase flow at different scales including accuracy and efficiency of the proposed methods.

Organizer: Andreas Rupp
Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

Organizer: Alexandre Ern
CERMICS ENPC, France

Organizer: Peter Knabner
Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

9:45-10:05 Multiderivative Time-stepping for HDG

Jochen Schuetz and Alexander Jaust, University of Hasselt, Belgium

10:10-10:30 Advances in DiSk++: A Generic Programming Framework for the Implementation of Discontinuous Skeletal Methods

Matteo Cicuttin, École des Ponts ParisTech, France

10:35-10:55 Construction and Analysis of HDG Methods for Two-phase Flows

Shinhoo Kang, Tan Bui-Thanh, and Todd Arbogast, University of Texas at Austin, U.S.

continued on next page

11:00-11:20 A Posteriori Error Estimates for Hybrid Discontinuous Galerkin Methods for Elliptic Problems

Dong-wook Shin, National Institute for Mathematical Sciences, Korea; Eun-Jae Park, Yonsei University, South Korea

11:25-11:45 A Combined GDM-ELLAM-MMOC (GEM) Scheme for Advection Dominated PDEs

Hanz Martin Cheng, Jerome Droniou, and Kim-Ngan Le, Monash University, Australia

Monday, March 11

MS3

Extended-model Versus Reduced-model Strategies for Full Waveform Inversion - Part I of II

9:45 a.m.-11:50 a.m.

Room: Briarpark 1/2

For Part 2 see MS18

Extracting the whole information from (seismic) wavefields for model reconstruction is challenging because the related PDE-constrained ptimization faces different difficulties when fighting against the dimensionality curse. One of widely used methods for such nonlinear constrained optimization is the Lagrange multipliers method where constraints are integrated into a Lagrangian function, leading to the Karush-Kuhn-Tucker (KKT) optimality conditions increasing drastically the search space size. Full waveform inversion is often performed using a reduced-model approach where only model parameters are considered. This reduced-model approach enforces exactly constrains through the wave PDE and the related adjoint PDE at each iteration, but non-linearity and ill-posedness of the problem increases, such as cycle-skipping issues. Various full-space approaches have been investigated (sub-surface offsets or time lags, wavefield or source extensions). Alternatively, reduced-model approaches have tried to overcome issues essentially by data comparison design (Wiener filter, for example), keeping low the dimensions of the model space. This session is devoted to highlight pros and cons of the different strategies and to see how to manage the mitigation of the dimensionality of the problem. Contributions from methodological and practical implementations are welcome, as well as synthetic and field-data examples.

Organizer: Jean Virieux

ISTerre, University Joseph Fourier, France

Organizer: Sue Minkoff

University of Texas, Dallas, U.S.

9:45-10:05 Dimension Reduction for Extended Space Approaches to Seismic Velocity Inversion

William Symes, Rice University, U.S.

continued in next column

10:10-10:30 Dual Formulations of Wavefield Reconstruction Inversion

Gabrio Rizzuti and Mathias Louboutin, Georgia Institute of Technology, U.S.; Rongrong Wang, Michigan State University, U.S.; Felix Herrmann, Georgia Institute of Technology, U.S.

10:35-10:55 Full Waveform Inversion by Model Extension

Guillaume Barnier, Biondo L. Biondi, and Ettore Biondi, Stanford University, U.S.

11:00-11:20 Seismic Inversion and Imaging via Model Order Reduction

Alexander V. Mamonov, University of Houston, U.S.; Liliana Borcea, University of Michigan, U.S.; Vladimir Druskin, Worcester Polytechnic Institute, U.S.; Mikhail Zaslavsky, Schlumberger-Doll Research, U.S.

11:25-11:45 Central Difference Time-lapse Full Waveform Inversion

Wei Zhou and David Lumley, University of Texas at Dallas, U.S.

Monday, March 11

MS4

Use of Adjoint Models in the Geosciences

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom C

Computing sensitivities of geosciences-related quantities of interest (QoI) to very high-dimensional state or parameter spaces in an efficient manner is of considerable interest. To understand model sensitivities derivatives are needed for relating the outputs of a model back to its inputs, i.e. control variables. Derivatives can be computed using the conventional approach of finite-difference approximation or by using adjoint models written by hand or generated through algorithmic differentiation. This mini symposium presents advances in the generation of efficient adjoint models.

Organizer: Sri Hari Krishn Narayanan
Argonne National Laboratory, U.S.

9:45-10:05 The Impacts of Initialisation Errors on Ice-sheet Forecasting

Daniel Goldberg, University of Edinburgh, United Kingdom

10:10-10:30 Uncertainty Quantification in the Subpolar North Atlantic Enabled by Adjoints

Nora Loose, University of Bergen, Norway

10:35-10:55 Greenland and Antarctica: Regional and Ice Sheet-wide Volume Sensitivities to Boundary and Initial Conditions

Elizabeth Curry-Logan, University of Texas at Austin, U.S.

11:00-11:20 Efficient Computation of Derivatives for Solving Optimization Problems in R and Python using Swig-generated Interfaces to Adol-C

Sri Hari Krishn Narayanan, Argonne National Laboratory, U.S.

11:25-11:45 Instability of Adjoint Pseudo-Acoustic Anisotropic Wave Equations

Huy Q. Le, Stewart Levin, and Biondi Biondo, Stanford University, U.S.

Monday, March 11

MS5

Scalable Methods for Coupling Water Resources Modeling and Parameter Estimation - Part I of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom B

For Part 2 see MS17

Numerical models for coupled, multiscale water resources problems can be challenging to solve, and have many applications such as density-driven flow in coastal aquifer, nearshore hydrodynamics, ice-sheet dynamics and so on. With recent advances in sensor technology, not only high-fidelity forward modeling is important but also efficient methods to infer model parameters to account for uncertainties in conceptual modeling and measurement collection are crucial for tackling realistic applications. This minisymposium aims at highlighting the current research status, model capabilities, and numerical methods for solving the water resources problems by utilizing recently advanced forward or inverse modeling or both coupled. Considered processes may also include contaminant remediation to levee erosion as well as surface water problems from flash flooding to nearshore coastal flows.

Organizer: Jonghyun Lee
University of Hawaii at Manoa, U.S.

Organizer: Sanghyun Lee
Florida State University, U.S.

Organizer: Matthew Farthing
US Army Corps of Engineers, U.S.

9:45-10:05 A Locally Conservative Enriched Galerkin for Coupling Flow and Transport

Sanghyun Lee, Florida State University, U.S.; Mary F. Wheeler, University of Texas at Austin, U.S.; Jonghyun Lee, University of Hawaii at Manoa, U.S.

10:10-10:30 The use of Entropy Production for Non-dilute Flow and Transport Models

Timothy Weigand, University of North Carolina at Chapel Hill, U.S.; Matthew Farthing, US Army Corps of Engineers, U.S.; Cass T. Miller, University of North Carolina at Chapel Hill, U.S.

10:35-10:55 A Hierarchical Solver for Extruded Meshes with Applications to Ice Sheet Modeling

Chao Chen and Leopold Cambier, Stanford University, U.S.; Erik G. Boman, Siva Rajamanickam, and Raymond S. Tuminaro, Sandia National Laboratories, U.S.; Eric F. Darve, Stanford University, U.S.

11:00-11:20 Finite Volume and Finite Element Methods for Shallow Water Flows on Surfaces

Elena Bachini, Universita di Padova, Italy; Clint Dawson, University of Texas at Austin, U.S.; Matthew Farthing, US Army Corps of Engineers, U.S.; Mario Putti, University of Padua, Italy; Corey Trahan, US Army Engineer Research and Development Center, U.S.

11:25-11:45 Using Bayesian Networks for Sensitivity Analysis of Complex Biogeochemical Models

Ming Ye, Florida State University, U.S.; Heng Dai, Jinan University, China; Xingyuan Chen and Xuehang Song, Pacific Northwest National Laboratory, U.S.; Glenn Hammond, Sandia National Laboratories, U.S.; John Zachara, Pacific Northwest National Laboratory, U.S.

continued in next column

Monday, March 11

MS6

HPC Methods in the Geosciences - Part I of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom EFGH

For Part 2 see MS14

Many phenomena in geophysics, such as mantle convection, seismic wave propagation, oceanic circulation, and the motion of land and sea ice are characterized by complex multiscale physical processes. Accurate computer simulations of these phenomena require suitable mathematical models, high spatial and temporal resolution and, thus, efficient parallel algorithms and implementations. The immense compute power on current and future supercomputers is indispensable for this research, but it brings along challenges for software development, mathematical modeling and the construction of efficient and scalable algorithms. This minisymposium is addressed at researchers working in the interdisciplinary field of complex modeling, mathematical algorithms and their implementation for grand-challenge applications in geophysics on state-of-the-art supercomputers. A special focus is on the reusability and the high-performance awareness of the presented approaches in different software packages.

Organizer: Lorenzo Colli
University of Houston, U.S.

Organizer: Markus Huber
Technische Universität München, Germany

Organizer: Georg Stadler
Courant Institute of Mathematical Sciences, New York University, U.S.

Organizer: Barbara Wohlmuth
Technische Universität München, Germany

9:45-10:05 Workflow Management Challenges for Exascale Seismology

Jeroen Tromp, Princeton University, U.S.

10:10-10:30 Linking Compositional Properties and Epeirogenic Movement in Mantle Flow Models

Siavash Ghelichkhan, Munich University of Applied Science, Germany

continued in next column

10:35-10:55 High-performance Computing for the Geodynamo

Alexandre Fournier and Thomas Gastine, Institut de Physique du Globe de Paris, France; Nathanaël Schaeffer, Institut des Sciences de la Terre de Grenoble, France

11:00-11:20 High-resolution Design and Simulation of Nonlinear Flow in Modern Subduction Systems

Margarete Jadamec, State University of New York at Buffalo, U.S.

11:25-11:45 Hijacking Multilevel Graph Partitioning for Three-dimensional Discrete Fracture Network Flow Simulations

Jeffrey Hyman and Aric Hagberg, Los Alamos National Laboratory, U.S.; Hayato Ushijima-Mwesigwa, Clemson University and Los Alamos National Laboratory, U.S.; Carl Gable and Satish Karra, Los Alamos National Laboratory, U.S.; Ilya Safro, Clemson University, U.S.; Gowri Srinivasan, Los Alamos National Laboratory, U.S.

Monday, March 11

MS7

High Order Schemes for Simulation of Flow and Transport in Porous Media - Part I of II

9:45 a.m.-11:50 a.m.

Room: Richmond 1/2

For Part 2 see MS16

Numerical simulation of flow and transport in porous media is complicated by processes such as fluid phase behavior, chemical reactions, formation heterogeneity, and buoyancy. The governing equations tend to exhibit strong parabolic and hyperbolic behavious, and steep gradients can form in the solution. Moreover, highly channelized flow can arise in many geologic formations. High order accurate numerical schemes can be used to improve the approximation of the solution. This minisymposium will bring together researchers working on various numerical schemes designed to give relatively high-order accurate approximation of flow and transport.

Organizer: Todd Arbogast
University of Texas at Austin, U.S.

9:45-10:05 High-order Discontinuous Galerkin Methods for Flows in Porous Media: High-fidelity Viscous Fingering Computations on Fully Unstructured Meshes

Guglielmo Scovazzi, Duke University, U.S.

10:10-10:30 High Order HDG for Two Phase Flow and Miscible Displacement

Maurice Fabien and Beatrice Riviere, Rice University, U.S.; Matthew G. Knepley, State University of New York at Buffalo, U.S.

10:35-10:55 Implicit Weno for Two-phase Flow

Xikai Zhao and Todd Arbogast, University of Texas at Austin, U.S.

11:00-11:20 On Accurate Semi-discrete Schemes for Multiphase Flow in Porous Media

Maicon R. Correa, University of Campinas, Brazil

11:25-11:45 Computational Modeling of Naturally Fractured Reservoirs with Geomechanical Coupling

Philippe Devloo, Omar Duran, and Pablo Carvalho, Universidade Estadual de Campinas, Brazil; Chensong Zhang, Chinese Academy of Sciences, China

Monday, March 11

Lunch Break

11:50 a.m.-1:20 p.m.

Attendees on their own

Monday, March 11

IP2

Homogenization Approach for Modeling of Reactive Transport in Porous Media

1:20 p.m.-2:05 p.m.

Room: Grand Ballroom EFGH

Chair: Lynn Schreyer, Washington State University, U.S.

My goal is to explain how homogenization theory can be applied to the modeling of reactive transport in porous media. The main idea is to derive macroscopic models, valid on a large scale, from microscopic equations, written at the pore scale, and to obtain effective formulas for the homogenized coefficients, in a mathematically rigorous framework. The typical microscopic equations are Stokes equations for a viscous fluid, convection-diffusion equations with reaction terms for several diluted species, and possibly a coupling with other effects (like electrokinetics or Poisson-Boltzmann model). An example of an important macroscopic effect to be modeled is that of the so-called Taylor dispersion which governs the effective diffusion of a diluted species. Our framework is that of periodic homogenization combined with singular perturbations and scaling considerations. This is a review of several joint works with R. Brizzi, J.-F. Dufreche, H. Hutridurga, A. Mikelic, A. Piatnitski.

Gregoire Allaire
Ecole Polytechnique, France

Intermission

2:05 p.m.-2:15 p.m.

Monday, March 11

MT1

Probabilistic Modeling and Computations with Polynomial Chaos for Heterogeneous Multiscale Environments

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom EFGH

This minitutorial will review polynomial chaos constructions and demonstrate their application for building stochastic representations for multiscale problems. The minitutorial will have the following structure: 1. Review of polynomial chaos constructions for functionals of random variables and processes. 2. Review of spectral expansions for stochastic processes: Karhunen-Loeve expansions and Polynomial Chaos. 3. Overview of some computational upscaling methods to compute coarse scale parameters. 4. Expression of coarse scale parameters as functionals of fine-scale structure and construction of the associated polynomial chaos representation. 5. Implications for modeling and prediction of flows in porous media.

Organizer and Speaker:
Roger Ghanem,
University of Southern California, U.S.

Monday, March 11

MS8

Scientific Machine Learning for Subsurface Geoscience

2:15 p.m.-4:20 p.m.

Room: Richmond 1/2

The geologic subsurface is full of complexity and uncertainty. Because of this, current subsurface interrogation methods are often expensive and yield limited accuracy. Machine learning has been used as a powerful tool in data analysis that has the potential to subsurface science. While machine learning methods continue to produce impressive successes in conventional AI tasks, their applicability in scientific analysis problems including ones related to the subsurface is even more challenging and exciting. There have been several pioneering research works incorporating different machine-learning techniques and applying them to geologic subsurface problems. The goal of this session is to introduce some of these recent results to the subsurface geoscience community. We welcome researchers and students to participate in this minisymposium and join the discussions about these exciting new directions.

Organizer: Youzuo Lin

Los Alamos National Laboratory, U.S.

Organizer: Dan O'Malley

Los Alamos National Laboratory, U.S.

2:15-2:35 Modeling Flow and Transport in Fracture Networks using Machine Learning and Graphs

Daniel O'Malley, Los Alamos National Laboratory, U.S.

2:40-3:00 Physics and Data Science for Geoscience Applications

Detlef Hohl, Shell Global Solutions, U.S.

3:05-3:25 Information-theoretic Approaches to Multiscale Learning

Francesca Boso and Daniel M. Tartakovsky, Stanford University, U.S.

3:30-3:50 Deep Multiscale Model Learning

Siu Wun Cheung, Texas A&M University, U.S.

3:55-4:15 VelocityGAN: Subsurface Velocity Image Estimation using Conditional Adversarial Networks

Youzuo Lin, Los Alamos National Laboratory, U.S.

Monday, March 11

MS9

Advanced Numerical Methods for Flow and Transport Simulations through Subsurface Fracture Networks

2:15 p.m.-4:20 p.m.

Room: Westchase 1/2

In several applications related to civil and industrial subsurface exploitation (geothermal energy extraction, long term storage of spent nuclear fuel, unconventional hydrocarbon extraction, and enhanced oil & gas production), fractures are the primary paths for flow and transport. This minisymposium will focus on recent advances in numerical methods associated with flow and transport simulations in fractured permeability media including mesh generation, discretization of the governing PDEs, Lagrangian methods for transport simulation, and methods for coupling physical phenomenon in the fractures with the surrounding rock matrix. Focus will be primarily on methods that explicitly represent fractures such as Discrete Fracture Networks (DFN) and Discrete Fracture Matrix (DFM) models.

Organizer: Jeffrey Hyman

Los Alamos National Laboratory, U.S.

Organizer: Stefano Berrone

Politecnico di Torino, Italy

Organizer: Sandra Pieraccini

Politecnico di Torino, Italy

2:15-2:35 Efficient and Reliable Adaptive Simulations in Large Scale DFNs

Stefano Berrone, Andrea Borio, Sandra Pieraccini, Stefano Scialo, and Fabio Vicini, Politecnico di Torino, Italy

2:40-3:00 Numerical Modeling of Fracture Reactivation in a Three-dimensional Domain Based on a Coulomb Friction Law

Runar Lie Berge, Inga Berre, Eirik Keilegavlen, and Jan M. Nordbotten, University of Bergen, Norway; Barbara Wohlmuth, Technische Universität München, Germany

continued in next column

3:05-3:25 Preconditioning Techniques for Mimetic Discretizations of Flow in Fractured Porous Media

Luca Formaggia, Paola F. Antonietti, Anna Scotti, and Jacopo De Ponti, Politecnico di Milano, Italy

3:30-3:50 Octree-refined Continuum Representation of Discrete Fracture Networks: Evaluation of Equivalent Permeability Expressions and Applications in Multiphysics Simulations

Matthew Sweeney, Jeffrey Hyman, Carl Gable, Satish Karra, Nataliia Makedonska, and Rajesh Pawar, Los Alamos National Laboratory, U.S.

3:55-4:15 Space Discretization Impacts on the FraC Mesh Quality and on Flow and Transport Simulations

Andre Fourno, IFP, France

Monday, March 11

MS10

Advances in Coupling Surface Flow to Subsurface Systems - Part I of II

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom A

For Part 2 see MS15

Interaction between surface flow and subsurface systems is important for a variety of environmental and industrial applications. Modeling such coupled problems poses substantial challenges for mathematicians and computational scientists due to the complexity of interface driven processes that are coupled, non-linear, and evolving on various spatial and temporal scales. Recently, there have been significant developments in coupling different free flow models (Navier-Stokes, shallow water, kinematic and diffusive wave equations) to subsurface models (single- and two-phase Darcy's law and Richards' equation). Nevertheless, many of the existing coupling concepts and numerical algorithms still deal with oversimplified flow equations and interface conditions. However, physically consistent descriptions of the interfaces as well as robust and efficient numerical solution strategies are needed to adequately simulate flow and transport processes in coupled systems. This minisymposium aims at bringing together researchers working on the development of new modeling concepts, analysis of coupled problems, and advanced computational algorithms to study flow and transport processes in coupled systems.

Organizer: Iryna Rybak
Universität Stuttgart, Germany

Organizer: Andreas Rupp
Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

2:15-2:35 Modeling, Analysis, and Implementation of a Coupled 3D Shallow Water--Darcy/Richards System

Andreas Rupp, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany; Vadym Aizinger, Alfred Wegener Institute, Germany; Iryna Rybak, Universität Stuttgart, Germany; Balthasar Reuter, Florian Frank, and Peter Knabner, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

continued in next column

2:40-3:00 Revisiting Coupling Approaches for Surface-subsurface Flow

Matthew Farthing, U.S. Army Engineer Research and Development Center, U.S.; Matteo Camporese, University of Padua, Italy; Claudio Paniconi, INRS-ETE Québec, Canada; *Mario Putti*, University of Padua, Italy

3:05-3:25 Complex Interfaces Between Free Flow and Porous Media Flow

Kilian Weishaupt, Timo Koch, and Rainer Helmig, Universität Stuttgart, Germany

3:30-3:50 Error Analysis for Coupled Time-dependent Navier-Stokes and Darcy Flows

Beatrice Riviere and Nabil Chaabane, Rice University, U.S.; Vivette Girault, University of Paris VI, France; Charles Puelz, Courant Institute of Mathematical Sciences, New York University, U.S.

3:55-4:15 Precice -- a Comprehensive Coupling Library for Large-scale Surface-coupled Multi-physics Problems

Miriam Mehl, Universität Stuttgart, Germany; Benjamin Uekermann, Technische Universität München, Germany

Monday, March 11

MS11

Porous Media Applications Involving Evolving Interfaces

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom B

In this minisymposium, we want to bring together experts dealing with the modeling, upscaling, analysis, and numerical treatment of porous media applications including evolving interfaces. Examples are, amongst others, two-phase flow with the inherent dynamic fluid-fluid interface or reactive transport processes including dissolution/precipitation reactions leading to a non-negligible evolution of the solid--fluid interface. We welcome contributions that operate on different spatial scales, e.g. pore-scale models, pore network models, micro-continuum models, hybrid models, and two-scale models.

Organizer: Nadja Ray
Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

Organizer: Peter Knabner
Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

2:15-2:35 Effects of Spatiotemporal Averaging on Predictions of Reactive Transport in Porous Media

Ilenia Battiato, Stanford University, U.S.

2:40-3:00 On a Two-scale Phase Field Model for Reactive Transport

Carina Bringedal, Universität Stuttgart, Germany; Iuliu Sorin Pop, Hasselt University, Belgium

3:05-3:25 Two-phase Flow in Porous Media: An Upscaling Approach

Stefan Metzger, Illinois Institute of Technology, U.S.

3:30-3:50 Reactive Transport in Porous Media: A Two-scale Level Set Approach

Nadja Ray and Jens Oberlander, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany; Peter Frolkovic, Slovak University of Technology, Slovakia

3:55-4:15 Immersed Boundary Method for Dissolving Interfaces

Chunsong Kwon, University of California, San Diego, U.S.; Daniel M. Tartakovsky, Stanford University, U.S.

Monday, March 11

MS12

Mixed-dimensional Partial Differential Equations in the Geosciences

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom C

Model reduction by reducing dimensionality has a long and rich history in the geosciences. As an illustrative example, groundwater aquifers have generally been modeled using two-dimensional representations. This has been justified heuristically and theoretically by appealing not just to geometrical aspect ratios, but also due to the fact that boundary conditions and the problems of interest lead to a two-dimensional structure of the solution. Historically, this dimension reduction allowed both for the construction of analytical solutions, as well as computationally feasible numerical representation. At present, there is a growing interest in so-called mixed-dimensional partial differential equations. These arise when models of reduced dimensionality are embedded into higher-dimensional models. Classical examples are those of fractured porous media (2D fracture plane representations embedded into a 3D matrix), and that of wells (1D well models embedded into a 3D matrix). However, mixed-dimensional models are also attractive when e.g. considering plant roots in the vadose zone, or when considering regional geomechancial models with several thin aquifers. This minisymposium draws attention to recent theoretical and computational advances for mixed-dimensional partial differential equations.

Organizer: Wietse Boon
Universität Stuttgart, Germany

Organizer: Jan M. Nordbotten
University of Bergen, Norway

2:15-2:35 Basis Construction in Finite Element Exterior Calculus, Revisited

Martin W. Licht, University of California, San Diego, U.S.

2:40-3:00 Numerical Approximation of Coupled PDEs on Embedded Manifolds with High Dimensionality Gap

Paolo Zunino, Politecnico di Milano, Italy

continued in next column

3:05-3:25 The Mathematical Structure of Coupled 1D-3D Models

Ingeborg G. Gjerde, University of Bergen, Norway; Kundan Kumar, Karlstad University, Sweden; Jan M. Nordbotten, University of Bergen, Norway

3:30-3:50 Stable Mixed Finite Elements for Linear Elasticity with Thin Inclusions

Wietse Boon, Universität Stuttgart, Germany

3:55-4:15 Hybrid Cellular Automata / PDE Modeling for Self-organisation of Soil Microaggregate Structures

Alexander Prechtel and Andreas Rupp, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany; Kai Uwe Totsche, University of Jena, Germany; Nadja Ray, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

Monday, March 11

MS13

Optimal Transport for Imaging in Geosciences - Part I of II

2:15 p.m.-4:20 p.m.

Room: Briarpark 1/2

For Part 2 see MS26

Full waveform inversion (FWI) is a seismic imaging method which is now part of the conventional imaging workflow in the industry. It is also used for global and regional scale imaging in seismology. Its main interest compared to tomography is its high-resolution power. FWI is formulated as a least-squares (L2) minimization problem. The L2 misfit function is highly nonconvex. Mitigating this nonconvexity is a longstanding difficulty. Despite important advances yielding successful applications through multi-scale approaches, obtaining robust and flexible FWI algorithms remains an open question. Recently, [Engquist and Froese, 2014] have proposed to use the Wasserstein distance as a misfit function. This distance, from the optimal transport (OT) theory, is convex with respect to shifted patterns. For FWI, the convexity with respect to time-shifts is a proxy for the convexity with respect to the subsurface velocities, making the Wasserstein distance a very attractive tool. However, its application to seismic data is not straightforward: OT assumes positivity and mass balance between compared quantities while seismic data is non-positive. Integrating OT within FWI also requires fast and robust numerical methods. The workshop will present recent advances to overcome these difficulties. Extending OT to signed measures will be discussed. Efficient implementations using linear programming or fluid-dynamic will be introduced. First industrial scale applications will be presented.

Organizer: Yunan Yang
Courant Institute of Mathematical Sciences, New York University, U.S.

Organizer: Ludovic Métivier
Université Grenoble Alpes, France

2:15-2:35 Optimal Transport for Full Waveform Inversion: Tackling the Nonlinearity

Yunan Yang, Courant Institute of Mathematical Sciences, New York University, U.S.

continued on next page

Monday, March 11

MS13

Optimal Transport for Imaging in Geosciences - Part I of II

continued

2:40-3:00 Optimal Transport for Full Waveform Inversion: A Graph Space Approach

Ludovic Métivier, Université Grenoble Alpes, France

3:05-3:25 Earth Mover's Distance with Dynamic Formulation and its Application in Full Waveform Inversion

Wenyuan Liao, University of Calgary, Canada

3:30-3:50 Wasserstein Metric-driven Bayesian Inversion with Applications to Wave Propagation Problems

Daniel Appelo, University of Colorado Boulder, U.S.

3:55-4:15 Resolution Analysis in Seismic Imaging using the Kronecker-factored Hessian

Gian Matharu, Wenlei Gao, and Mauricio D. Sacchi, University of Alberta, Canada

Coffee Break

4:20 p.m.-4:50 p.m.

Room: Grand Ballroom D

Monday, March 11

CP1

Wave Propagation and Inversion

4:50 p.m.-6:10 p.m.

Room: Richmond 1/2

Chair: Laurent White, ExxonMobil, U.S.

4:50-5:05 Shape-Constrained Inversion in Geoscience

Jeremy Brandman, ExxonMobil Corporate Strategic Research, U.S.; Huseyin Denli, ExxonMobil, U.S.

5:10-5:25 Reflection Coefficient for a Seismic Fractional Interface

Olivier Lafitte, Université Paris 13, France; Laurent Demanet, Massachusetts Institute of Technology, U.S.

5:30-5:45 Full-Waveform Inversion in Shallow-Water Environments

Laurent White, ExxonMobil, U.S.; Martin Lacasse, ExxonMobil Research and Engineering, U.S.

5:50-6:05 Model Misspecification and Robust Bayesian Inference in Seismic Inversion

Andrea Scarinci, Massachusetts Institute of Technology, U.S.

Monday, March 11

CP2

Climate I

4:50 p.m.-6:10 p.m.

Room: Grand Ballroom A

Chair: Babak Poursartip, University of Texas at Austin, U.S.

4:50-5:05 Forecasting the Gulf of Mexico Loop Current: A Machine Learning Approach

Cole Harris, Chevron Information Technology Company, U.S.; James Stear, Chevron Energy Technology Company, U.S.

5:10-5:25 Large-Scale Simulation of Flow in Channel Networks Using 1D Shallow Water Equations

Babak Poursartip and Clint Dawson, University of Texas at Austin, U.S.

5:30-5:45 Power Laws and Self-Similarity in Tornadogenesis

Mikhail M. Shvartsman, University of St. Thomas, U.S.; Pavel Belik, Augsburg University, U.S.; Douglas Dokken and Kurt Scholz, University of St. Thomas, U.S.; Corey Potvin, National Oceanic and Atmospheric Administration, U.S.

5:50-6:05 Comparative Analysis of Groundwater Modeling Software to Describe the Interaction Between Surface Water and Groundwater During Floods

Pablo Merchan-Rivera, Gabriele Chiogna, and Markus Disse, Technische Universität München, Germany

Monday, March 11

CP3

Data Assimilation and Uncertainty Quantification I

4:50 p.m.-6:10 p.m.

Room: Grand Ballroom B

Chair: Olga Fuks, Stanford University, U.S.

4:50-5:05 Multilevel Monte Carlo Uncertainty Quantification for Finite Volumes

Andrew T. Barker, Lawrence Livermore National Laboratory, U.S.; Stephan Gelever, Portland State University, U.S.; Chak Lee and Panayot Vassilevski, Lawrence Livermore National Laboratory, U.S.

5:10-5:25 Uncertainty Quantification of the Multi-centennial Response of the Antarctic Ice Sheet to Climate Change

Kevin Bulthuis and Maarten Arnst, Université de Liège, Belgium; Sainan Sun and Frank Pattyn, Université Libre de Bruxelles, Belgium

5:30-5:45 Can a High Dimensional Parameter Space be Acceptable for a Lumped Hydrological Karst Model?

Gabriele Chiogna, Daniel Bittner, Mario Parente, Steven A. Mattis, and Barbara Wohlmuth, Technische Universität München, Germany

5:50-6:05 Distribution-Based Method for Uncertainty Propagation of Compositional Displacements

Olga Fuks, Fayadhoi Ibrahima, Pavel Tomin, and Hamdi Tchelepi, Stanford University, U.S.

Monday, March 11

CP4

Multiscale Methods

4:50 p.m.-6:10 p.m.

Room: Briarpark 1/2

Chair: Joe Umhoefer, Oregon State University, U.S.

4:50-5:05 Adaptive Numerical Homogenization: a Novel Approach for Simulation of Fluid Flow in Highly Heterogeneous Porous Media

Manuela Bastidas and Iuliu Sorin Pop, Hasselt University, Belgium; Carina Bringedal, Universität Stuttgart, Germany

5:10-5:25 Honmogenization Wavelet Reconstruction for Approximate Solution of Elliptic Partial Differential Equations

Joseph V. Koebbe, SINTEF Digital, Norway; Abibat Lasisi, Virginia Military Institute, U.S.

5:30-5:45 Approximating Permeability Density Functions for Flow and Transport in Obstructed Porous Media

Joe Umhoefer and Malgorzata Peszynska, Oregon State University, U.S.; Timothy Costa, Numerical Solutions, Inc., U.S.

5:50-6:05 Homogenized Model of Immiscible Incompressible Two-phase Flow in Double Porosity Media

Anja Vrbaski, University of Zagreb, Croatia; Brahim Amaziane, Université de Pau, France; Mladen Jurak, University of Zagreb, Croatia; Leonid Pankratov, Université de Pau, France

Monday, March 11

CP5

Fractures and Poroelasticity

4:50 p.m.-6:10 p.m.

Room: Westchase 1/2

Chair: Shriram Srinivasan, Los Alamos National Laboratory, U.S.

4:50-5:05 Isogeometric Analysis of a Coupled Stokes-Biot System

Elisa Bergkamp, Clemens Verhoosel, Joris Remmers, and David Smeulders, Eindhoven University of Technology, Netherlands

5:10-5:25 Semi-infinite Fracture Driven by Herschel-Bulkley Fluid

Alena Bessmertnykh, University of Houston, U.S.; Egor Dontsov, W.D. Von Gonten Laboratories, Houston, U.S.; Kalyana Nakshatrala, University of Houston, U.S.

5:30-5:45 Approximation and Wavelet-based Modelling in Poroelasticity

Bianca Kretz, Universität Siegen, Germany

5:50-6:05 System Reduction for Fractured Porous Media through a Machine-learning Approach that Identifies Main Flow Pathways

Shriram Srinivasan, Satish Karra, Jeffrey Hyman, Hari Viswanathan, and Gowri Srinivasan, Los Alamos National Laboratory, U.S.

Monday, March 11

CP6

Numerical Methods I

4:50 p.m.-5:50 p.m.

Room: Grand Ballroom C

Chair: Rencheng Dong, University of Texas at Austin, U.S.

4:50-5:05 Iterative Solvers for Poromechanics with Large Deformation

Manuel Borregales, Florin Adrian Radu, Kundan Kumar, and Jan M. Nordbotten, University of Bergen, Norway; Francisco José Gaspar and Carmen Rodrigo, University of Zaragoza, Spain

5:10-5:25 Enriched Galerkin Methods for Matrix Acidizing in Fractured Carbonate Reservoirs

Rencheng Dong and Mary F. Wheeler, University of Texas at Austin, U.S.

5:30-5:45 A Pore-scale Study of the Transport of Inertial Particles in Porous Media

Max A. Endo Kokubun, University of Bergen, Norway; Adrian Muntean, Karlstad University, Sweden; Iuliu Sorin Pop, Hasselt University, Belgium; Florin Radu, Eirik Keilegavlen, Kundan Kumar, and Kristine Spildo, University of Bergen, Norway

5:50-6:05 Improving Reservoir Simulator Performance through Ensemble Based Robust Optimization

Rohith Nair, Netherlands Organisation for Applied Scientific Research, Netherlands

SIAG/GS Business Meeting

6:15 p.m.-7:15 p.m.

Room: Grand Ballroom EFGH

Complimentary beer and wine will be served.

Intermission

7:15 p.m.-7:30 p.m.

Monday, March 11

MT2

Phase Transitions in Porous Media

7:30 p.m.-9:30 p.m.

Room: Grand Ballroom EFGH

Chair: Malgorzata Peszynska, Oregon State University, U.S.

Multiple fluid phases are ubiquitous in subsurface modeling and other geoscience applications. Multiple components can be present in the liquid, solid, or gaseous phases. When pressure and temperature conditions change, phase transitions can occur; depending on the time scale of the process relative to the transport, they are modeled as equilibrium or kinetic, and the models must respect various thermodynamic constraints. Accounting for these requires a phase equilibrium solver, and/or a transient solver directing the phase behavior towards equilibria. In a computational model, one can account for sharp phase interfaces, or use diffuse interface models. Furthermore, one can include or ignore the effects of confinement by porous media.
In this minitutorial we overview the basic models for phase behavior; we touch on equilibria, kinetics and phase transitions, and mathematical and computational models for evolution under constraints. Part of the session will be a general overview; another part will focus on crystal and bubble formation, dissolution, and dissociation such as that in modeling water in all three phases, and natural gas hydrates.

Speakers:

Malgorzata Peszynska, Oregon State University, U.S.

Mark D. White, Pacific Northwest National Laboratory, U.S.

Tuesday, March 12

Registration

8:00 a.m.-5:15 p.m.

Room: Westchase 3/4

Remarks and SIAG/GS Early Career and SIAG/GS Career Prize Presentations

8:25 a.m.-8:30 a.m.

Room: Grand Ballroom EFGH

Tuesday, March 12

SP1

SIAG/GS Career Prize Lecture: Large-scale Bayesian Inversion for Geoscience Problems

8:30 a.m.-9:15 a.m.

Room: Grand Ballroom EFGH

Chair: To Be Determined

Ever since Tarantola's pioneering work in the 1980s, the Bayesian framework has offered a rational and systematic means of accounting for uncertainty in the solution of inverse problems, given uncertainty in observational data, forward models, and any prior information.

However, Bayesian inversion has remained out of reach for many geoscience problems, due to the infinite-dimensional nature of typical parameter fields (high-dimensional after discretization), and the complexity of forward models of many geoscience processes. We discuss recently-developed methods inspired by large-scale optimization ideas that have shown promise in overcoming these challenges. Applications to several geophysical inverse problems are presented.

Omar Ghattas

University of Texas at Austin, U.S.

Tuesday, March 12

PP1

Coffee Break and Poster Session **Posters will be on display during Tuesday coffee breaks**

9:15 a.m.-9:45 a.m.

Room: Grand Ballroom D

Efficient Numerical Solution for 3D Partial Differential Equation

Badr Alqahtani, King Saud University, Saudia Arabia

The use of Res2dinv Software in Assessing the Subsurface of a Landfill

Atiat (allison) Alsaaideh and Amy Barrett, Oakland City University, U.S.

Modeling the Change in Electric Potential due to Lightning in a Sphere

Beyza C. Aslan, University of North Florida, U.S.

Equilibrium Statistics and Entropy Computation for Vortex Filaments on a Cubic Lattice: A Modified Pivot Algorithm

Pavel Belik, Aleksandr Lukanen, and Robert Laskowski, Augsburg University, U.S.; Douglas Dokken, Kurt Scholz, and Mikhail M. Shvartsman, University of St. Thomas, U.S.

Modeling Ice/Water Phase Transition at the Porescale

Lisa Bigler and Malgorzata Peszynska, Oregon State University, U.S.

Re-stating the Four-Color Theorem, using Graph Theory

Jorge Diaz-Castro, University of Puerto Rico, Río Piedras, Puerto Rico

Seismic Data Interpolation and Denoising based on Orthogonal Tensor Dictionary Learning

Erena Diriba Gemechu and Ma Jianwei, Harbin Institute of Technology, China

Simulating the Viscous Fingering Effect in Porous Media

Bryan T. Doyle and Beatrice Riviere, Rice University, U.S.; Michael Sekachev, Total E&P Research & Technology, U.S.

continued in next column

Economics of a Sustainable Geothermal System for Air-conditioning a Typical House in Moderate Climates

Georgios Florides, Lazaros Aresti, Vassilios Messaritis, Lazaros Lazaris, and Paul Christodoulides, Cyprus University of Technology, Cyprus

Fast Least-Squares Reverse Time Migration with Hessian Matrix Approximated by the Superposition of Kronecker Product

Wenlei Gao, Gian Matharu, and Mauricio D. Sacchi, University of Alberta, Canada

Upscaling Procedure to Estimate Permeability of Three Carbonate Core Plug Samples using Textures of X-Ray Micro-Computed Tomography Images

Mohamed S. Jouini, Khalifa University and Petroleum Institute, United Arab Emirates; Ali AlSumaiti, Moussa Tembely, and Khurshed Rahimov, Khalifa University, United Arab Emirates

Impact of Time-dependent Wettability Alteration on Capillary Pressure

Abay Kassa, University of Bergen, Norway; Sarah Gasda, NORCE Norwegian Research Centre, Norway; Kundan Kumar and Florin Radu, University of Bergen, Norway

Inelastic Wedge Failure and Along-Strike Variations of Tsunami Generation in the Shallow Subduction Zone

Shuo Ma and Shiying Nie, San Diego State University, U.S.

A Model Reduction Method for Multiscale Elliptic PDEs with Random Coefficients using an Optimization Approach

Dingjiong Ma, University of Hong Kong, China; Thomas Y. Hou, California Institute of Technology, U.S.; Zhiwen Zhang, University of Hong Kong, Hong Kong

Advanced Nonlinear Solvers for a Discrete Fracture Model in Adaptive Space Parameterization

Kiarash Mansourpour and Denis Voskov, Technical University of Delft, Netherlands; Luca Formaggia and Alberto Guadagnini, Politecnico di Milano, Italy

Two-scale Finite Volume Method for Flows in Fractured Media

Kirill Nikitin, Russian Academy of Sciences, Russia

continued on next page

Tuesday, March 12

PP1

Coffee Break and Poster Session **Posters will be on display during Tuesday coffee breaks**

continued

Development of a Numerical Framework for the Study of Solid Earth Tides

Mattia Penati, Edie Miglio, and Simone Carriero, Politecnico di Milano, Italy

Characterizing Volumetric Strain at Brady Hot Springs, Nevada, USA using InSAR, GPS, Numerical Models and Prior Information

Elena C. Reinisch, Michael Cardiff, and Kurt L. Feigl, University of Wisconsin, Madison, U.S.

Effective Models for Two-phase Flow in Porous Media with Evolving Interfaces at the Pore Scale

Sohely Sharmin and Iuliu Sorin Pop, Hasselt University, Belgium; Carina Bringedal, Universität Stuttgart, Germany

Novel Principles for Effective Earth Model Grid Management While Geosteering

Erich Suter and Helmer Andre Friis, NORCE Norwegian Research Centre, Norway; Terje Kårstad and Alejandro Escalona, University of Stavanger, Norway; Erlend Vefring, NORCE Norwegian Research Centre, Norway

Imaging of Densely Located Many Point-like Scatterers by the Application of the Pseudo Projection Method and Kirchhoff Migration

Terumi Touhei and Taizo Maruyama, Tokyo University of Science, Japan

Joint Inversion of Surface Wave Dispersion and Bouguer Gravity Anomalies using Constrained Optimization

Azucena Zamora, University of Texas at El Paso, U.S.; Anibal Sosa, Universidad Icesi, Colombia; Aaron Velasco, University of Texas at El Paso, U.S.

continued in next column

Generalized Approximate Static Condensation Method for a Heterogeneous Multi-material Diffusion Problem

Alexander Zhiliakov, University of Houston, U.S.

Performance and Cost Analysis of Single and Double U-Tube Ground Heat Exchangers

Paul Christodoulides, Cyprus University of Technology, Cyprus; Mateusz Zerun, Polish Geological Institute, National Research Institute, Poland; Lazaros Aresti, Soteris Kalogirou, and Georgios Florides, Cyprus University of Technology, Cyprus

Mathematical Modelling of the Removal of Micropollutants.I Linear Cometabolism Model

Rubayyi Alqahtani, Imam University, Saudi Arabia

Advances in use of Meshless Computational Methods in Geosciences and Related Topics

T.V. Hromadka II, United States Military Academy, U.S.; Kameron Grubaugh, Independent Researcher; Aidan Doyle and Anton Nelson, United States Military Academy, U.S.; Bryce Wilkins, Massachusetts Institute of Technology, U.S.

Tuesday, March 12

MS14

HPC Methods in the Geosciences - Part II of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom EFGH

For Part 1 see MS6

Many phenomena in geophysics, such as mantle convection, seismic wave propagation, oceanic circulation, and the motion of land and sea ice are characterized by complex multiscale physical processes. Accurate computer simulations of these phenomena require suitable mathematical models, high spatial and temporal resolution and, thus, efficient parallel algorithms and implementations. The immense compute power on current and future supercomputers is indispensable for this research, but it brings along challenges for software development, mathematical modeling and the construction of efficient and scalable algorithms. This minisymposium is addressed at researchers working in the interdisciplinary field of complex modeling, mathematical algorithms and their implementation for grand-challenge applications in geophysics on state-of-the-art supercomputers. A special focus is on the reusability and the high-performance awareness of the presented approaches in different software packages.

Organizer: Lorenzo Colli
University of Houston, U.S.

Organizer: Markus Huber
Technische Universität München, Germany

Organizer: Georg Stadler
Courant Institute of Mathematical Sciences, New York University, U.S.

Organizer: Barbara Wohlmuth
Technische Universität München, Germany

9:45-10:05 Improved Newton Linearization for L^1-Norm-type Minimization with Application to Viscoplastic Fluid Solvers

Johann Rudi, University of Texas at Austin, U.S.; Georg Stadler, Courant Institute of Mathematical Sciences, New York University, U.S.; Omar Ghattas, University of Texas at Austin, U.S.

continued on next page

10:10-10:30 Accurately Utilizing Particle-in-cell Methods for Adaptively Refined Finite-element Models of Mantle Convection and Lithosphere Dynamics

Rene Gassmoeller, Harsha Lokavarapu, and Elbridge G. Puckett, University of California, Davis, U.S.; Wolfgang Bangerth, Colorado State University, U.S.

10:35-10:55 A Comparison of IMEX Time Integrators for the Simulation of Thermal Convection in an Annulus

Venkatesh Gopinath, Thomas Gastine, and Alexandre Fournier, Institut de Physique du Globe de Paris, France

11:00-11:20 Towards Mantle Convection Simulations in the Exa-scale Era: Real World Models

Markus Huber and Simon Bauer, Technische Universität München, Germany; Hans-Peter Bunge, Ludwig-Maximilians-Universität München, Germany; Barbara Wohlmuth, Technische Universität München, Germany; Ulrich J. Ruede, University of Erlangen-Nuremberg, Germany; Marcus Mohr, Technische Universität München, Germany; Siavash Ghelichkhan, Munich University of Applied Science, Germany

11:25-11:45 More Than Gradients: Dynamical Attribution in Ocean Science using Adjoint Models

Patrick Heimbach, University of Texas at Austin, U.S.; Nora Loose, University of Bergen, Norway; An Nguyen, Helen Pillar, and Timothy Smith, University of Texas at Austin, U.S.

Tuesday, March 12

MS15

Advances in Coupling Surface Flow to Subsurface Systems - Part II of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom A

For Part 1 see MS10

Interaction between surface flow and subsurface systems is important for a variety of environmental and industrial applications. Modeling such coupled problems poses substantial challenges for mathematicians and computational scientists due to the complexity of interface driven processes that are coupled, non-linear, and evolving on various spatial and temporal scales. Recently, there have been significant developments in coupling different free flow models (Navier-Stokes, shallow water, kinematic and diffusive wave equations) to subsurface models (single- and two-phase Darcy's law and Richards' equation). Nevertheless, many of the existing coupling concepts and numerical algorithms still deal with oversimplified flow equations and interface conditions. However, physically consistent descriptions of the interfaces as well as robust and efficient numerical solution strategies are needed to adequately simulate flow and transport processes in coupled systems. This minisymposium aims at bringing together researchers working on the development of new modeling concepts, analysis of coupled problems, and advanced computational algorithms to study flow and transport processes in coupled systems.

Organizer: Iryna Rybak

Universität Stuttgart, Germany

Organizer: Andreas Rupp

Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

9:45-10:05 Efficient Solution of Coupled Flow and Porous Media Problems by Monolithic Multigrid Methods

Carmen Rodrigo, University of Zaragoza, Spain; Peiyao Luo, Delft University of Technology, Netherlands; Francisco José Gaspar, University of Zaragoza, Spain; Cornelis W. Oosterlee, Centrum voor Wiskunde en Informatica (CWI), Netherlands

10:10-10:30 Time-accurate, Doubly-adaptive Artificial Compression Methods for Prediction of Fluid Motion

William Layton, University of Pittsburgh, U.S.

10:35-10:55 A Conforming Mixed Finite Element Method for the Navier--Stokes/Darcy--Forchheimer Coupled Problem

Sergio Caucao, University of Pittsburgh, U.S.; Marco Discacciati, Loughborough University, United Kingdom; Gabriel N. Gatica, Universidad de Concepcion, Chile; Ricardo Oyarzua, Universidad del Bío-Bío, Chile

11:00-11:20 Effective Model for Crystal Precipitation and Dissolution in a Porous Medium with Perforated Solid Matrix

Raphael Schulz, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

11:25-11:45 Reduced Stokes/Darcy Model for Flow in Fractured Porous Media

Iryna Rybak, Universität Stuttgart, Germany; Stefan Metzger, Illinois Institute of Technology, U.S.

continued in next column

Tuesday, March 12

MS16

High Order Schemes for Simulation of Flow and Transport in Porous Media - Part II of II

9:45 a.m.-11:50 a.m.

Room: Richmond 1/2

For Part 1 see MS7

Numerical simulation of flow and transport in porous media is complicated by processes such as fluid phase behavior, chemical reactions, formation heterogeneity, and buoyancy. The governing equations tend to exhibit strong parabolic and hyperbolic behavious, and steep gradients can form in the solution. Moreover, highly channelized flow can arise in many geologic formations. High order accurate numerical schemes can be used to improve the approximation of the solution. This minisymposium will bring together researchers working on various numerical schemes designed to give relatively high-order accurate approximation of flow and transport.

Organizer: Todd Arbogast

University of Texas at Austin, U.S.

9:45-10:05 Enhanced Galerkin using Serendipity Spaces on Quadrilaterals for Miscible Displacement

Todd Arbogast and Zhen Tao, University of Texas at Austin, U.S.

10:10-10:30 Comparison of Implicit Discontinuous Galerkin and Weno Schemes on Stratigraphic and Unstructured Grids

Øystein Klemetsdal, Norwegian University of Science and Technology, Norway; Knut-Andreas Lie and Olav Møyner, SINTEF, Norway; Trine Mykkeltvedt, IRIS Energy - Reservoir Group, Norway

10:35-10:55 New Finite Element Solvers for Poroelasticity in the 2-field Approach

Jiangguo Liu, Colorado State University, U.S.

continued in next column

11:00-11:20 MIN3P-HPC: A High Performance Code for Subsurface Flow and Reactive Transport Simulation

Danyang Su and K. Ulrich Mayer, University of British Columbia, Canada; Kerry MacQuarrie, University of New Brunswick, Canada

11:25-11:45 Conservative Multirate Multiscale Method for Multiphase Flow in Heterogeneous Porous Media

Ludovica Delpopolo Carciopolo and Luca Formaggia, Politecnico di Milano, Italy; Hadi Hajibeygi, Technical University of Delft, Netherlands; Anna Scotti, Politecnico di Milano, Italy

Tuesday, March 12

MS17

Scalable Methods for Coupling Water Resources Modeling and Parameter Estimation - Part II of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom B

For Part 1 see MS5

Numerical models for coupled, multiscale water resources problems can be challenging to solve, and have many applications such as density-driven flow in coastal aquifer, nearshore hydrodynamics, ice-sheet dynamics and so on. With recent advances in sensor technology, not only high-fidelity forward modeling is important but also efficient methods to infer model parameters to account for uncertainties in conceptual modeling and measurement collection are crucial for tackling realistic applications. This minisymposium aims at highlighting the current research status, model capabilities, and numerical methods for solving the water resources problems by utilizing recently advanced forward or inverse modeling or both coupled. Considered processes may also include contaminant remediation to levee erosion as well as surface water problems from flash flooding to nearshore coastal flows.

Organizer: Jonghyun Lee

University of Hawaii at Manoa, U.S.

Organizer: Sanghyun Lee

Florida State University, U.S.

Organizer: Matthew Farthing

US Army Corps of Engineers, U.S.

9:45-10:05 Quantifying Uncertainties in Large-scale Bayesian Linear Inverse Problems using Krylov Subspace Methods

Arvind Saibaba, North Carolina State University, U.S.; Julianne Chung, Virginia Tech, U.S.; Katrina Petroske, North Carolina State University, U.S.

continued on next page

10:10-10:30 Bayesian Transmissivity Estimation using Continually Refined Local Surrogate Models within Parallel MCMC

Andrew Davis, US Army Corps of Engineers, U.S.; Youssef M. Marzouk, Massachusetts Institute of Technology, U.S.; Aaron Smith, University of Ottawa, Canada; Natesh Pillai, Harvard University, U.S.

10:35-10:55 Global Sensitivity Analysis and Parameter Estimation for Nearshore Wave Models

Daniel Reich, North Carolina State University, U.S.; Matthew Farthing, US Army Corps of Engineers, U.S.; Tyler Hesser, U.S. Army Research Development Engineering Command, U.S.; C.T. Kelley, North Carolina State University, U.S.; Matthew Parno, US Army Corps of Engineers, U.S.

11:00-11:20 Robust Parameter Estimation using Inverse Modeling and Advanced Machine Learning Techniques

Hojat Ghorbanidehno, Stanford University, U.S.; Jonghyun Lee, University of Hawaii at Manoa, U.S.; Matthew Farthing, US Army Corps of Engineers, U.S.; Tyler Hesser, U.S. Army Research Development Engineering Command, U.S.; Peter K Kitanidis and Eric F. Darve, Stanford University, U.S.

11:25-11:45 Ensemble Pattern-learning for Calibration of Subsurface Flow Models with Complex Geologic Facies Descriptions

Reza Khaninezhad, Apache Corporation, U.S.; Benham Jafarpour, University of Southern California, U.S.

Tuesday, March 12

MS18

Extended-model Versus Reduced-model Strategies for Full Waveform Inversion - Part II of II

9:45 a.m.-11:50 a.m.

Room: Briarpark 1/2

For Part 1 see MS3

Extracting the whole information from (seismic) wavefields for model reconstruction is challenging because the related PDE-constrained ptimization faces different difficulties when fighting against the dimensionality curse. One of widely used methods for such nonlinear constrained optimization is the Lagrange multipliers method where constraints are integrated into a Lagrangian function, leading to the Karush-Kuhn-Tucker (KKT) optimality conditions increasing drastically the search space size. Full waveform inversion is often performed using a reduced-model approach where only model parameters are considered. This reduced-model approach enforces exactly constrains through the wave PDE and the related adjoint PDE at each iteration, but non-linearity and ill-posedness of the problem increases, such as cycle-skipping issues. Various full-space approaches have been investigated (sub-surface offsets or time lags, wavefield or source extensions). Alternatively, reduced-model approaches have tried to overcome issues essentially by data comparison design (Wiener filter, for example), keeping low the dimensions of the model space. This session is devoted to highlight pros and cons of the different strategies and to see how to manage the mitigation of the dimensionality of the problem. Contributions from methodological and practical implementations are welcome, as well as synthetic and field-data examples.

Organizer: Jean Virieux

ISTerre, University Joseph Fourier, France

Organizer: Sue Minkoff

University of Texas, Dallas, U.S.

9:45-10:05 Reconstructed Full Waveform Inversion with Extended Source: Increasing Depth and Resolution

Chao Wang, ION, U.S.

continued in next column

10:10-10:30 Seeding Waveform Inversion from Bandwidth Extension

Laurent Demanet and *Hongyu Sun*, Massachusetts Institute of Technology, U.S.

10:35-10:55 Extending the Search Space of Full Waveform Inversion (FWI) by Alternating Direction Method of Multipliers (ADMM)

Hossein Aghamiry, University of Cote d'Azur, France; Ali Gholami, University of Tehran, Iran; *Stephane Operto*, Université de Nice, France

11:00-11:20 Seismic Velocity Analysis: What is the Need for a Non-physical Extended Space to Derive a Proper Solution?

Herve Chauris, Mines ParisTech, France

11:25-11:45 On the Parametrization of Slope Tomography: Its Implication on the Velocity-position Coupling

Serge Sambolian, Stéphane Operto, Alessandra Ribodetti, and Borhan Tavakoli F., University of Cote d'Azur, France; Jean Virieux, ISTerre, University Joseph Fourier, France

Tuesday, March 12

MS19

Modeling of Moving Interfaces at the Pore Scale

9:45 a.m.-11:50 a.m.

Room: Westchase 1/2

Processes like multi-phase flow or reactive transport in porous media often involve moving boundaries at the scale of the pores. These appear either as a moving fluid-fluid interface, or a moving fluid-solid interface. The evolving interfaces have impact on various properties up to larger scales, such as the permeability or porosity of the medium. Therefore, to understand processes like the ones mentioned above, the moving interfaces appearing at the pore scale need to be taken into account explicitly, although this complicates the mathematical models and their mathematical and numerical analysis. This minisymposium will address issues related to how to account for moving interfaces in the mathematical models (like level-set or phase fields), the upscaling of such models, their analysis and numerical discretization.

Organizer: Carina Bringedal
Universität Stuttgart, Germany

Organizer: Iuliu Sorin Pop
Hasselt University, Belgium

9:45-10:05 Phase Field Models for Multi-phase Pore-scale Processes with Microstructural Evolution

Lars Von Wolff and Christian Rohde, Universität Stuttgart, Germany

10:10-10:30 FSI with Multi-layered Poroelastic Tissue

Suncica Canic, University of California, U.S.

10:35-10:55 A Multiscale Formulation of Multiphase Flow at the Pore Scale

Yashar Mehmani and Hamdi Tchelepi, Stanford University, U.S.

11:00-11:20 Numerical Analysis of a System of Variational Inequalities for Biofilm Growth at Porescale

Azhar Alhammali and Malgorzata Peszynska, Oregon State University, U.S.

continued in next column

11:25-11:45 Level Set-Immersed Boundary Method for Pore-scale Simulations of Precipitation-dissolution Processes in Porous Media

Mehrdad Yousefzadeh and Ilenia Battiato, Stanford University, U.S.

Lunch Break

11:50 a.m.-1:20 p.m.

Attendees on their own

Tuesday, March 12

IP3

Challenges in Recovering Deep Low-wavenumber Updates in Full Waveform Inversion

1:20 p.m.-2:05 p.m.

Room: Grand Ballroom EFGH

Chair: Jean Virieux, Université Joseph Fourier, France

Full Waveform Inversion (FWI) is a method for recovering unknown coefficients (medium properties) in the wave equation given recorded waveforms on a boundary of the domain of propagation. Over the past decade it emerged as a method of choice for determining subsurface properties in exploration seismology. While the fundamentals of FWI have been known for over 30 years, its robust application on industrial scale still presents a formidable challenge, given limited surface coverage of available recordings. Many early FWI applications were focused on working with diving waves (transmitted arrivals). However, in exploration seismology these types of waves sample only relatively shallow depths. Recently, significant efforts have been directed towards extending FWI's reach deeper into the subsurface by obtaining information about large-scale characteristics of subsurface properties from reflected arrivals. Extraction of the so-called ``tomographic" mode associated with this task is a difficult problem in practical FWI applications because it is weak relative to other parts of the objective function gradient. This talk will cover the fundamentals of FWI, followed by challenges, solutions, and open problems associated with exploiting the tomographic mode, including the choice of objective functions, methods of separating various components of the gradient, and use of constraints.

Anatoly Baumstein
ExxonMobil Upstream Research Company, U.S.

Intermission

2:05 p.m.-2:15 p.m.

Tuesday, March 12

MS20

Advances in Modeling of Non-linear Elasticity and Plasticity for Geomaterials

2:15 p.m.-4:20 p.m.

Room: Westchase 1/2

Mechanical deformations in the context of subsurface engineering applications such as geothermal energy recovery and carbon sequestration, occur as a response to subsurface engineering, and they are also relevant in understanding the geological development of a formation. Deformations are typically characterized by elasto-plastic behaviour. In plasticity modeling, classical models, e.g. capped Drucker-Prager, Cam-Clay, Mohr-Coulomb, are frequently used. These models are characterized by plastic compaction, hardening (softening), and a possibly non-linear elastic law. Plastic anisotropy is also an important feature in many circumstances of practical interest, e.g. fractured materials. Furthermore, the coupling between plastic solid behaviour and single- and multi-phase flow through the pores is not yet fully understood. All these features make the formulation of a computationally efficient yet representative constitutive model a difficult task for many geomaterials. The scope of the session is therefore to bring together novel mathematical models and advanced computational methods for non-linear elasticity and plasticity relevant to subsurface engineering applications. The focus will be on constitutive modelling and solution algorithms in the context of classical continuum mechanics, with a particular interest in fractures and modelling of fractured rocks as homogenized media.

Organizer: Michele Starnoni
University of Bergen, Norway

Organizer: Jonny Rutqvist
Lawrence Berkeley National Laboratory, U.S.

Organizer: Inga Berre
University of Bergen, Norway

2:15-2:35 Challenges in Modelling the Anisotropic Poroelastoplastic Behaviour of Fractured Rocks as Homogenized Media

Michele Starnoni, Inga Berre, Eirik Keilegavlen, and Jan M. Nordbotten, University of Bergen, Norway

continued in next column

2:40-3:00 Reliable and Fast Solving of Small-strain Plasticity Problems with a Nonsmooth Multigrid Method

Patrick Jaap and Oliver Sander, Technische Universität Dresden, Germany

3:05-3:25 Numerical Formulations and Applications for Geomaterial Cap Plasticity Models

Ruijie Liu, University of Texas, San Antonio, U.S.; Zhijun Liu, Lanzhou University, China; Ben Ganis and Mary F. Wheeler, University of Texas at Austin, U.S.

3:30-3:50 Numerical Methods for Fault Slip Computation in Poroelastic Media

Anna Scotti and Luca Formaggia, Politecnico di Milano, Italy

3:55-4:15 Numerical Simulation of a Poroelastic Model with Random Coefficients using Polynomial Chaos and High-order Polyhedral Methods

Pierre Sochala, BRGM, France; Michele Botti, University of Montpellier, France; Olivier Le Ma\^itre, Centre National de la Recherche Scientifique, France; Daniele Di Pietro, University of Montpellier, France

Tuesday, March 12

MS21

Upscaled Models for Multiscale and Multi-physics Problems - Part I of II

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom B

For Part 2 see MS31

Many practical applications require sophisticated mathematical models. To give realistic simulated solutions, these models typically consist of coupled equations for various physical components of the problem. The solutions to these systems usually have multiscale natures due to media heterogeneities and system nonlinearities. Solving these problems directly is computationally expensive, and thus upscaled models are beneficial. The focus of this minisymposium is some recent advances in upscaling techniques for solving these complex systems. Another purpose of this minisymposium is to gather researchers in related fields and provide a forum to exchange ideas.

Organizer: Eric Chung
Chinese University of Hong Kong, Hong Kong

Organizer: Yalchin Efendiev
Texas A&M University, U.S.

Organizer: Maria Vasilyeva
Texas A&M University, U.S. and North-Eastern Federal University, Russia

2:15-2:35 Adaptive Multiscale Methods for Multiphase Simulation of Complex Reservoir Models

Knut-Andreas Lie, Olav Møyner, and Øystein Klemetsdal, SINTEF, Norway

2:40-3:00 Upscaling as Acceleration of Optimization and Inversion for Field Development

Xiao-Hui Wu, ExxonMobil Upstream Research Company, U.S.

3:05-3:25 A Novel Transient Diffuse Source Algorithm for Multiscale Simulation in Porous Media

Mike King, *Krishna Nunna*, and Ching-Hsien Liu, Texas A&M University, U.S.

continued on next page

Tuesday, March 12

MS21

Upscaled Models for Multiscale and Multi-physics Problems - Part I of II

continued

3:30-3:50 Constraint Energy Minimizing Generalized Multiscale Finite Element Method

Eric Chung, Chinese University of Hong Kong, Hong Kong

3:55-4:15 Generalized Rough Polyharmonic Splines for Numerical Homogenization

Xinliang Liu and *Lei Zhang*, Shanghai Jiao Tong University, China

Tuesday, March 12

MS22

Solvers for Petroleum Reservoir Simulation

2:15 p.m.-4:20 p.m.

Room: Briarpark 1/2

The use of reservoir simulators in the oil and gas industry is essential to the development of new oil fields and in generating production forecasts for existing oil fields. Reservoir simulation involves the solution of mathematical models for the flow of fluids (typically oil, water and gas) through porous media, potentially coupled with other physics such as thermal effects and poromechanics. The complexity of such models, and the time each simulation takes motivates the need for highly efficient solvers. In this minisymposium, recent advances on multigrid methods, preconditioning, and nonlinear solvers for petroleum reservoir simulation will be presented.

Organizer: Thomas Roy

University of Oxford, United Kingdom

Organizer: Andy Wathen

Oxford University, United Kingdom

Organizer: Tom B. Jonsthovel

Schlumberger, United Kingdom

2:15-2:35 Block Preconditioners for Non-isothermal Flow through Porous Media

Thomas Roy, University of Oxford, United Kingdom; Tom B. Jonsthovel and Christopher Lemon, Schlumberger, United Kingdom; Andy Wathen, Oxford University, United Kingdom

2:40-3:00 A Scalable Multigrid Reduction Framework for Coupled Multiphase Poromechanics

Quan M. Bui, Daniel Osei-Kuffuor, Nicola Castelletto, and Joshua A. White, Lawrence Livermore National Laboratory, U.S.

3:05-3:25 System-AMG as a Framework for the Full Linear Solution Process in Fully Implicit Reservoir Simulations

Sebastian Gries, Fraunhofer Institute for Algorithms and Scientific Computing, Germany

3:30-3:50 Inexact Newton Method for General Purpose Reservoir Simulation

Arthur Moncorge and Soham Sheth, Total E&P, United Kingdom

3:55-4:15 Projected Infinite-dimensional Solutions as Embarrassingly Parallel Strong Linear Preconditioners

Rami M. Younis, University of Tulsa, U.S.

continued in next column

Tuesday, March 12

MS23

Physics-based Rupture and Tsunami Simulation - Part I of II

2:15 p.m.-4:20 p.m.

Room: Richmond 1/2

For Part 2 see MS36

Recent data of tsunami earthquakes revealed a large variability in mechanisms, geometric features, physical processes and hence tsunami wave variation when impacting coastal regions. At the same time the modeling and simulation capabilities, utilizing HPC infrastructures and modern numerical methods, are now able to represent realistic rupture behavior and coupled earthquake-tsunami simulations. This minisymposium focuses on coupled modeling workflows for tsunami earthquakes. We invite presentations related to earthquake cycling, rupture processes, and tsunami simulation, including near- and on-shore processes. The presentations should address computational issues, validation of modeling chains, process studies as well as mathematical approaches to formulate concise process simulations.

Organizer: Jörn Behrens
Universität Hamburg, Germany

Organizer: Alice A. Gabriel
Ludwig-Maximilians-Universität München, Germany

Organizer: Michael Bader
Technische Universität München, Germany

2:15-2:35 Development of Runge-Kutta Discontinuous Galerkin Methods for Well-balanced Tsunami Inundation

Jörn Behrens, Universität Hamburg, Germany; Nicole Beisiegel, University College Dublin, Ireland; Stefan Vater, Freie Universität Berlin, Germany

2:40-3:00 Uncertainty Quantification Techniques for Tsunamis

Kyle T. Mandli, Columbia University, U.S.

continued in next column

3:05-3:25 Multilayer Non-hydrostatic Shallow-water Models for Tsunami Simulations

Jorge Macias Sanchez, Universidad de Málaga, Spain

3:30-3:50 A Simulation Pipeline for the Simulation of Earthquakes and Resulting Tsunamis

Michael Bader, Leonhard Rannabauer, and Carsten Uphoff, Technische Universität München, Germany

3:55-4:15 Efficient Tsunami Modeling on Adaptive Grids with Graphics Processing Units (GPUs)

Xinsheng Qin, University of Washington, Seattle, U.S.; Randall LeVeque and Michael Motley, University of Washington, U.S.

Tuesday, March 12

MS24

Modeling with Constraints and Phase Transitions - Part I of II

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom A

For Part 2 see MS34

Multicomponent multiphase models are ubiquitous in subsurface modeling; equally important is accounting for energy equation and nonisothermal effects, the latter with even broader applications in geosciences. Various time and spatial scales require equilibrium and kinetic models, and several applications call for pointwise constraints on the solutions. While the applications are disparate, the algorithms and analyses share challenges and successes. In this minisymposium we bring researchers involved in various aspects and applications.

Organizer: Malgorzata Peszynska
Oregon State University, U.S.

Organizer: Michel Kern
Inria & Maison de la Simulation, France

2:15-2:35 Parametrization Technique for Reactive Multiphase Flow and Transport

Stephan de Hoop and Denis Voskov, Technical University of Delft, Netherlands

2:40-3:00 Numerical Simulation Approaches for Modeling Natural Gas Hydrate Systems in Geologic Media Subject to Geomechanical Stresses

Mark D. White, Pacific Northwest National Laboratory, U.S.

3:05-3:25 Numerical Modelling of High Temperature Geothermal Systems with a Soil-atmosphere Boundary Condition

Laurence Beaude and Roland Masson, Université de Nice, Sophia Antipolis, France; Simon Lopez and Farid Smai, Brgm Centre-Val De Loire - Site D'orléans, France

3:30-3:50 New Numerical and Physical Developments in Chemical EOR Simulation

Hamid Lashgari, Gary Pope, and Matthew Balhoff, University of Texas at Austin, U.S.

continued on next page

Tuesday, March 12

MS24

Modeling with Constraints and Phase Transitions - Part I of II

continued

3:55-4:15 Analysing Spatial Scaling Effects in Mineral Reaction Rates in Porous Media with a Hybrid Numerical Model

Po-Wei Huang, ETH Zürich, Switzerland; *Bernd Flemisch*, Universität Stuttgart, Germany; Anozie Ebigbo, Universität Stuttgart, Germany; Martin Saar, ETH Zürich, Switzerland

Tuesday, March 12

MS25

Practical Aspects of Large-scale Sparsity-promoting Seismic Inversion - Part I of II

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom EFGH

For Part 2 see MS35

Sparsity-promoting regularization, long a key technology in imaging sciences, has great theoretical significance in seismic imaging and full-waveform inversion (FWI) applications. The importance of sparsity-promoting regularization in seismic inversion stems from its ability to help resolve compact features of structural subsurface models from noisy band-limited data. Despite the existence of a plethora of general-purpose optimization algorithms involving non-smooth regularization (such as L1 or TV), their adoption in practical FWI applications is hindered by the computational complexity of FWI that typically requires inversion of structural earth models with billions degrees of freedom. Computational feasibility, which often does not correlate very well with asymptotic convergence properties of employed algorithms, is key to the successful application of non-smooth regularization in FWI. In this minisymposium we focus on bringing the cost of L1/TV-regularized FWI closer to that of FWI with smooth objective functions. Both synthetic and field-data experiments will be included, with emphasis on computational feasibility while demonstrating uplift from the regularization. Although the stress is on practical aspects of regularized FWI, theoretical works and contributions from other fields that may help deliver a speed-up in FWI are welcome as well. Sample topics of interest: smoothing of L1/TV-regularized misfits, primal-dual and splitting methods, convergence acceleration.

Organizer: Musa Maharramov
ExxonMobil Upstream Research Company, U.S.

Organizer: Anatoly Baumstein
ExxonMobil Upstream Research Company, U.S.

2:15-2:35 Challenges and Opportunities of Sparsity-promoting FWI

Musa Maharramov, Anatoly Baumstein, and Partha Routh, ExxonMobil Upstream Research Company, U.S.

2:40-3:00 Shaping Regularization

Sergey Fomel, University of Texas at Austin, U.S.

3:05-3:25 Adaptive ADMM with Spectral Penalty Parameter Selection

Zheng Xu, University of Maryland, U.S.; Mario A. T. Figueiredo, Instituto Superior Tecnico, Portugal; Tom Goldstein, University of Maryland, U.S.

3:30-3:50 TV-regularized Extended LS RTM

Yunyue Elita Li, National University of Singapore, Singapore

3:55-4:15 Sparsity in Multichannel Blind Deconvolution via Focusing Constraints

Pawan Bharadwaj, Laurent Demanet, and Aime Fournier, Massachusetts Institute of Technology, U.S.

continued in next column

Tuesday, March 12

Coffee Break and Poster Session **Posters will be on display during Tuesday coffee breaks**

4:20 p.m.-4:50 p.m.

Room: Grand Ballroom D

Tuesday, March 12

MT3

Data-driven Discovery for Geophysical Systems: Integrating Machine Learning and Dynamical Systems for Learning Multiscale Physics Systems

4:50 p.m.-6:55 p.m.

Room: Grand Ballroom EFGH

A major challenge in the study of dynamical systems is that of model discovery: turning data into models that are not just predictive, but provide insight into the nature of the underlying dynamical system that generated the data. We introduce a number of data-driven strategies for discovering nonlinear multiscale dynamical systems and their embeddings from data. We consider two canonical cases: (i) systems for which we have full measurements of the governing variables, and (ii) systems for which we have incomplete measurements. For systems with full state measurements, we show that the recent sparse identification of nonlinear dynamical systems (SINDy) method can discover governing equations with relatively little data and introduce a sampling method that allows SINDy to scale efficiently to problems with multiple time scales, noise and parametric dependencies. For systems with incomplete observations, we show that the Hankel alternative view of Koopman (HAVOK) method, based on time-delay embedding coordinates, can be used to obtain a linear models and Koopman invariant measurement systems that nearly perfectly captures the dynamics of nonlinear quasiperiodic systems. We introduce two strategies for using HAVOK on systems with multiple time scales. Together, these approaches provide a suite of mathematical strategies for reducing the data required to discover and model nonlinear multiscale systems.

Organizer and Speaker:

Nathan Kutz,
University of Washington, U.S.

Tuesday, March 12

MS26

Optimal Transport for Imaging in Geosciences - Part II of II

4:50 p.m.-6:55 p.m.

Room: Briarpark 1/2

For Part 1 see MS13

Full waveform inversion (FWI) is a seismic imaging method which is now part of the conventional imaging workflow in the industry. It is also used for global and regional scale imaging in seismology. Its main interest compared to tomography is its high-resolution power. FWI is formulated as a least-squares (L2) minimization problem. The L2 misfit function is highly nonconvex. Mitigating this nonconvexity is a longstanding difficulty. Despite important advances yielding successful applications through multi-scale approaches, obtaining robust and flexible FWI algorithms remains an open question. Recently, [Engquist and Froese, 2014] have proposed to use the Wasserstein distance as a misfit function. This distance, from the optimal transport (OT) theory, is convex with respect to shifted patterns. For FWI, the convexity with respect to time-shifts is a proxy for the convexity with respect to the subsurface velocities, making the Wasserstein distance a very attractive tool. However, its application to seismic data is not straightforward: OT assumes positivity and mass balance between compared quantities while seismic data is non-positive. Integrating OT within FWI also requires fast and robust numerical methods. The workshop will present recent advances to overcome these difficulties. Extending OT to signed measures will be discussed. Efficient implementations using linear programming or fluid-dynamic will be introduced. First industrial scale applications will be presented.

Organizer: Yunan Yang
Courant Institute of Mathematical Sciences, New York University, U.S.

Organizer: Ludovic Métivier
Université Grenoble Alpes, France

4:50-5:10 The Wasserstein-Fisher-Rao Metric for Waveform Based Earthquake Location

Hao Wu, Tsinghua University, China

continued on next page

Tuesday, March 12

MS26

Optimal Transport for Imaging in Geosciences - Part II of II

continued

5:15-5:35 Full Waveform Inversion with Unbalanced Optimal Transport

Lingyun Qiu, Petroleum Geo-Services, Inc, Norway

5:40-6:00 An Inversion Strategy Based on Optimal Transport and Time-windowing for Elastic Anisotropic FWI

Weiguang He, Université Grenoble Alpes, France

6:05-6:25 An Optimal Transport Approach to Inversion of P-wave Receiver Functions

Navid Hedjazian and Thomas Bodin, Université de Lyon, France; Ludovic Métivier, Université Grenoble Alpes, France

6:30-6:50 Reflection Full-waveform Inversion with Sliced Wasserstein Distance

Fuqiang Chen and Daniel Peter, King Abdullah University of Science & Technology (KAUST), Saudi Arabia

Tuesday, March 12

MS27

Optimization of Sequential Decisions under Uncertainty for Subsurface Applications

4:50 p.m.-6:55 p.m.

Room: Richmond 1/2

The final purpose of most developments in applied science is recommendations for making decisions. Many subsurface applications involve sequential decision-making; for example, hydrocarbon production optimization and geosteering. Closed-loop workflows (CLW) are standard for treating uncertainty in sequential decision-making in reservoir management. CLWs continuously update the stochastic subsurface model and use it to optimize decisions. CLW is computationally viable even when complex simulation models are involved because it ignores the evolution of uncertainty due to future data gathering. This trade-off implies possibly suboptimal decisions. An alternative is to use dynamic programming (DP) approaches that consider full decision trees of a discretized sequential decision problem. An issue of using DP to account for the evolution of uncertainty is the curse of dimensionality. Although many approximate DP methods were proposed, most of them are still limited to small problems. Thus, new compromises should be developed to allow for fast yet accurate decision optimization for subsurface applications involving bigdata and computationally-expensive models.
We encourage the participants to share the formulation of problems and methods for both discrete and continuous optimization. Specific focus is set on problem-specific methods that explore compromises for complete workflows relevant to subsurface applications of any kind.

Organizer: Sergey Alyaev
NORCE Norwegian Research Centre, Norway

4:50-5:10 The Full Structure of Reservoir Management

Aojie Hong and Reidar Bratvold, University of Stavanger, Norway; Cuthbert S. W. Ng, Norwegian University of Science and Technology, Norway

continued in next column

5:15-5:35 Decision Analyses for Contaminant Remediation

Velimir V. Vesselinov and D. O'Malley, Los Alamos National Laboratory, U.S.

5:40-6:00 Decision Making under Uncertanty - Field Development: Results, Challenges and Learnings

Remus G. Hanea, Equinor, Norway

6:05-6:25 Real-time Decision Making for Geosteering

Sergey Alyaev, NORCE Norwegian Research Centre, Norway; Reidar Bratvold and Aojie Hong, University of Stavanger, Norway; Erich Suter, Nazanin Jahani, and Benoit Daireaux, NORCE Norwegian Research Centre, Norway

6:30-6:50 Value of Sequential Information in Mud Weight Window Assessment

Jacopo Paglia and Jo Eidsvik, Norwegian University of Science and Technology, Norway

Tuesday, March 12

MS28

Advanced Models and Methods for Underground Flows in Complex Geometries with Applications - Part II of II

4:50 p.m.-6:55 p.m.

Room: Westchase 1/2

For Part 1 see MS1

A wide range of applications, such as exploitation of subsurface resources or geological waste disposal, requires accurate description of flows in underground basins. The subsoil is a porous medium, typically crossed by intricate networks of fractures and with an intrinsic multiscale nature, where complex physical phenomena, like solute transport, single and multi-phase flows, take place. Unconventional mathematical models and numerical schemes, able to deal with such challenges are thus crucial for effective and reliable predictions. Examples are robust meshing strategies, non-conforming or polygonal discretization methods, reduced order models, coupling strategies for mixed-dimensional problems. This minisymposium is aimed at collecting the most recent methods and models based on non-standard approximation strategies in complex domains for simulating underground flows and related applications.

Organizer: Alessio Fumagalli
University of Bergen, Norway

Organizer: Anna Scotti
Politecnico di Milano, Italy

Organizer: Stefano Scialo
Politecnico di Torino, Italy

4:50-5:10 Derivation of Effective Models for Unsaturated Flow in Fractured Porous Media

Iuliu Sorin Pop, Hasselt University, Belgium; Florian List, University of Sydney, Australia; Kundan Kumar and Florin Adrian Radu, University of Bergen, Norway

continued in next column

5:15-5:35 An Upscaled Model for Solute Transport in Fractured Media with Advective Trapping

Insa Neuweiler, University of Hannover, Germany; Juan J. Hidalgo and Marco Dentz, IDAEA and Spanish National Research Council (CSIC), Spain

5:40-6:00 Coupling Virtual Element Methods and Finite Volume Schemes for Computational Geomechanics on General Meshes

Julien Coulet and Isabelle Faille, IFP Energies nouvelles, France; Vivette Girault, University of Paris VI, France; Nicolas Guy, IFP Energies nouvelles, France; Frédéric Nataf, CNRS and UPMC, France

6:05-6:25 Sparse Grid Approximation of Elliptic PDEs with Lognormal Diffusion Coefficient

Lorenzo Tamellini, Istituto di Matematica Applicata e Tecnologie Informatiche-CNR, Italy

6:30-6:50 Two-phase Flows in Porous Media with the Multiscale Robin Coupled Method

Franciane F. Rocha, University of Texas at Dallas, U.S.; Fabricio S. Sousa and Roberto Ausas, Universidade de Sao Paulo, Brazil; Gustavo Buscaglia, Instituto de Ciencias Matematicas e Computacao, Brazil; Felipe Pereira, University of Texas, Dallas, U.S.

Tuesday, March 12

CP7

Climate II

4:50 p.m.-6:10 p.m.

Room: Grand Ballroom B

Chair: Sourav Dutta, U.S. Army Engineer Research and Development Center, U.S.

4:50-5:05 A Multilayer Approach to Landslide Generated Tsunamis

Jorge Macías, *Manuel Castro*, and Cipriano Escalante, Universidad de Málaga, Spain

5:10-5:25 Efficient Numerical Ice-sheet Simulations over Long Time Spans

Gong Cheng, Per Lötstedt, and Lina von Sydow, Uppsala University, Sweden

5:30-5:45 An Efficient Non-intrusive Reduced Order Model for Approximation of Shallow Water Flows

Sourav Dutta, U.S. Army Engineer Research and Development Center, U.S.; Matthew Farthing, US Army Corps of Engineers, U.S.

5:50-6:05 Targeted Re-investigation of Paleoclimate Records using Information Theory

Joshua Garland, Santa Fe Institute, U.S.; Tyler Jones, University of Colorado Boulder, U.S.; Elizabeth Bradley, University of Colorado, Boulder and Santa Fe Institute, U.S.; Michael Neuder and James White, University of Colorado Boulder, U.S.

Tuesday, March 12

CP8

Efficient Algorithms and Implementations

4:50 p.m.-6:50 p.m.

Room: Grand Ballroom A

Chair: Het Y. Mankad, University of Texas at Dallas, U.S.

4:50-5:05 Conservative Explicit Local Time-stepping Schemes for the Shallow Water Equations

Thi-Thao-Phuong Hoang, Auburn University, U.S.; Wei Leng, Chinese Academy of Sciences, China; Lili Ju and Zhu Wang, University of South Carolina, U.S.; Konstantin Pieper, Florida State University, U.S.

5:10-5:25 The Multiscale Perturbation Method for Elliptic Equations

Het Y. Mankad and Abdallah Alsadig, University of Texas at Dallas, U.S.; Felipe Pereira, University of Texas, Dallas, U.S.; Fabricio Sousa, University of Sao Paulo, Brazil

5:30-5:45 A Scalable Parallel Implementation of Double Porosity / Permeability Model

Mohammad Sarraf Joshaghani and Kalyana Nakshatrala, University of Houston, U.S.

5:50-6:05 Finite-3lement Approximation for Practical Simulation of Oil-water Systems

Dimitar Trenev, ExxonMobil Research, U.S.; Laurent White, ExxonMobil, U.S.; Jeremy Brandman, ExxonMobil Corporate Strategic Research, U.S.

6:10-6:25 Multiparameter Full-Waveform Inversion with Near-Interface Sources using Staggered-grid Finite Differences

Joseph Jennings, Martin Almquist, and Eric M. Dunham, Stanford University, U.S.

6:30-6:45 `Streamline' Flux-form Semi-Lagrangian Methods for Scalar Transport

Darren Engwirda, Columbia University and NASA Goddard Institute for Space Studies, U.S.

Wednesday, March 13

Registration

8:00 a.m.-5:15 p.m.

Room: Westchase 3/4

Remarks

8:25 a.m.-8:30 p.m.

Room: Grand Ballroom EFGH

Wednesday, March 13

IP4

Sea Ice Model Complexity

8:30 a.m.-9:15 a.m.

Room: Grand Ballroom EFGH

Chair: Kenneth M. Golden, University of Utah, U.S.

The CICE sea ice model is used extensively by climate and Earth system research groups, and also by operational centers for applications such as numerical weather prediction and guidance for military operations. A current discussion thread within the sea ice modeling community hinges on how complex such models need to be. This talk delves into the complexity of physical processes represented in the CICE model, including how the model evolved and why such complexity might — or might not — be needed.

Elizabeth Hunke

Los Alamos National Laboratory, U.S.

Coffee Break

9:15 a.m.-9:45 a.m.

Room: Grand Ballroom D

Wednesday, March 13

MS29

Fracture Formation Coupled with Fluid Flow and Wave Propagation in the Porous Media - Part I of II

9:45 a.m.-11:50 a.m.

Room: Westchase 1/2

For Part 2 see MS52

This minisymposium is dedicated to both analytical and numerical aspects of wave propagation coupled with non-linear flows in porous media. Recent advances in engineering and industry related to fracturing and associated problems in hydrodynamic and geo-mechanics of porous media bring new challenging questions in understanding the non-linear nature of the wave propagation in the media coupled with fluid flow. These processes require new models, sophisticated analysis and efficient algorithms. The goal of the minisymposium is to present and discuss new results in all of these aspects, particularly, in non-linear PDE models, stability analysis, long-time dynamics, numerical simulations, etc.

Organizer: Viktoria Savatorova
University of Nevada Las Vegas, U.S. and National Research Nuclear University, Russia

Organizer: Akif Ibragimov
Texas Tech University, U.S.

Organizer: Aleksey S. Telyakovskiy
University of Nevada, U.S.

9:45-10:05 Approximate Analytical Solution to the Groundwater Flow in Unconfined Aquifers

Aleksey S. Telyakovskiy, University of Nevada, U.S.

10:10-10:30 A Power Law Analysis of Non-Newtonian Fluid Flow through Porous Media

Mohamed Soliman and Fahd Siddiqui, University of Houston, U.S.; Waylon House, Texas Tech University, U.S.

continued in next column

10:35-10:55 Perturbative Theory of Flow-driven Deformation of Small Pores

Ivan C. Christov, Purdue University, U.S.

11:00-11:20 Fully Coupled Geomechanical and Dynamic Reservoir Simulations

Vasilii Shelkov, Rock Flow Dynamics LLC, Russia

11:25-11:45 Analytical, Numerical and Geometric Methods with Applications to Fractured Porous Media Modeling

Pushpi Paranamana, Rutgers University, U.S.; Eugenio Aulisa, Akif Ibragimov, and Magdalena Toda, Texas Tech University, U.S.

Wednesday, March 13

MS30

Uncertainty Quantification in Subsurface Flow and Transport

9:45 a.m.-11:50 a.m.

Room: Richmond 1/2

Problems of subsurface flow and transport are often complicated by inevitable uncertainties in initial conditions, boundary conditions, and parameter fields. Studying the effects of such uncertainties on quantities of interest is complicated by the fact that accurate modeling often requires simulations that are computationally prohibitive due to high-dimensional parameter spaces and expensive forward models. However, in many cases it is essential to consider the effects of uncertainty in order to make accurate observations and reliable predictions. This minisymposium focuses on recent advances in uncertainty quantification methodologies and applications to problems in subsurface flow and transport as well as novel applications of uncertainty quantification techniques to problems of utmost interest to the community.

Organizer: Steven A. Mattis
Technische Universität München, Germany

Organizer: Gabriele Chiogna
Technische Universität München, Germany

9:45-10:05 Accelerating Prediction under Uncertainty for Groundwater Problems

Steven A. Mattis and Barbara Wohlmuth, Technische Universität München, Germany

10:10-10:30 Uncertainty Quantification and Sensitivity Analysis in Reservoirs with Fractures

Sam Estes, University of Texas at Austin, U.S.

10:35-10:55 Impact of Highly Transient Boundary Conditions on the Groundwater Flow Field and its Implication for Mixing

Mónica Basilio Hazas and Gabriele Chiogna, Technische Universität München, Germany

continued on next page

Wednesday, March 13

MS30

Uncertainty Quantification in Subsurface Flow and Transport

continued

11:00-11:20 Emulating Mesoscale Physics in Subsurface Systems through Machine Learning

Nishant Panda, Dave Osthus, Diane Oyen, Gowri Srinivasan, and Humberto C. Godinez, Los Alamos National Laboratory, U.S.

11:25-11:45 Fast and Scalable Joint Subsurface Inversion using Hydrological-geophysical Datasets with a Parallel Black-box Fast Multipole Method

Niels Grobbe and Jonghyun Lee, University of Hawaii at Manoa, U.S.; Ruoxi Wang, Google Brain, U.S.; Chao Chen and Eric Darve, Stanford University, U.S.

Wednesday, March 13

MS31

Upscaled Models for Multiscale and Multi-physics Problems - Part II of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom B

For Part 1 see MS21

Many practical applications require sophisticated mathematical models. To give realistic simulated solutions, these models typically consist of coupled equations for various physical components of the problem. The solutions to these systems usually have multiscale natures due to media heterogeneities and system nonlinearities. Solving these problems directly is computationally expensive, and thus upscaled models are beneficial. The focus of this minisymposium is some recent advances in upscaling techniques for solving these complex systems. Another purpose of this minisymposium is to gather researchers in related fields and provide a forum to exchange ideas.

Organizer: Eric Chung
Chinese University of Hong Kong, Hong Kong

Organizer: Yalchin Efendiev
Texas A&M University, U.S.

Organizer: Maria Vasilyeva
Texas A&M University, U.S. and North-Eastern Federal University, Russia

9:45-10:05 Using Pore Scale Simulations to Improve Continuum Modeling of Straining of Particulate Suspensions in Porous and Fractured Media

Masa Prodanovic, University of Texas at Austin, U.S.

10:10-10:30 Model-order Reduction of Coupled Flow and Geomechanics in Unconventional Reservoirs

Eduardo Gildin and Horacio Florez, Texas A&M University, U.S.

10:35-10:55 Darcy-Brinkman-Stokes Framework for Modeling of Reactive Dissolution

Pavel Tomin, Stanford University, U.S.; Denis Voskov, Technical University of Delft, Netherlands

11:00-11:20 Nonlinear Nonlocal Multicontinua Upscaling Method

Wing Tat Leung, University of Texas at Austin, U.S.; Eric T. Chung, Chinese University of Hong Kong, Hong Kong; Yalchin Efendiev, Texas A&M University, U.S.

11:25-11:45 Numerical Upscaling of Perturbed Diffusion Problems

Tim Keil, Universität Münster, Germany

continued in next column

Wednesday, March 13

MS32

Advanced Mathematical Approaches for Simulation of Fault Reactivation - Part I of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom EFGH

For Part 2 see MS43

Continuous industrial activities related to energy extraction or injection operations can cause significant changes of pore-pressure in subsurface formations. As consequences, the overburden state is changing and so does its effective stress. In-situ stress in the subsurface is growing due to the variation in mechanical load and structural changes. The reservoirs with pre-existing faults or fractures become prone to slipping because of these changes. Consequently, the induced seismic activities with the abrupt fault or fracture slip become inevitable. Reliable prediction of the subsurface dynamics over time and space relies heavily on modeling the field-scale dynamics while resolving the small-scale phenomena related to nonlinear fluid-rock physics and the faults properties. The predictive modeling of induced seismicity events is still a challenging task. In this minisymposium, we will overview existing numerical approaches for the modeling of faults or pre-existing fractures reactivation due to the human activity.

Organizer: Patrick Jenny
ETH Zürich, Switzerland

Organizer: Denis Voskov
Technical University of Delft, Netherlands

9:45-10:05 Fully Coupled Model for Chemically Induced Fault Slippage

Denis Voskov, Technical University of Delft, Netherlands; Timur T. Garipov, Stanford University, U.S.

10:10-10:30 A Geomechanical Workflow for Simulation of Fault Reactivation: Numerical Issues and Applications

Luigi Vadacca, Daniele Rossi, Anna Scotti, and Stefano Micheletti, Politecnico di Milano, Italy

continued in next column

10:35-10:55 Numerical Modeling of Fault Activation and Induced Seismicity in Gas Storage Reservoirs: The Netherlands Case

Massimiliano Ferronato, Universita di Padova, Italy; Andrea Franceschini, ; Carlo Janna, University of Padova, Italy; Pietro Teatini and Claudia Zoccarato, Universita di Padova, Italy

11:00-11:20 An Embedded Discontinuity Model for the Simulation of Fracture Deformations in Enhanced Geothermal Reservoirs

Igor Shovkun, Timur T. Garipov, and Hamdi Tchelepi, Stanford University, U.S.

11:25-11:45 Linking Oklahoma Seismicity and Saltwater Disposal with a Hydromechanical Rate and State Friction Model

Jack Nortbeck, Fervo Energy, U.S.; Justin Rubinstein, United States Geological Survey, U.S.

Wednesday, March 13

MS33

Recent Advances in Computational Modeling of Coupled Flow and Geomechanics in the Subsurface Environment - Part I of II

9:45 a.m.-11:50 a.m.

Room: Briarpark 1/2

For Part 2 see MS56

This minisymposium seeks to gather the most recent advancements in numerical and analytical techniques for coupling geomechanics and flow in the subsurface. Numerical models involving the coupled PDEs can be challenging to solve due to strong nonlinearity and high heterogeneity as well as different length and time scales between individual physics. This mini-symposium aims at spotlighting the current research state of the art, model capabilities, and numerical methods in reservoir, environmental, and civil engineering with applications such as hydraulic fracturing, $CO2$ sequestration, gas hydrate deposits, enhanced geothermal systems, induced seismicity, and wellbore-stability. In particular, topics of interest include various formulations and discretization techniques, multiscale methods, stability and convergence of sequential solution strategies, computer code development, and scalable linear and nonlinear solvers.

Organizer: Jihoon Kim
Texas A&M University, U.S.

Organizer: Sanghyun Lee
Florida State University, U.S.

Organizer: George Moridis
Lawrence Berkeley National Laboratory, U.S.

9:45-10:05 Advanced Simulation for Strongly Coupled Nonisothermal Flow and Geomechhanics for the Gas Hydrate Deposits

Jihoon Kim, Texas A&M University, U.S.; Sanghyun Lee, Florida State University, U.S.; George Moridis, Lawrence Berkeley National Laboratory, U.S.

continued on next page

Wednesday, March 13

MS33

Recent Advances in Computational Modeling of Coupled Flow and Geomechanics in the Subsurface Environment - Part I of II

continued

10:10-10:30 Coupling Geomechanics and Flow in Porous Media

Mary F. Wheeler, University of Texas at Austin, U.S.; Vivette Girault, University of Paris VI, France; Saumik Dana, University of Texas at Austin, U.S.; Tameem Almani, Saudi Aramco Oil Company, Saudi Arabia

10:35-10:55 An Extended Fixed Stress Split for Nonlinear Coupling Between Flow, Transport and Geomechanics

Marcio A. Murad, National Laboratory of Scientific Computation (LNCC) - MCTIC, Brazil; Maicon R. Correa, University of Campinas, Brazil; Rafael Silva, Cenpes and Petrobras, Brazil; Marcio Borges, National Laboratory of Scientific Computation and Ministry of Science, Technology, Innovation and Communication, Brazil

11:00-11:20 A Generalized Framework to Couple Reservoir and Geomechanics Simulators for Full-field Poromechanics Modelling

Bin Wang, *Yifan Zhou*, Gary Li, and Baris Guyaguler, Chevron Corporation, U.S.

11:25-11:45 Multiscale Preconditioning Strategies for Coupled Poromechanics

Sergey Klevtsov, Stanford University, U.S.; Nicola Castelletto and Joshua A. White, Lawrence Livermore National Laboratory, U.S.; Hamdi Tchelepi, Stanford University, U.S.

Wednesday, March 13

MS34

Modeling with Constraints and Phase Transitions - Part II of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom A

For Part 1 see MS24

Multicomponent multiphase models are ubiquitous in subsurface modeling; equally important is accounting for energy equation and nonisothermal effects, the latter with even broader applications in geosciences. Various time and spatial scales require equilibrium and kinetic models, and several applications call for pointwise constraints on the solutions. While the applications are disparate, the algorithms and analyses share challenges and successes. In this minisymposium we bring researchers involved in various aspects and applications.

Organizer: Malgorzata Peszynska

Oregon State University, U.S.

Organizer: Michel Kern

Inria & Maison de la Simulation, France

9:45-10:05 Close-contact Melting in Ice - Modeling and Simulation of Phase-change in the Presence of a On-local Pressure Constraint

Julia Kowalski, RWTH Aachen University, Germany

10:10-10:30 A Posteriori Error Estimates and Adaptive Stopping Criteria for Compositional Two-phase Flow with Nonlinear Complementarity Constraints

Ibtihel Ben Gharbia, IFP Energies nouvelles, France; *Jad Dabaghi*, Inria, France; Vincent Martin, Université de Technologie de Compiègne, France; Martin Vohralík, Inria Paris-Rocquencourt, France

10:35-10:55 A Non Linear Preconditioner for Coupling Transport with Chemistry in Porous Media

Laila Amir, University of Marrakech, Morocco; Michel Kern, Inria & Maison de la Simulation, France

continued in next column

11:00-11:20 Stability Analysis and Solvers for Phase Transitions in Hydrate Formation

Choah Shin and Malgorzata Peszynska, Oregon State University, U.S.

11:25-11:45 Modelling Coupled Phase Transitions in Gas Hydrate Geosystems

Shubhangi Gupta, Helmholtz Center for Ocean Research Kiel, Germany; Barbara Wohlmuth, Technische Universität München, Germany; Matthias Haeckel, Helmholtz Center for Ocean Research Kiel, Germany

Lunch Break

11:50 a.m.-1:20 p.m.

Attendees on their own

Wednesday, March 13

SP2

SIAG/GS Early Career Prize Lecture: Multi-scale simulation of Porous Media Flow: Obstacles, Opportunities and Open-source

1:20 p.m.-2:05 p.m.

Room: Grand Ballroom EFGH

Chair: To Be Determined

CO2 storage and hydrocarbon recovery is modelled by mixed hyperbolic-elliptic PDEs, posed on unstructured, polyhedral grids with large aspect ratios. Such models are strongly nonlinear, have a truly multiscale behavior, and contain complex tabulated data or analytic submodels that makes linearization and solution nontrivial. Herein, I discuss challenges faced when developing new (multiscale) simulation methods for industry use. To overcome these challenges, we use the open-source MATLAB Reservoir Simulation Toolbox for rapid prototyping and bootstrapping of new methods, and to leverage the effort of others in a reproducible manner.

Olav Moyner
SINTEF Digital, Norway

Intermission

2:05 p.m.-2:15 p.m.

Wednesday, March 13

MS35

Practical Aspects of Large-scale Sparsity-promoting Seismic Inversion - Part II of II

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom EFGH

For Part 1 see MS25

Sparsity-promoting regularization, long a key technology in imaging sciences, has great theoretical significance in seismic imaging and full-waveform inversion (FWI) applications. The importance of sparsity-promoting regularization in seismic inversion stems from its ability to help resolve compact features of structural subsurface models from noisy band-limited data. Despite the existence of a plethora of general-purpose optimization algorithms involving non-smooth regularization (such as L1 or TV), their adoption in practical FWI applications is hindered by the computational complexity of FWI that typically requires inversion of structural earth models with billions degrees of freedom. Computational feasibility, which often does not correlate very well with asymptotic convergence properties of employed algorithms, is key to the successful application of non-smooth regularization in FWI. In this minisymposium we focus on bringing the cost of L1/TV-regularized FWI closer to that of FWI with smooth objective functions. Both synthetic and field-data experiments will be included, with emphasis on computational feasibility while demonstrating uplift from the regularization. Although the stress is on practical aspects of regularized FWI, theoretical works and contributions from other fields that may help deliver a speed-up in FWI are welcome as well. Sample topics of interest: smoothing of L1/TV-regularized misfits, primal-dual and splitting methods, convergence acceleration.

Organizer: Musa Maharramov
ExxonMobil Upstream Research Company, U.S.

Organizer: Anatoly Baumstein
ExxonMobil Upstream Research Company, U.S.

2:15-2:35 New Algorithms for Projections onto Intersections of Multiple Convex and Non-convex Sets and Application to Full-waveform Inversion

Bas Peters, University of British Columbia, Canada; Felix Herrmann, Georgia Institute of Technology, U.S.

2:40-3:00 Use of a Deep-learning-based Geological Parameterization within the Context of Production Data Assimilation

Louis J. Durlofsky and Yimin Liu, Stanford University, U.S.

3:05-3:25 Edge-preserving FWI via Regularization by Denoising

Amsalu Y. Anagaw and Mauricio D. Sacchi, University of Alberta, Canada

3:30-3:50 Implementing Bound Constraints and Hybrid Total-variation+Tikhonov Regularization in Wavefield Reconstruction Inversion with the Aalternating Direction Method of Multiplier

Hossein Aghamiry, University of Cote d'Azur, France; Ali Gholami, University of Tehran, Iran; *Stephane Operto*, Université de Nice, France

3:55-4:15 Efficient Implementation of the L^1 Total-Variation Regularization for Large-scale problems

Lingyun Qiu and *Alejandro Valenciano Mavillo*, Petroleum Geo-Services, U.S.; Xiao Liu, Rice University, U.S.

continued in next column

Wednesday, March 13

MS36

Physics-based Rupture and Tsunami Simulation - Part II of II

2:15 p.m.-4:20 p.m.

Room: Richmond 1/2

For Part 1 see MS23

Recent data of tsunami earthquakes revealed a large variability in mechanisms, geometric features, physical processes and hence tsunami wave variation when impacting coastal regions. At the same time the modeling and simulation capabilities, utilizing HPC infrastructures and modern numerical methods, are now able to represent realistic rupture behavior and coupled earthquake-tsunami simulations. This minisymposium focuses on coupled modeling workflows for tsunami earthquakes. We invite presentations related to earthquake cycling, rupture processes, and tsunami simulation, including near- and on-shore processes. The presentations should address computational issues, validation of modeling chains, process studies as well as mathematical approaches to formulate concise process simulations.

Organizer: Jörn Behrens
Universität Hamburg, Germany

Organizer: Alice A. Gabriel
Ludwig-Maximilians-Universität München, Germany

Organizer: Michael Bader
Technische Universität München, Germany

2:15-2:35 Fully Coupled Earthquake-tsunami Simulations and Real-time Tsunami Wavefield Reconstruction using the Ensemble Kalman Filter

Yuyun Yang and Eric M. Dunham, Stanford University, U.S.

2:40-3:00 Challenges and Status of GPS Enhanced Operational Near-field Tsunami Forecasting and Warning

Diego Melgar Moctezuma and Amy Williamson, University of Oregon, U.S.; Brendan Crowell, University of Washington, U.S.; Diego Arcas, National Oceanic and Atmospheric Administration, U.S.; Tim Melbourne, Central Washington University, U.S.; Bock Yehuda, University of California, San Diego, U.S.

continued in next column

3:05-3:25 Unraveling Earthquake Dynamics through Large-scale Multi-physics Simulations

Alice Gabriel, Technische Universität München, Germany

3:30-3:50 High-order Discontinous Galerkin Methods for Coastal Hydrodynamics Applications

Ethan Kubatko, Ohio State University, U.S.

3:55-4:15 3D Inelastic Wedge Failure and Along-strike Variations of Tsunami Generation in the Shallow Subduction Zone

Shuo Ma, San Diego State University, U.S.

Wednesday, March 13

MS37

Modeling and Numerical Methods for Complex Subsurface Flow - Part I of II

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom A

For Part 2 see MS50

Subsurface flow is of great importance to everyday life. The modeling and the subsequent development of efficient and long-time stable numerical algorithms remain challenging for subsurface flow due to a number of factors including the complex geometry, the enormous scales involved, the presence of uncertainty, the coupling of different dynamics. This minisymposium aims to provide a forum for researchers from different fields to discuss recent advances on the modeling and numerical methods for complex subsurface flow.

Organizer: Xiaoming He
Missouri University of Science and Technology, U.S.

Organizer: Daozhi Han
Missouri University of Science and Technology, U.S.

2:15-2:35 Modeling and Numerical Methods for Two-phase Underground Water Flow

Daozhi Han, Missouri University of Science and Technology, U.S.

2:40-3:00 Enforcing Discrete Maximum Principles in Discontinuous Galerkin Schemes: Application to Phase-field Methods

Florian Frank and Andreas Rupp, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany; Dmitri Kuzmin, Technische Universität Dortmund, Germany

3:05-3:25 Convergence of a Numerical Method for 3D Interfacial Flow with Surface Tension

David Ambrose, Drexel University, U.S.

3:30-3:50 Coupling and Decoupling of Free Flow and Flow in Porous Media

Xiaoming Wang, Florida State University, U.S.

3:55-4:15 A Stable and Fast Linearization Scheme for Nonlinear Porous Media Problems

Koondanibha Mitra, Eindhoven University of Technology, Netherlands; Iuliu Sorin Pop, Hasselt University, Belgium

Wednesday, March 13

MS38

Efficient Solvers for Nonlinear Flows

2:15 p.m.-4:20 p.m.

Room: Grand Ballroom B

Many computational challenges arise from the numerical approximation of nonlinear flows that appear in geoscience modeling. The particular discretization of a problem determines uniqueness and regularity of solutions, stability in the neighborhood of a solution, and conservation of important quantities, which may not necessarily agree with those corresponding to the problem or model on the continuous level. Moreover, specialized linearization and preconditioning techniques may be necessary to obtain the approximate solution of such nonlinear discrete problems. The focus of this session is on recent innovations in both well-posedness and efficient and robust solution techniques used to obtain discrete solutions to these nonlinear systems.

Organizer: Sara Pollock
University of Florida, U.S.

2:15-2:35 Uniqueness of Discrete Solutions of Quasilinear PDE on 2D and 3D Nonuniform Meshes

Sara Pollock, University of Florida, U.S.

2:40-3:00 Auxiliary Space Preconditioning for Mixed Finite Element Discretizations of Richards Equation

Juan Batista, Pennsylvania State University, U.S.

3:05-3:25 Multigrid and Multilevel HDG Approaches for Nonlinear Single-phase Flows

Sriramkrishnan Muralikrishnan, University of Texas at Austin, U.S.; Tim Wildey, Sandia National Laboratories, U.S.; Tan Bui, University of Texas at Austin, U.S.

continued in next column

3:30-3:50 Efficient and Accurate Solvers for Nonhydrostatic Simulations of the Atmosphere: The Interaction of High-order ImEx Methods and Customized Algebraic Solvers

Daniel R. Reynolds, Southern Methodist University, U.S.; Christopher J. Vogl and David J. Gardner, Lawrence Livermore National Laboratory, U.S.; Andrew J. Steyer, Sandia National Laboratories, U.S.; Paul Ullrich, University of California, Davis, U.S.

3:55-4:15 Quasi-static Crack Propagation in Nonlinear Elastic Solids

Mallikarjunaiah Muddamallappa, Texas A&M University, U.S.

Wednesday, March 13

MS39

Advances in Modeling and Simulation of Pore Scale Flows

2:15 p.m.-4:20 p.m.

Room: Briarpark 1/2

The continuing increase in computational resources and performance has made digital rock a valuable complement to lab experiments for the understanding of multi-phase flow in porous media at the micro-scale. This minisymposium discusses the recent advances in modeling, simulation and software development. Methodologies include, but are not restricted to, level set methods, thermodynamics-based models, pore network models and lattice-Boltzmann methods. While these techniques are well established for single phase or two-phase flows, the talks will present advances in the complexity of the physics or chemistry such as three-phase flow, non-Newtonian flows, foam modeling and reactive flow, to name a few.

Organizer: Beatrice Riviere
Rice University, U.S.

Organizer: Masa Prodanovic
University of Texas at Austin, U.S.

2:15-2:35 Phase Field Model for Partially Miscible Fluids at Porescale

Malgorzata Peszynska, Oregon State University, U.S.

2:40-3:00 Applications for Neural Networks in Digital Rock Physics

James McClure, Virginia Tech, U.S.

3:05-3:25 Simulation of Capillary Trapping in Three-phase Displacement using a Level Set Approach with Local Volume Preservation

Johan Olav Helland, NORCE Norwegian Research Centre, Norway; Espen Jettestuen, International Research Institute of Stavanger (IRIS), Norway; Helmer André Friis, NORCE Norwegian Research Centre, Norway

continued on next page

Wednesday, March 13

MS39

Advances in Modeling and Simulation of Pore Scale Flows

continued

3:30-3:50 Discontinuous Galerkin Methods for Solving Non-Newtonian Two-phase Pore Scale Flows

Chen Liu, Rice University, U.S.; Florian Frank, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany; Faruk O. Alpak, Shell International Exploration and Production, U.S.; Beatrice Riviere, Rice University, U.S.

3:55-4:15 Mathematical Modelling of the Bio-plug Technology: Laboratory Experiments, Upscaling, and Numerical Simulations

David Landa-Marbán, University of Bergen, Norway; Na Liu, Centre for Integrated Petroleum Research/ University of Bergen, Norway; Iuliu Sorin Pop, Hasselt University, Belgium; Kundan Kumar, University of Bergen, Norway; Per Pettersson, Gunhild Bødtker, and Bartek Florczyk Vik, Centre for Integrated Petroleum Research/ University of Bergen, Norway; Florin Adrian Radu, University of Bergen, Norway

Wednesday, March 13

MS40

Verification Benchmarks for Single-phase Flow in Three-dimensional Fractured Porous Media - Part I of II

2:15 p.m.-4:20 p.m.

Room: Westchase 1/2

For Part 2 see MS47

Verification is an indispensable ingredient for assuring the correctness of a computational model. For the complex geometries and heterogeneities that are encountered in modelling flow and transport in fractured porous media, analytical solutions are typically not available for comparison. We therefore propose benchmarks by means of well-defined case descriptions, computational grids, reference solutions and comparison measures to aid in the verification process. In this minisymposium, we focus on benchmarks for verifying single-phase flow in three-dimensional fractured porous media. Relevant cases will be described and discussed on the basis of a call for participation published at arXiv. The speakers will present their computational models and methods to solve the proposed problems. The audience will be invited to participate in a joint study of the proposed cases. All participants are expected to contribute their solutions to a joint data repository in order to maximize the transparency and such that the available methods can be compared quantitatively.

Organizer: Inga Berre
University of Bergen, Norway

Organizer: Wietse Boon
Universität Stuttgart, Germany

Organizer: Bernd Flemisch
Universität Stuttgart, Germany

Organizer: Alessio Fumagalli
University of Bergen, Norway

Organizer: Dennis Gläser
Universität Stuttgart, Germany

Organizer: Eirik Keilegavlen
University of Bergen, Norway

Organizer: Anna Scotti
Politecnico di Milano, Italy

Organizer: Ivar Stefansson
University of Bergen, Norway

Organizer: Alexandru Tatomir
University of Göttingen, Germany

2:15-2:35 Verification Benchmarks for Single-phase Flow in Three-dimensional Fractured Porous Media

Alessio Fumagalli and Inga Berre, University of Bergen, Norway; Wietse Boon and Dennis Gläser, Universität Stuttgart, Germany; Eirik Keilegavlen, University of Bergen, Norway; Anna Scotti, Politecnico di Milano, Italy; Ivar Stefansson, University of Bergen, Norway; Alexandru Tatomir, University of Göttingen, Germany

2:40-3:00 Finite Volume-based Discrete Fracture Modeling of Flow, Transport and Deformation in Fractured Porous Media

Dennis Gläser, Universität Stuttgart, Germany

3:05-3:25 A Novel Enriched Galerkin Method for Flow and Transport in Fractured Porous Media

Teeratorn Kadeethum and Hamid M. Nick, Technical University of Denmark, Denmark; Sanghyun Lee, Florida State University, U.S.; Francesco Ballarin, SISSA-ISAS International School for Advanced Studies, Italy; C N. Richardson, University of Cambridge, United Kingdom; Saeed Salimzadeh, Technical University of Denmark, Denmark

3:30-3:50 Algebraic Dynamic Multilevel Method for Projection-based Embedded Discrete Fracture Model

Mousa HosseiniMehr, Kees Vuik, and Hadi Hajibeygi, Technical University of Delft, Netherlands

3:55-4:15 Multiscale Simulation of Reactive Transport in Shales

Ziyan Wang and Ilenia Battiato, Stanford University, U.S.

Coffee Break

4:20 p.m.-4:50 p.m.

Room: Grand Ballroom D

continued in next column

Wednesday, March 13

MS41

Advances in Bayesian Estimation Strategies in Subsurface Processes

4:50 p.m.-6:55 p.m.

Room: Westchase 1/2

An accurate estimation of subsurface geological properties like permeability, porosity etc. is essential for many fields specially where such predictions can have large economic or environmental impact, for instance prediction of oil or gas reservoir locations. The major challenge in accurate deduction of state and/or parameters is our limited knowledge of the physical process, lack of required number of observations and the high computational expenses. The goal of this minisymposium is to discuss the most recent advancements in Bayesian approaches for state and/or parameter estimations which could overcome these challenges and could lead to more reliable and effective simulations.

Organizer: Sangeetika Ruchi
Centrum voor Wiskunde en Informatica (CWI), Netherlands

Organizer: Xiaodong Luo
International Research Institute of Stavanger (IRIS), Norway

Organizer: Ibrahim Hoteit
King Abdullah University of Science & Technology (KAUST), Saudi Arabia

4:50-5:10 Tempered Ensemble Transform Particle Filter for Non-Gaussian Elliptic Problems

Sangeetika Ruchi, Centrum voor Wiskunde en Informatica (CWI), Netherlands; Svetlana Dubinkina, CWI, Amsterdam, Netherlands; Marco Iglesias, University of Nottingham, United Kingdom

5:15-5:35 Ensemble Kalman Filtering with Iterative One-step-ahead Smoothing for History Matching

Yanhui Zhang, Boujemaa Ait-El-Fquih, and Ibrahim Hoteit, King Abdullah University of Science & Technology (KAUST), Saudi Arabia

continued in next column

5:40-6:00 Use of the Particle Filter for Fault-slip Estimation

Femke C. Vossepoel and Shiran Levy, Technical University of Delft, Netherlands; Marie Bocher, ETH Zürich, Switzerland; Ylona Dinther, Utrecht University, Netherlands

6:05-6:25 Strategies for Ensemble-based Conditioning of Multiple-point Statistical Facies Simulation on Nonlinear Subsurface Flow Data

Wei Ma and Behnam Jafarpour, University of Southern California, U.S.

6:30-6:50 New Advances in History Matching and Uncertainty Quantification Formulated Within the Bayesian Inference Framework

Guohua Gao, Shell Global Solutions, U.S.; Chaohui Chen, Shell International Exploration & Production B.V., Netherlands; Yaakoub ElKhamra, Shell Global Solutions, U.S.; Jeroen C. Vink, Shell Global Solutions International B.V., Rijswijk, Netherlands; Fredrik J.F.E. Saaf, Shell Global Solutions, U.S.

Wednesday, March 13

MS42

Coupled Problems of Poromechanics - Part I of II

4:50 p.m.-6:55 p.m.

Room: Briarpark 1/2

For Part 2 see MS46

Coupled poromechanical processes with interfaces and singular or degenerate behavior of coefficients or solutions are important in the description of subsurface fluid flow. Presentations will describe modeling, analysis and simulation of such processes and approaches to deal with resulting multiphysics and multiscale issues.

Organizer: Ralph Showalter
Oregon State University, U.S.

4:50-5:10 The Biot-Stokes System with Unilateral Constraints

Ralph Showalter and Alireza Hosseinkhan, Oregon State University, U.S.

5:15-5:35 The Role of Compressibility on the Blow-up of Solutions of Poro-visco-elastic Models

Maurizio Verri, Politecnico di Milano, Italy; Giovanna Guidoboni, Indiana University - Purdue University Indianapolis, U.S.; *Lorena Bociu*, North Carolina State University, U.S.; Riccardo Sacco, Politecnico di Milano, Italy

5:40-6:00 Microscale Analysis Demonstrating the Significance of Shear and Plasticity in Hydrostatic Compression of Porous Media

Howard Schreyer and Brandon Lampe, University of New Mexico, U.S.; *Lynn Schreyer*, Washington State University, U.S.; John Stormont, University of New Mexico, U.S.

6:05-6:25 Multiphysics Numerical Methods for a Nonlinear Poroelasticity Model

Xiaobing Feng, University of Tennessee, Knoxville, U.S.

continued on next page

Wednesday, March 13

MS42

Coupled Problems of Poromechanics - Part I of II

continued

6:30-6:50 Gradient Flow Perspective on Poromechanics

Jakub Both, University of Bergen, Norway; Kundan Kumar, Karlstad University, Sweden; Jan M. Nordbotten and Florin Radu, University of Bergen, Norway

Wednesday, March 13

MS43

Advanced Mathematical Approaches for Simulation of Fault Reactivation - Part II of II

4:50 p.m.-6:55 p.m.

Room: Grand Ballroom EFGH

For Part 1 see MS32

Continuous industrial activities related to energy extraction or injection operations can cause significant changes of pore-pressure in subsurface formations. As consequences, the overburden state is changing and so does its effective stress. In-situ stress in the subsurface is growing due to the variation in mechanical load and structural changes. The reservoirs with pre-existing faults become prone to slipping because of these changes. Consequently, the induced seismic activities with the abrupt fault or fracture slip become inevitable. Reliable prediction of the subsurface dynamics over time and space relies heavily on modeling the field-scale dynamics while resolving the small-scale phenomena related to nonlinear fluid-rock physics and the faults properties. The predictive modeling of induced seismicity events is still a challenging task. In this minisymposium, we will overview existing numerical approaches for the modeling of faults or pre-existing fractures reactivation due to the human activity.

Organizer: Denis Voskov

Technical University of Delft, Netherlands

Organizer: Patrick Jenny

ETH Zürich, Switzerland

4:50-5:10 The Modeling of Fault Activation and Induced Seismicity by using Coupled Flow-geomechanics Simulation and its Field Application

Hyun Yoon and Jihoon Kim, Texas A&M University, U.S.

5:15-5:35 Rate-and-State-Based Simulation of Induced Seismicity and Coupling to Reservoir Processes

Kayla Kroll, Lawrence Berkeley National Laboratory, U.S.; James Dieterich and Keith Richards-Dinger, University of California, Riverside, U.S.; Thomas Buscheck, Lawrence Berkeley National Laboratory, U.S.; Joshua A. White, Lawrence Livermore National Laboratory, U.S.

continued in next column

5:40-6:00 Data Assimilation for State Estimation of Fault Behavior

Shiran Levy and Femke C. Vossepoel, Technical University of Delft, Netherlands; Marie Bocher, ETH Zürich, Switzerland; Ylona Dinther, Utrecht University, Netherlands

6:05-6:25 Regularized Extended Finite Volume Method for Flow Induced Shear Failure

Rajdeep Deb and Patrick Jenny, ETH Zürich, Switzerland

6:30-6:50 Modeling Simultaneous Propagation of Multiple Pseudo-3D Hydraulic Fractures

Innokentiy Protasov, University of Houston, U.S.; Egor Dontsov, W.D. Von Gonten Laboratories, Houston, U.S.

Wednesday, March 13

MS44

Convergence Verification and Challenges in Climate and Weather Simulations - Part I of II

4:50 p.m.-6:55 p.m.

Room: Richmond 1/2

For Part 2 see MS49

As scientific codes become more complex through incorporation of more comprehensive physical effects, use of sophisticated algorithms and parallelization procedures, the probability of implementation inconsistencies and implementation mistakes that affect the computed solution increases. In this environment, rigorous code verification through use of order-of-accuracy studies becomes essential to provide confidence that the intended code solves its governing equations correctly. Within simulations using parameterized physics, where first order convergent algorithms are intended, numerous examples have developed that show a loss of convergence. This minisymposium will elaborate on some of these examples and discuss methods for identifying loss of convergence within these simulations. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-757786.

Organizer: Carol S. Woodward
Lawrence Livermore National Laboratory, U.S.

Organizer: David J. Gardner
Lawrence Livermore National Laboratory, U.S.

4:50-5:10 Overview of Code and Calculation Verification Practices and their use in Scientific Computinguting

Carol S. Woodward, Lawrence Livermore National Laboratory, U.S.

5:15-5:35 Development and Verification of a Numerical Library for Solving Global Terrestrial Multi-physics Processes

Gautam Bisht and William Riley, Lawrence Berkeley National Laboratory, U.S.

continued in next column

5:40-6:00 Assessing and Improving the Numerical Solution of Atmospheric Physics in E3SM

David J. Gardner, Lawrence Livermore National Laboratory, U.S.; Phil Rasch and Panos Stinis, Pacific Northwest National Laboratory, U.S.; Christopher J. Vogl, Lawrence Livermore National Laboratory, U.S.; Hui Wan, Pacific Northwest National Laboratory, U.S.; Carol S. Woodward, Lawrence Livermore National Laboratory, U.S.; Shixuan Zhang, Battelle Pacific Northwest Laboratory, U.S.

6:05-6:25 Improving the Convergence Rate of Stochastic Approximations for Physics-dynamics Coupling

Panos Stinis, Huan Lei, and Hui Wan, Pacific Northwest National Laboratory, U.S.

6:30-6:50 Quasi-Newton Methods for Atmospheric Chemistry Simulations

Emre Esenturk, University of Warwick, United Kingdom

Wednesday, March 13

CP9

Data Assimilation and Uncertainty Quantification II

4:50 p.m.-6:50 p.m.

Room: Grand Ballroom B

Chair: Sarah King, US Naval Research Laboratory, U.S.

4:50-5:05 A Data Assimilation Procedure for Calibrating Relative Permeability using Data of Multiple Types

Vladislav Bukshtynov, Florida Institute of Technology, U.S.; Oleg Volkov, Louis J. Durlofsky, and Khalid Aziz, Stanford University, U.S.

5:10-5:25 Sparse Level Set based Ensemble Smoother for History Matching of Reservoirs

Clement Etienam, University of Manchester, United Kingdom; Rossmary Villegas, Prince Mohammad bin Fahd University, Saudi Arabia; Oliver Dorn, University of Manchester, United Kingdom

5:30-5:45 Projected Gaussian Filtering with Sampled Covariance Updating

Sarah King, US Naval Research Laboratory, U.S.; Kazufumi Ito, North Carolina State University, U.S.; Daniel Hodyss, Naval Research Laboratory, U.S.

5:50-6:05 Solution of Density Driven Groundwater Flow with Uncertain Porosity and Permeability Coefficients

Alexander Litvinenko, RWTH Aachen University, Germany; Raul F. Tempone, Dmitry Logashenko, Gabriel Wittum, and David E. Keyes, King Abdullah University of Science & Technology (KAUST), Saudi Arabia

6:30-6:45 Uncertainty Quantification and Reduction by Data Assimilation Techniques in Land Subsidence Modeling

Laura Gazzola, Pietro Teatini, Claudia Zoccarato, and Massimiliano Ferronato, Universita di Padova, Italy

Wednesday, March 13

CP10

Numerical Methods II

4:50 p.m.-7:10 p.m.

Room: Grand Ballroom A

Chair: Hamdi Tchelepi, Stanford University, U.S.

4:50-5:05 Linearization and Domain Decomposition Methods for Two-phase Flow in Porous Media

Stephan B. Lunowa and Iuliu Sorin Pop, Hasselt University, Belgium; Barry Koren, Eindhoven University of Technology, Netherlands

5:10-5:25 A Domain Decomposition Projection Method for the Navier-Stokes Equations Based on the Multiscale Robin Coupled Method

Camila F. Lages, University of Texas at Dallas, U.S.; Fabricio S. Sousa and Roberto Ausas, Universidade de Sao Paulo, Brazil; Gustavo Buscaglia, Instituto de Ciencias Matematicas e Computacao, Brazil; Felipe Pereira, University of Texas, Dallas, U.S.

5:30-5:45 Sequential-Implicit Newton Method for Reservoir Simulation

Zhi Yang Wong, Pavel Tomin, and *Hamdi Tchelepi*, Stanford University, U.S.

5:50-6:05 Iterative Coupling of Nonlinear Thermo-poroelasticity

Mats K. Brun, Elyes Ahmed, Inga Berre, Jan M. Nordbotten, and Florin Radu, University of Bergen, Norway

6:10-6:25 A Study on Iterative Schemes for Fully Coupled Reactive Transport and Flow in Variably Saturated Porous Media

Davide Illiano, University of Bergen, Norway

6:30-6:45 Fully Implicit Multidimensional Hybrid Upwind Scheme for Coupled Flow and Transport

Francois P. Hamon, Lawrence Berkeley National Laboratory, U.S.; Brad Mallison, Chevron Energy Technology Company, U.S.

continued in next column

6:50-7:05 Improving Reservoir Simulator Performance through Ensemble Based Robust Optimization

Alf Rustad, Equinor, Norway; Markus Blatt, HPC-Simulation-Software & Services, Germany

Wednesday, March 13

PD1

Career Panel

8:00 p.m.-9:00 p.m.

Room: Grand Ballroom EFGH

Chair: Sue Minkoff, University of Texas, Dallas, U.S.

Students often wonder what they will do with a PhD degree after they graduate. They are somewhat familiar with what their advisor and other faculty do at their own institutions, but rarely do they understand the advantages and disadvantages of working in other employment sectors such as industry or government labs. And generally students don't even see the complete picture of what life in academia is really like for faculty. In this panel we will explore different employment opportunities for mathematical geoscience students by hearing from experts in all three employment sectors (industry, labs, and academia both in the US and outside the US). Discussion will also include how and why one might pursue an internship to better clarify future employment opportunities. The panel will begin with each panelists speaking briefly about what their job entails and what they see as pluses and minuses of their type of employment. The chair of the panel will then ask questions of the panel to allow the panelists to further compare the different opportunities available for students when they graduate. Lastly the audience will be given a chance to ask questions of interest to themselves. Please come expecting a lively discussion!

Panelists:

Gregoire Allaire

École Polytechnique, Paris, France

Amr El-Bakry

Exxon Mobil Upstream Research Company, U.S.

Kenneth Golden

University of Utah, U.S.

Elizabeth Hunke

Los Alamos National Laboratory, U.S.

Thursday, March 14

Registration

8:00 a.m.-3:00 p.m.

Room: Westchase 3/4

Closing Remarks

8:20 a.m.-8:30 a.m.

Room: Grand Ballroom EFGH

Thursday, March 14

IP5

Multicomponent Elastic Imaging: New Insights from the Old Equations

8:30 a.m.-9:15 a.m.

Room: Grand Ballroom EFGH

Chair: Amr El-Bakry, ExxonMobil Upstream Research Company, U.S.

Elastic wave imaging has been a significant challenge in the exploration industry due to the complexities in wave physics and numerical implementation. We have separated the governing equations for P- and S-wave propagation without the assumptions of homogeneous Lamé parameters to capture the mode conversion between the two body waves in an isotropic, constant-density medium. The resulting set of two coupled second-order equations for P- and S-potentials clearly demonstrates that mode conversion only occurs at the discontinuities of the shear modulus. Applying the Born approximation to the new equations, we derive the PP, PS, SP, and SS imaging conditions from the first gradients of waveform matching objective functions. The resulting images are consistent with the physical perturbations of the elastic parameters, and, hence, they are automatically free of the polarity reversal artifacts in the converted images. When implementing elastic reverse time migration (RTM), we find that scalar wave equations can be used to back propagate the recorded P-potential, as well as individual components in the vector field of the S-potential. Compared with conventional elastic RTM, the proposed elastic RTM implementation using acoustic propagators not only simplifies the imaging condition, it but also reduces the computational cost and the artifacts in the images. We have demonstrated the accuracy of our method using 2D and 3D numerical examples.

Yunyue Elita Li
National University of Singapore, Singapore

Coffee Break

9:15 a.m.-9:45 a.m.

Room: Grand Ballroom D

Thursday, March 14

MS45

Uncertainty Quantification for Geophysical Inverse Problems

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom EFGH

Geophysical inversion is used to solve a wide range of earth science problems, from velocity estimation for exploration seismology to monitoring the risk of large-scale events like volcanic eruptions. Since the estimated quantities are used to determine the effectiveness of hydrocarbon exploration and production as well as preparation for geological events, it is critical that we recover uncertainty information rather than a single deterministic model. The talks in this session will explore issues and techniques for quantifying uncertainty, including methods for thorough construction of the probability distribution of the model and methods to reduce computational cost. Specifically, the assembled talks will address techniques including Kalman filtering, trans-dimensional methods, and reducing computational expense of the stochastic methods used in uncertainty quantification.

Organizer: Georgia Stuart
University of Texas, Dallas, U.S.

9:45-10:05 Reducing the Computational Cost of Uncertainty Quantification for Seismic Inversion

Georgia Stuart, Susan Minkoff, and Felipe Pereira, University of Texas, Dallas, U.S.

10:10-10:30 An Ensemble Kalman Filter Method for Uncertainty Quantification in Full Waveform Inversion

Julien G. Thurin and Ludovic Métivier, Université Grenoble Alpes, France; Romain Brossier, ISTerre, France

10:35-10:55 Trans-D Methods for Quantifying Uncertainty in Seismic Inversion

Anandaroop Ray, Chevron Corporation, U.S.

11:00-11:20 Using Fast Forward Solvers to Enable Uncertainty Quantification in Seismic Imaging

Maria Kotsi and Alison Malcolm, Memorial University, Newfoundland, Canada; Gregory Ely, Massachusetts Institute of Technology, U.S.

11:25-11:45 Uncertainty Quantification and Volcanic Hazards

E. Bruce Pitman, State University of New York at Buffalo, U.S.

Thursday, March 14

MS46

Coupled Problems of Poromechanics - Part II of II

9:45 a.m.-11:50 a.m.

Room: Briarpark 1/2

For Part 1 see MS42

Coupled poromechanical processes with interfaces and singular or degenerate behavior of coefficients or solutions are important in the description of subsurface fluid flow. Presentations will describe modeling, analysis and simulation of such processes and approaches to deal with resulting multiphysics and multiscale issues.

Organizer: Ralph Showalter
Oregon State University, U.S.

9:45-10:05 A Nonlinear Stokes-Biot Model for the Interaction of a Non-Newtonian Fluid with Poroelastic Media

Ivan Yotov, University of Pittsburgh, U.S.; Ilona Ambartsumyan, University of Texas at Austin, U.S.; Vincent J. Ervin, Clemson University, U.S.; Truong Nguyen, University of Pittsburgh, U.S.

10:10-10:30 Coupling of Flow and Mechanics in Fractured Porous Media

Kundan Kumar, University of Bergen, Norway; Mary F. Wheeler, University of Texas at Austin, U.S.; Vivette Girault, University of Paris VI, France; Tameem Almani, Saudi Aramco Oil Company, Saudi Arabia; Florin Radu, University of Bergen, Norway

10:35-10:55 Augmented Lagrangian Methods for Coupling Flow and Deformation in Poroelastic Media with Non-linear Elastic Fractures

Josue S. Barroso, Marcio A. Murad, and Patricia Pereira, National Laboratory of Scientific Computation (LNCC) - MCTIC, Brazil

11:00-11:20 Adaptive Fixed-stress Iterative Coupling Schemes based on a Posteriori Error Estimates for Biot's Consolidation Model

Elyes Ahmed, Florin Adrian Radu, and Jan M. Nordbotten, University of Bergen, Norway

continued in next column

11:25-11:45 Simulations of Coupled Flow and Geomechanics in Porous Media with Embedded Discrete Fractures

Matteo Cusini, Technical University of Delft, Netherlands; Nicola Castelletto and Joshua A. White, Lawrence Livermore National Laboratory, U.S.

Thursday, March 14

MS47

Verification Benchmarks for Single-phase Flow in Three-dimensional Fractured Porous Media - Part II of II

9:45 a.m.-11:50 a.m.

Room: Westchase 1/2

For Part 1 see MS40

Verification is an indispensable ingredient for assuring the correctness of a computational model. For the complex geometries and heterogeneities that are encountered in modelling flow and transport in fractured porous media, analytical solutions are typically not available for comparison. We therefore propose benchmarks by means of well-defined case descriptions, computational grids, reference solutions and comparison measures to aid in the verification process. In this minisymposium, we focus on benchmarks for verifying single-phase flow in three-dimensional fractured porous media. Relevant cases will be described and discussed on the basis of a call for participation published at arXiv. The speakers will present their computational models and methods to solve the proposed problems. The audience will be invited to participate in a joint study of the proposed cases. All participants are expected to contribute their solutions to a joint data repository in order to maximize the transparency and such that the available methods can be compared quantitatively.

Organizer: Inga Berre
University of Bergen, Norway

Organizer: Wietse Boon
Universität Stuttgart, Germany

Organizer: Bernd Flemisch
Universität Stuttgart, Germany

Organizer: Alessio Fumagalli
University of Bergen, Norway

Organizer: Dennis Gläser
Universität Stuttgart, Germany

Organizer: Eirik Keilegavlen
University of Bergen, Norway

Organizer: Anna Scotti
Politecnico di Milano, Italy

continued on next page

Organizer: Ivar Stefansson
University of Bergen, Norway

Organizer: Alexandru Tatomir
University of Göttingen, Germany

9:45-10:05 From Discrete to Continuum Concepts of Flow in Fractured Porous Media

Alexandru Tatomir, University of Göttingen, Germany

10:10-10:30 Numerical Methods for Flow in Fractured Porous Media in a Unified Implementation

Ivar Stefansson, Inga Berre, Alessio Fumagalli, and Eirik Keilegavlen, University of Bergen, Norway

10:35-10:55 A Finite-volume Approach to Dynamically Fracturing Porous Media

Samuel Burbulla and Christian Rohde, Universität Stuttgart, Germany

11:00-11:20 Mixed-dimensional Discrete Fracture Matrix Models with Heterogeneous Discretizations and Non-matching Grids

Eirik Keilegavlen, Alessio Fumagalli, Ivar Stefansson, Inga Berre, and Jan M. Nordbotten, University of Bergen, Norway

11:25-11:45 A Generalized Finite Element Method for Flows in Fractured Porous Media

Siyang Wang, Chalmers University of Technology, Sweden, and University of Gothenburg, Sweden; Axel Målqvist, Chalmers University of Technology, Sweden

Thursday, March 14

MS48

New Approaches for Coupled Nonlinear and Discontinuous Problems in Hydrology

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom B

Modeling of subsurface processes has a significant impact for many applications for agricultural, environmental and engineering purposes. The physically based description of these processes is generally accomplished by advection diffusion equations,whose treatise is often a challenge from the mathematical and numerical points of views. The detailed modelling of the aforementioned problems in the study of flow through saturated and unsaturated porous media, often requires to appropriately deal with strong non-linear and discontinuous terms in the equations. This session will bring together applied mathematicians and hydrologists studying applied flow and transport processes, to discuss novel modelling and numerical approaches for facing these difficulties. In particular, we are interested in giving some sparks about these topics, with significant applications in the vadose zone modeling, first and foremost in the modeling of root distributions. The presentations will have a multidisciplinary approach and content. Contributions will cover the modeling of plant roots growth by optimal transport, and numerical simulations of OT based plant-root dynamics under variable stresses, as well as the modeling of root water uptake by a discontinuous forcing term in Richards equation. Moreover, the modeling of Richards'equation in layered soils is modeled by a Filippov approach, and a multiscale analysis non-linear transport problems in porous media will be considered.

Organizer: Marco Berardi
Consiglio Nazionale delle Ricerche, Italy

Organizer: Mario Putti
University of Padua, Italy

Organizer: Matteo Icardi
University of Nottingham, United Kingdom

9:45-10:05 Modeling Roots Water Uptake by Discontinuous Forcing Terms in Richards' Equation

Marco Berardi, Consiglio Nazionale delle Ricerche, Italy; Marcello D'Abbicco, Università di Bari, Italy; Michele Vurro, Consiglio Nazionale delle Ricerche, Italy; Luciano Lopez, Università di Bari, Italy

10:10-10:30 Multiscale Analysis of Non-linear Transport Problems in Porous Media

Matteo Icardi, University of Nottingham, United Kingdom

10:35-10:55 Plant Root Modeling via Optimal Transport

Enrico Facca, University of Padova, Italy; Mario Putti, University of Padua, Italy

11:00-11:20 Three Dimensional Simulation of Optimal Transport Based Plant-root Dynamics under Variable Stresses

Gabriele Manoli and Sara Bonetti, ETH Zürich, Switzerland; Enrico Facca, University of Padova, Italy; Damiano Pasetto, École Polytechnique Fédérale de Lausanne, Switzerland; Mario Putti, University of Padua, Italy

11:25-11:45 A Mixed MoL-TMoL Approach for Solving 2D Richards' Equation in Layered Soils

Fabio Difonzo, Code Architects Automation, Italy; Marco Berardi, Consiglio Nazionale delle Ricerche, Italy; Luciano Lopez, Università di Bari, Italy

continued in next column

Thursday, March 14

MS49

Convergence Verification and Challenges in Climate and Weather Simulations - Part II of II

9:45 a.m.-11:50 a.m.

Room: Richmond 1/2

For Part 1 see MS44

As scientific codes become more complex through incorporation of more comprehensive physical effects, use of sophisticated algorithms and parallelization procedures, the probability of implementation inconsistencies and implementation mistakes that affect the computed solution increases. In this environment, rigorous code verification through use of order-of-accuracy studies becomes essential to provide confidence that the intended code solves its governing equations correctly. Within simulations using parameterized physics, where first order convergent algorithms are intended, numerous examples have developed that show a loss of convergence. This minisymposium will elaborate on some of these examples and discuss methods for identifying loss of convergence within these simulations. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-757786.

Organizer: Carol S. Woodward
Lawrence Livermore National Laboratory, U.S.

Organizer: David J. Gardner
Lawrence Livermore National Laboratory, U.S.

continued in next column

9:45-10:05 Loss and Restoration of Time-step Convergence in an Atmosphere Model with Simplified Physics

Shixuan Zhang, Battelle Pacific Northwest Laboratory, U.S.; Hui Wan, Pacific Northwest National Laboratory, U.S.; Carol S. Woodward and Christopher J. Vogl, Lawrence Livermore National Laboratory, U.S.; Panos Stinis, Pacific Northwest National Laboratory, U.S.; David J. Gardner, Lawrence Livermore National Laboratory, U.S.; Phil Rasch, Pacific Northwest National Laboratory, U.S.; Xubin Zeng, University of Arizona, U.S.; Vincent Larson, University of Wisconsin, Milwaukee, U.S.; Balwinder Singh, Pacific Northwest National Laboratory, U.S.

10:10-10:30 Addressing Convergence Issues in a Simplified Condensation Model with a Rigorous Modelling of Subgrid Processes

Christopher J. Vogl, David J. Gardner, and Carol S. Woodward, Lawrence Livermore National Laboratory, U.S.; Shixuan Zhang, Battelle Pacific Northwest Laboratory, U.S.; Hui Wan and Panos Stinis, Pacific Northwest National Laboratory, U.S.

10:35-10:55 Verification of Aerosol Microphysics Parameterizations in the E3sm Atmosphere Model

Kai Zhang, Jian Sun, Hui Wan, and Richard Easter, Pacific Northwest National Laboratory, U.S.

11:00-11:20 Automated Verification of Earth System Models with EVV

Joseph H. Kennedy, Oak Ridge National Laboratory, U.S.; Peter Caldwell, Lawrence Livermore National Laboratory, U.S.; Katherine J. Evans and Salil Mahajan, Oak Ridge National Laboratory, U.S.; Balwinder Singh and Hui Wan, Pacific Northwest National Laboratory, U.S.

11:25-11:45 Evaluation of the Convergence at High Resolution in Time of an Ostensibly First-order Microphysics Model

Sean Santos, University of Washington, U.S.

Thursday, March 14

MS50

Modeling and Numerical Methods for Complex Subsurface Flow - Part II of II

9:45 a.m.-11:50 a.m.

Room: Grand Ballroom A

For Part 1 see MS37

Subsurface flow is of great importance to everyday life. The modeling and the subsequent development of efficient and long-time stable numerical algorithms remain challenging for subsurface flow due to a number of factors including the complex geometry, the enormous scales involved, the presence of uncertainty, the coupling of different dynamics. This minisymposium aims to provide a forum for researchers from different fields to discuss recent advances on the modeling and numerical methods for complex subsurface flow.

Organizer: Xiaoming He
Missouri University of Science and Technology, U.S.

Organizer: Daozhi Han
Missouri University of Science and Technology, U.S.

9:45-10:05 Numerical Study of Coupled Free Flow with a Poroelastic Medium

Prince Chidyagwai, Loyola University, U.S.; Aycil Cesmelioglu, Oakland University, U.S.

10:10-10:30 Discontinuous Galerkin Method for Solving the Black-oil Problem in Porous Media

Loic Cappanera and Beatrice Riviere, Rice University, U.S.

10:35-10:55 Weak Galerkin Finite Element Method with Curvilinear Elements for Darcy Flow with Complex Boundary and Interface

Qingguang Guan, Missouri University of Science and Technology, U.S.

11:00-11:20 Modeling and Numerical Methods for Coupling Dual-porosity Flows and Free Flows

Xiaoming He, Missouri University of Science and Technology, U.S.

continued on next page

11:25-11:45 A Posteriori Error Estimates and Stopping Criteria for Space-time Domain Decomposition for Two-phase Flow with Discontinuous Capillary Pressure

Michel Kern, Inria & Maison de la Simulation, France; Sarah Ali Hassan, Inria, France; Elyes Ahmed, University of Bergen, Norway; Caroline Japhet, Université Paris XIII, France; Martin Vohralik, Inria Paris-Rocquencourt, France

Lunch Break

11:50 a.m.-1:20 p.m.

Attendees on their own

Thursday, March 14

IP6

Learning from Sparse Observations: The Global Ocean State and Parameter Estimation Problem

1:20 p.m.-2:05 p.m.

Room: Grand Ballroom EFGH

Chair: Clint Dawson, University of Texas at Austin, U.S.

Because of the formidable challenge of observing the time-evolving full-depth global ocean circulation, numerical simulations play an essential role in quantifying the ocean's role in climate variability and long-term change. For the same reason, predictive capabilities are confounded by the high-dimensional space of uncertain variables (initial conditions, internal parameters and external forcings). Inverse methods that optimally extract and merge information from observations and models are powerful tools to enable rigorously calibrated and initialized predictive models to optimally learn from the sparse data. State and parameter estimation, in particular, provides the machinery for doing so systematically and quantitatively. Key enabling computational approaches are the use of adjoint methods for solving a nonlinear least-squares optimization problem and the use of algorithmic differentiation for maintaining derivative codes alongside a state-of-the-art ocean general circulation model. Emerging capabilities involving Hessians are the prior-to-posterior uncertainty propagation informed by the observations, and the application of optimal network design methods for developing observing systems. We argue that even CS&E methods that are scalable and applicable to real-world problems remain under-utilized in ocean climate modeling. Realizing their full potential faces considerable practical hurdles, but is indispensable for tackling pressing issues in climate science.

Patrick Heimbach
University of Texas at Austin, U.S.

Coffee Break

2:05 p.m.-2:35 p.m.

Room: Grand Ballroom D

Thursday, March 14

MS51

Seismic Tensor Completion

2:35 p.m.-4:40 p.m.

Room: Richmond 1/2

Tensor algebra is an emerging field with a variety of applications. Tensor completion has use in geoscience for recovering high dimensional data. This minisymposium will cover the effectiveness of various tensor completion methods and their advantages. Speakers will discuss methods of tensor completion on high order tensors, with applications including recovery of seismic data.

Organizer: Jonathan Popa
University of Texas, Dallas, U.S.

2:35-2:55 Comparison of Tensor and Matrix Completion

Jonathan Popa, University of Texas, Dallas, U.S.

3:00-3:20 A Robust Tensor Completion Method and its Application to 5D Seismic Data Reconstruction

Mauricio D. Sacchi and Fernanda Carozzi, University of Alberta, Canada

3:25-3:45 Seismic Tensor Completion

Jianwei Ma, Harbin Institute of Technology, China

3:50-4:10 Tensor-based Algorithms for Seismic Data Reconstruction

Lihua Fu, China University of Geosciences, China

4:15-4:35 How Much Information is there in Dense, Continuous Seismic Data?

Eileen R. Martin, Virginia Tech, U.S.; Fantine Huot and Biondo Biondi, Stanford University, U.S.

Thursday, March 14

MS52

Fracture Formation Coupled with Fluid Flow and Wave Propagation in the Porous Media - Part II of II

2:35 p.m.-4:40 p.m.

Room: Westchase 1/2

For Part 1 see MS29

This minisymposium is dedicated to both analytical and numerical aspects of wave propagation coupled with non-linear flows in porous media. Recent advances in engineering and industry related to fracturing and associated problems in hydrodynamic and geo-mechanics of porous media bring new challenging questions in understanding the non-linear nature of the wave propagation in the media coupled with fluid flow. These processes require new models, sophisticated analysis and efficient algorithms. The goal of the minisymposium is to present and discuss new results in all of these aspects, particularly, in non-linear PDE models, stability analysis, long-time dynamics, numerical simulations, etc.

Organizer: Viktoria Savatorova
University of Nevada Las Vegas, U.S. and National Research Nuclear University, Russia

Organizer: Akif Ibragimov
Texas Tech University, U.S.

Organizer: Aleksey S. Telyakovskiy
University of Nevada, U.S.

2:35-2:55 Nonlinear Elasticity with Density Dependent Material Properties: Acoustic Behavior with Application to Modeling Damage Initiation in Porous Media
Jay R. Walton and K. R. Rajagopal, Texas A&M University, U.S.

3:00-3:20 CFD-DEM Modeling of Fracture Initiation Induced by Fluid Injection
Sun Zhuang, University of Texas at Austin, U.S.

3:25-3:45 Acoustic Waves Propagation in Fractured Porous Materials: High and Low Frequency Approximation
Viktoria Savatorova, University of Nevada Las Vegas, U.S. and National Research Nuclear University, Russia; Aleksei Talonov, University of Nevada, Las Vegas, U.S.

continued in next column

3:50-4:10 Frequency-dependent Seismic Reflectivity of Randomly Fractured Fluid-saturated Media
Anna Krylova, University of Houston, U.S.

4:15-4:35 A Global Sensitivity Approach for Optimizing Hydraulic Fracture Propagation and Recovery in Horizontal Wells
Ali Rezaei, Kalyana Nakshatrala, Fahd Siddiqui, and Mohamed Soliman, University of Houston, U.S.

Thursday, March 14

MS53

Novel Computational Methods and Stabilization of Fingering Instabilities for Porous Media Flows in Chemical EOR

2:35 p.m.-4:40 p.m.

Room: Grand Ballroom A

Flow of Newtonian and non-Newtonian fluids through heterogeneous porous media occurs in a wide variety of situations including industrial applications such as chemical enhanced oil recovery. The speakers in this minisymposium will present talks on novel computational methods for chemical enhanced oil recovery and theoretical results on stabilization of fingering instability in Newtonian and non-Newtonian porous media flows.

Organizer: Prabir Daripa
Texas A&M University, U.S.

2:35-2:55 Mathematical and Computational Challenges for Multi-phase Porous Media Flows in Chemical EOR
Prabir Daripa, Texas A&M University, U.S.

3:00-3:20 Results on the Stabilization of Fingering Instabilities in Porous Media Flows
Craig Gin, University of Washington, U.S.

3:25-3:45 Pore-Scale Analysis of Interfacial Instabilities in Porous Media
Mayank Tyagi, Louisiana State University, U.S.

3:50-4:10 On the Immiscible Displacement of Viscoelastic Fluids in a Hele-Shaw Cell
Zhiying Hai, Texas A&M University, U.S.

4:15-4:35 Stabilizing Effect of Reversible Precipitation Reaction on Fingering Instability
Priyanka Shukla, Indian Institute of Tecnology Madras, India

Thursday, March 14

MS54

New Computational Approaches to Storm Surge Modelling

2:35 p.m.-4:40 p.m.

Room: Grand Ballroom EFGH

Today's flood forecasts heavily depend on numerical computer simulations. We use computer models to forecast storm events as a means to inform and warn the public, as well as to hindcast past events in the interest of furthering our understanding of the governing physics of storm surges. Latest developments in high-performance computing architecture offer new resources that can improve the efficiency and accuracy of state-of-the-art numerical algorithms, and furthermore increase the viability to push the operational capabilities towards street level inundation. With an ever changing climate, we are expecting a change in storminess at many coasts around the globe. To further study anticipated near- and on-shore impacts, we require an improved model of physical processes to accurately represent the coastal impact of storm waves. In this minisymposium, we will highlight and discuss latest developments in the area of storm surge models from both, a research perspective and an operational point of view.

Organizer: Nicole Beisiegel
University College Dublin, Ireland

Organizer: Jörn Behrens
Universität Hamburg, Germany

2:35-2:55 A Survey of Recent Advances in Storm Surge Simulations

Nicole Beisiegel, University College Dublin, Ireland

3:00-3:20 Application of Adjoint Methods to Storm Surge Sensitivity Analysis

Simon C. Warder and Stephan Kramer, Imperial College London, United Kingdom; Athanasios Angeloudis, University of Edinburgh, United Kingdom; Colin J. Cotter, Imperial College London, United Kingdom; Kevin Horsburgh, National Oceanography Centre, United Kingdom; Matthew Piggott, Imperial College of London, United Kingdom

continued in next column

3:25-3:45 Surge Dynamics Across a Complex Bay Coastline, Galveston Bay, Texas

Jennifer Proft, University of Texas at Austin, U.S.

3:50-4:10 Modeling Hurricane Waves and Storm Surge

Clint Dawson, Maximillian Bremer, and Kazbek Kazhyken, University of Texas at Austin, U.S.

4:15-4:35 A Green's Function Approach to Efficient Shallow Water Uncertainty Quantification

Will D. Mayfield, Oregon State University, U.S.

Thursday, March 14

MS55

Multiscale Computation of Subsurface Processes

2:35 p.m.-4:40 p.m.

Room: Grand Ballroom B

Understanding and ultimately predicting subsurface dynamics is important in a number of geoscientific applications including geologic carbon storage, geothermal energy, groundwater hydrology, and hydrocarbon recovery. Advanced computational methods are often required to resolve a wide range of spatiotemporal scales as well as to capture intricately coupled nonlinearities inherent to the physics. From an engineering viewpoint, mathematical techniques capable of accelerating computations are especially attractive as they enable predictive control of subsurface dynamics through optimization and uncertainty quantification. The aim of this minisymposium is to bring together expertise and ideas from a wide range of applications (fluid, solid, thermal, reactive processes) that focus on multiscale computational methods designed to approximate, accelerate, or resolve scales/non-linearities in the subsurface.

Organizer: Yashar Mehmani
Stanford University, U.S.

Organizer: Nicola Castelletto
Lawrence Livermore National Laboratory, U.S.

2:35-2:55 Upscaling of Multi-phase Flow and Transport using Non-local Multi-continuum Approach

Eric T. Chung, Chinese University of Hong Kong, Hong Kong; *Yalchin Efendiev*, Texas A&M University, U.S.; Wing Tat Leung, University of Texas at Austin, U.S.; Maria Vasilyeva, Texas A&M University, U.S. and North-Eastern Federal University, Russia

3:00-3:20 Nonlinear Multigrid Solvers for Finite Volume Problems using Spectral Coarsening

Chak Lee, Nicola Castelletto, Panayot Vassilevski, and Joshua A. White, Lawrence Livermore National Laboratory, U.S.

3:25-3:45 Multi-scale Modelling Based on Non-linear Finite-volume Schemes

Martin Schneider, Rainer Helmig, and Bernd Flemisch, Universität Stuttgart, Germany

continued on next page

Thursday, March 14

MS55

Multiscale Computation of Subsurface Processes

continued

3:50-4:10 Multiscale Data-model Integration using an Event-driven Approach for Understanding Nutrient Cycles in Plant-microbe-soil Systems

Timothy D. Scheibe and Kurt H. Maier, Pacific Northwest National Laboratory, U.S.

4:15-4:35 Multiscale Formulation for Pore-scale Compressible Darcy-Stokes Flow

Bo Guo, University of Arizona, U.S.; Yashar Mehmani and Hamdi Tchelepi, Stanford University, U.S.

Thursday, March 14

MS56

Recent Advances in Computational Modeling of Coupled Flow and Geomechanics in the Subsurface Environment - Part II of II

2:35 p.m.-4:40 p.m.

Room: Briarpark 1/2

For Part 1 see MS33

This minisymposium seeks to gather the most recent advancements in numerical and analytical techniques for coupling geomechanics and flow in the subsurface. Numerical models involving the coupled PDEs can be challenging to solve due to strong nonlinearity and high heterogeneity as well as different length and time scales between individual physics. This mini-symposium aims at spotlighting the current research state of the art, model capabilities, and numerical methods in reservoir, environmental, and civil engineering with applications such as hydraulic fracturing, CO2 sequestration, gas hydrate deposits, enhanced geothermal systems, induced seismicity, and wellbore-stability. In particular, topics of interest include various formulations and discretization techniques, multiscale methods, stability and convergence of sequential solution strategies, computer code development, and scalable linear and nonlinear solvers.

Organizer: Jihoon Kim
Texas A&M University, U.S.

Organizer: Sanghyun Lee
Florida State University, U.S.

Organizer: George Moridis
Lawrence Berkeley National Laboratory, U.S.

2:35-2:55 Phase-field Fracture Modeling of Fluid-filled Fractures in Porous Media

Sanghyun Lee, Florida State University, U.S.; Andro Mikelic, Universite Lyon 1, France; Mary F. Wheeler, University of Texas at Austin, U.S.; *Thomas Wick*, Leibniz Universität Hannover, Germany

3:00-3:20 Constrained Energy Minimization Based Upscaling for Coupled Flow and Mechanics in Fractured Porous Media

Maria Vasilyeva, Texas A&M University, U.S. and North-Eastern Federal University, Russia; Eric T. Chung, Chinese University of Hong Kong, Hong Kong; Yalchin Efendiev and Jihoon Kim, Texas A&M University, U.S.

3:25-3:45 Coupling Fem and Meshfree Peridynamics for Efficient Simulation of Hydraulic Fracturing

John Foster, University of Texas at Austin, U.S.

3:50-4:10 Fully Coupled Multimesh Algorithms for Nonisothermal Multiphase Flow and Mechanics in Geological Formations

Alejandro Queiruga, Lawrence Berkeley National Laboratory, U.S.

continued in next column

SIAM Conference on
Mathematical & Computational Issues in the Geosciences

March 11 – March 14, 2019
Houston Marriott Westchase
Houston, Texas, U.S.

IP1

Numerical Models for Earthquake Ground Motion

Physics-based numerical simulations provide a powerful tool to study the ground motion induced by earthquakes in regions threatened by seismic hazards. They can be used to better understand the physics of earthquakes, improve the design of site-specific structures, and enhance seismic risk maps. The distinguishing features of a numerical method designed for seismic wave propagation are: accuracy, geometric flexibility and parallel scalability. High-order methods ensure low dissipation and dispersion errors. Geometric flexibility allows complicated geometries and sharp discontinuities of the mechanical properties to be addressed. Finally, since earthquake models are typically posed on domains that are very large compared to the wavelengths of interest, scalability allows to efficiently solve the resulting algebraic systems featuring several millions of unknowns. In this talk we present a spectral element discontinuous Galerkin method on hybrid (non-conforming) grids for the numerical solution of three-dimensional wave propagation problems in heterogeneous media. We analyze the stability and the theoretical properties of the scheme and present some simulations of large-scale seismic events in complex media: from far-field to near-field including soil-structure interaction effects. Our numerical results have been obtained using the open-source numerical code SPEED (https://speed.mox.polimi.it).

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IP2

Homogenization Approach for Modeling of Reactive Transport in Porous Media

My goal is to explain how homogenization theory can be applied to the modeling of reactive transport in porous media. The main idea is to derive macroscopic models, valid on a large scale, from microscopic equations, written at the pore scale, and to obtain effective formulas for the homogenized coefficients, in a mathematically rigorous framework. The typical microscopic equations are Stokes equations for a viscous fluid, convection-diffusion equations with reaction terms for several diluted species, and possibly a coupling with other effects (like electrokinetics or Poisson-Boltzmann model). An example of an important macroscopic effect to be modeled is that of the so-called Taylor dispersion which governs the effective diffusion of a diluted species. Our framework is that of periodic homogenization combined with singular perturbations and scaling considerations. This is a review of several joint works with R. Brizzi, J.-F. Dufreche, H. Hutridurga, A. Mikelic, A. Piatnitski.

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IP3

Challenges in Recovering Deep Low-wavenumber Updates in Full Waveform Inversion

Full Waveform Inversion (FWI) is a method for recovering unknown coefficients (medium properties) in the wave equation given recorded waveforms on a boundary of the domain of propagation. Over the past decade it emerged as a method of choice for determining subsurface properties in exploration seismology. While the fundamentals of FWI have been known for over 30 years, its robust application on industrial scale still presents a formidable challenge, given limited surface coverage of available recordings. Many early FWI applications were focused on working with diving waves (transmitted arrivals). However, in exploration seismology these types of waves sample only relatively shallow depths. Recently, significant efforts have been directed towards extending FWI's reach deeper into the subsurface by obtaining information about large-scale characteristics of subsurface properties from reflected arrivals. Extraction of the so-called “tomographic” mode associated with this task is a difficult problem in practical FWI applications because it is weak relative to other parts of the objective function gradient. This talk will cover the fundamentals of FWI, followed by challenges, solutions, and open problems associated with exploiting the tomographic mode, including the choice of objective functions, methods of separating various components of the gradient, and use of constraints.

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IP4

Sea Ice Model Complexity

The CICE sea ice model is used extensively by climate and Earth system research groups, and also by operational centers for applications such as numerical weather prediction and guidance for military operations. A current discussion thread within the sea ice modeling community hinges on how complex such models need to be. This talk delves into the complexity of physical processes represented in the CICE model, including how the model evolved and why such complexity might or might not be needed.

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IP5

Multicomponent Elastic Imaging: New Insights from the Old Equations

Elastic wave imaging has been a significant challenge in the exploration industry due to the complexities in wave physics and numerical implementation. We have separated the governing equations for P- and S-wave propagation without the assumptions of homogeneous Lam parameters to capture the mode conversion between the two body waves in an isotropic, constant-density medium. The resulting set of two coupled second-order equations for P- and S-potentials clearly demonstrates that mode conversion only occurs at the discontinuities of the shear modulus. Applying the Born approximation to the new equations, we derive the PP, PS, SP, and SS imaging conditions from the first gradients of waveform matching objective functions. The resulting images are consistent with the physical perturbations of the elastic parameters, and, hence, they are automatically free of the polarity reversal artifacts in the converted images. When implementing elastic reverse time migration (RTM), we find that scalar wave equations can be used to back propagate the recorded P-potential, as well as individual components in the vector field of the S-potential. Compared with conventional elastic RTM, the proposed elastic RTM implementation using acoustic propagators not only simplifies the imaging condition, it but also reduces the computational cost and the artifacts in the images. We have demonstrated the accuracy of our method using 2D and 3D numerical examples.

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IP6

Learning from Sparse Observations: The Global Ocean State and Parameter Estimation Problem

Because of the formidable challenge of observing the time-evolving full-depth global ocean circulation, numerical simulations play an essential role in quantifying the oceans role in climate variability and long-term change. For the same reason, predictive capabilities are confounded by the high-dimensional space of uncertain variables (initial conditions, internal parameters and external forcings). Inverse methods that optimally extract and merge information from observations and models are powerful tools to enable rigorously calibrated and initialized predictive models to optimally learn from the sparse data. State and parameter estimation, in particular, provides the machinery for doing so systematically and quantitatively. Key enabling computational approaches are the use of adjoint methods for solving a nonlinear least-squares optimization problem and the use of algorithmic differentiation for maintaining derivative codes alongside a state-of-the-art ocean general circulation model. Emerging capabilities involving Hessians are the prior-to-posterior uncertainty propagation informed by the observations, and the application of optimal network design methods for developing observing systems. We argue that even CS&E methods that are scalable and applicable to real-world problems remain under-utilized in ocean climate modeling. Realizing their full potential faces considerable practical hurdles, but is indispensable for tackling pressing issues in climate science.

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SP1

SIAG/GS Career Prize Lecture: Large-scale Bayesian Inversion for Geoscience Problems

Ever since Tarantola's pioneering work in the 1980s, the Bayesian framework has offered a rational and systematic means of accounting for uncertainty in the solution of inverse problems, given uncertainty in observational data, forward models, and any prior information. However, Bayesian inversion has remained out of reach for many geoscience problems, due to the infinite-dimensional nature of typical parameter fields (high-dimensional after discretization), and the complexity of forward models of many geoscience processes. We discuss recently-developed methods inspired by large-scale optimization ideas that have shown promise in overcoming these challenges. Applications to several geophysical inverse problems are presented.

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SP2

SIAG/GS Early Career Prize Lecture: Multiscale Simulation of Porous Media Flow: Obstacles, Opportunities and Open-source

CO2 storage and hydrocarbon recovery is modelled by mixed hyperbolic-elliptic PDEs, posed on unstructured, polyhedral grids with large aspect ratios. Such models are strongly nonlinear, have a truly multiscale behavior, and contain complex tabulated data or analytic submodels that makes linearization and solution nontrivial. Herein, I discuss challenges faced when developing new (multiscale) simulation methods for industry use. To overcome these challenges, we use the open-source MATLAB Reservoir Simulation Toolbox for rapid prototyping and bootstrapping of new methods, and to leverage the effort of others in a reproducible manner.

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CP1

Shape-Constrained Inversion in Geoscience

Non-uniqueness of geophysical inverse problems is particularly acute when multiple physical parameters are unknown (e.g. density and wave speed). Inverting for geologic shapes, rather than cell-based parameter values, can mitigate this non-uniqueness by ensuring that the unknown parameters share a common set of interfaces across which they may change abruptly. This talk will highlight the impact of shape-constrained inversion in Geoscience utilizing either a Mumford-Shah or phase-field shape representation. Examples will be drawn from multi-parameter inversion for flow in porous media, multi-scale FWI, FWI-based salt inversion, and joint inversion.

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CP1

Reflection Coefficient for a Seismic Fractional Interface

We consider a medium in which propagates a high frequency elastic wave, which presents an interface at which the fractional derivative of the wave velocity $D^\alpha c$ is discontinuous ($0 < \alpha < +\infty$). The reflection coefficient induced by this interface, in the high frequency regime, away from the glancing points is not zero and is equal to

$$R = \frac{[D^\alpha(\frac{\omega^2}{c^2})]}{(2i)^{\alpha+2}k_\perp^{\alpha+2}}$$

where $k_\perp = \sqrt{\frac{\omega^2}{c^2} - k^2}$ is the normal component of the wave vector, $[]$ denotes the jump of the quantity at the interface. This result is consistent with the analysis of the layer and shows that, outside from the glancing points ($k_\perp \neq 0$) R is a pseudodifferential operator of order $-\alpha$.

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CP1

Model Misspecification and Robust Bayesian Inference in Seismic Inversion

In the Bayesian setting, model misspecification can lead to overconfidence in the posterior distribution associated with any quantity of interest (QoI), i.e., under-reporting of uncertainty. The usual approach to mitigating the impact of model misspecification is to introduce better physical models (when feasible) or improved statistical discrepancy models. These approaches, however, typically increase computational cost and may compromise parameter identifiability. In the context of seismic waveform inversion, we present a methodology that instead exploits the physics of the forward model to extract, from simulated data, features that are simultaneously informative about the parameters we wish to estimate and insensitive to model misspecification. In particular, modelling of the propagation velocity [V] of a seismic wave is generally approximate and inaccurate, due to the difficulty of characterizing the subsurface medium (e.g., three-dimensional spatial inhomogeneities). Mischaracterization of V can, however, impact one's ability to infer other QoIs such as the hypocenter [X] and the moment tensor [m] (focal mechanism) of a seismic event. Our approach applies transformations to the data that extract features relevant to m or X and relatively insensitive to V. Inference is then performed with the transformed data, which is equivalent to building a likelihood function that is less sensitive to the nuisance effect introduced by the misspecification of V.

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CP1

Full-Waveform Inversion in Shallow-Water Environments

Full-waveform inversion is a PDE-constrained parameter-estimation problem that seeks to infer subsurface properties, such as wave velocity and density, by iteratively minimizing a misfit between seismic responses measured in the field and those obtained from a computer model based on the wave equation (acoustic, elastic, or more physics-rich) and an initial characterization of the subsurface. Full-waveform inversion is computationally expensive and ill-posed. The ill-posedness manifests itself in the extreme difficulty to converge to an earth model that both minimizes the misfit between measured and modeled seismic responses and also represents realistic geology. Shallow-water assets, whereby the seismic source wavelength is on the same order of magnitude of (or smaller than) the water-layer depth, are even more difficult to characterize by full-waveform inversion. In shallow-water environments, the inability to distinguish between water-layer multiples and deeper reflections, the fact that the water layer acts as a wave guide, and the high sensitivity of far-offset responses to water-layer depth all tend to exacerbate ill-posedness (as compared to deep-water assets). Numerical experiments are presented to illustrate these challenges and to assess inversion resilience to the increased ill-posedness.

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CP2

Forecasting the Gulf of Mexico Loop Current: A Machine Learning Approach

The Loop Current is the dominant circulation feature in the Gulf of Mexico (GOM). It is a warm current that enters through the Yucatan Channel, proceeds north and then loops east and then south to exit through the Florida Straits. On a semi-annual cycle the Loop Current will extend into the northern and central Gulf, and shed large anti-cyclonic eddies, referred to as Loop Current Eddies (LCEs). The Loop Current and its associated LCEs can have significant impacts on oil and gas operations in the deep water GOM. When these features overlap a site, they bring strong currents that penetrate deep into the water column, posing significant design and operating hazards. These currents can be a major source of downtime for deep water drilling and installation activities. Ocean physics-based numerical models are used to forecast the evolution of the Loop and LCEs over periods up to two weeks. Ensemble run schemes of these models are used to project the statistics of encounters at time horizons up to eight weeks, with mixed success. For long-lead projects, forecasts in excess of two months would be of great value. This presentation documents an investigation of machine learning approaches to the problem of very long range (2+ month) Loop Current / LCE forecasting. Early results suggest that this approach may result in a forecasting capability skillful enough to provide significant benefits to major capital project and drilling campaign planning in the deep water GOM.

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CP2

Comparative Analysis of Groundwater Modeling Software to Describe the Interaction Between Surface Water and Groundwater During Floods

The dynamic of groundwater flow and the interactions between streams and aquifers can be highly influenced by extreme river stage fluctuations during floods. One approach for investigating the spatiotemporal responses induced by transient river stages on the aquifer is numerical modeling. Many hydrological models are capable of simulating integrated surface water and subsurface flow and they are all different under several aspects (e.g., description of the boundary conditions, numerical solvers, discretization method). Their validity is generally tested comparing the numerical results to relatively simple analytical solutions, but it has not been deeply studied for extreme conditions such as floods. This study aims to identify the applicability, performance, and results (i.e., hydraulic head distribution and flow fields) of three widely used hydrogeological simulation tools (MIKE SHE, MODFLOW and ParFlow) for modeling the interaction between surface water and groundwater during floods. We developed a sophisticated benchmark problem based on the flood event occurred in the valley of the river Alz (Germany). The comparative analysis included the evaluation of the results, the representation of the physical processes, the formulation of the governing equations, the interface boundary conditions, and the numerical solvers. The study provides a framework for researchers and practitioners to assess the simulation engines as the field of coupled hydrologic modeling advances.

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CP2

Large-Scale Simulation of Flow in Channel Networks Using 1D Shallow Water Equations

Coastal areas are vulnerable to flooding not only because of hurricane storm surge but also because of the rainfall that often accompanies hurricanes. However, coastal surge models do not typically incorporate the impact of rainfall across the coastal floodplain, mainly because the coastal ocean hydrodynamics has been decoupled from the upland rainfall-runoff physics. Here, we develop a computational model to simulate flow in channel networks using 1D shallow water equations and provide directions to couple this model with the current tools of storm surge simulation, such as ADCIRC. We present a mathematical framework to efficiently implement a high-resolution (second-order) explicit scheme for the solution of nonlinear, one-dimensional Shallow Water Equations, including the source terms. We use the Lax-Wendroff finite volume method, in combination with the upwind scheme and flux limiter, of different types, which allows us to capture shocks and jumps in the simulation. We parallelize our algorithm to increase the efficiency of the model for large-scale simulations. We verify our implementation with analytical results and apply the technique to synthetic channel networks. Due to the use of explicit time schemes, this model is highly scalable in massively parallel HPC platforms.

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CP2

Power Laws and Self-Similarity in Tornadogenesis

We discuss a power law for vorticity and velocity fields in a tornadic supercell. We also calculate an approximate fractal dimension of a cross section of a tornado vortex. Then we attempt to relate a power law and an approximate fractal dimension of the cross section of the vortex.

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CP3

Multilevel Monte Carlo Uncertainty Quantification for Finite Volumes

We consider the problem of quantifying the forward propagation of uncertainty in a finite volume reservoir model. We introduce a framework for multilevel Monte Carlo for finite volumes, where the underlying idea of taking many samples on coarse grids and few samples on fine grids ensures high accuracy with minimal computational cost. By using finer levels not to measure a quantity of interest directly, but rather to estimate a correction to the quantity on the next coarser level, we ensure that the variance is reduced on finer levels and therefore fewer samples are required. In addition, the use of a PDE-based sampler as in [Osborn, Vassilevski, Villa 2017] allows for scalable Monte Carlo sampling that is consistent between all levels of the discretization. The multilevel finite volume discretization in this work is based on the multigrid-based graph upscaling of [Barker, Lee, Vassilevski 2018]. We present numerical results showing the robustness, accuracy, and parallel scalability of our methods.

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CP3

Uncertainty Quantification of the Multi-centennial Response of the Antarctic Ice Sheet to Climate Change

Uncertainties in ice-sheet models limit the ability to provide accurate sea-level rise projections. Here, we apply probabilistic methods to investigate the influence of several sources of uncertainty (atmospheric forcing, basal sliding, grounding-line flux parameterisation, calving, sub-shelf melting, ice-shelf rheology and bedrock relaxation) on the response of the Antarctic ice sheet to climate change. We provide probabilistic projections of sea-level rise and grounding-line retreat and we carry out stochastic sensitivity analyses to determine the most influential sources of uncertainty. We find that all sources of uncertainty, except perhaps the bedrock relaxation times, contribute to the uncertainty in the projections. We show that the sensitivity of the projections to uncertainties increases and the contribution of the uncertainty in sub-shelf melting to the uncertainty in the projections becomes more and more dominant as the scenario gets warmer. We show that the significance of the contribution to sea-level rise is controlled by instabilities in marine basins, especially in the West Antarctic ice sheet (WAIS). We find that, irrespectively of parametric uncertainty, the RCP 2.6 scenario prevents the collapse of the WAIS, that in both RCP 4.5 and RCP 6.0 scenarios the occurrence of instabilities in marine basins is more sensitive to parametric uncertainty and that, almost irrespectively of parametric uncertainty, RCP 8.5 triggers the collapse of the WAIS.

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CP3

Can a High Dimensional Parameter Space be Acceptable for a Lumped Hydrological Karst Model?

Modeling karst aquifers using hydrological distributed models is challenging. In fact, the complex network of conduits, caves and fractures is generally unknown and therefore it is difficult to represent physical processes such as infiltration and spring discharge generation. Lumped models are affected by the problem of model equifinality. Their parameters cannot be generally derived through field measurements and therefore different combinations of model parameters may display the same misfit between measurements and model results. The purpose of this work is to apply the active subspace method, to investigate how the parameters of a newly proposed hydrological model for karst aquifers (LuKARS, Land use change modeling in KARSt systems) are informed by discharge data. Our results show that all 21 model parameters are informed by the available spring discharge data and therefore it is not possible to apply any model reduction scheme. A more traditional method, Nelder-Mead simplex algorithm, is then applied to identify a local optimum for the misfit function.

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CP3

Distribution-Based Method for Uncertainty Propagation of Compositional Displacements

Current work presents a novel approach for uncertainty propagation of transport in multicomponent two-phase systems. This approach originates from the distribution method of [Ibrahima, F., Tchelepi, H. A., Meyer, D. W. An efficient distribution method for nonlinear two-phase flow in highly heterogeneous multidimensional stochastic porous media], called FROST, developed for obtaining the probability distribution of phase saturation in water-oil displacements. We describe here how the FROST formalism is suitable for a large class of hyperbolic problems describing one-dimensional gas-oil displacements where both phases can be mixtures of multiple components. These problems arise during enhanced oil recovery through gas injection, and they are known to be challenging in terms of the numerical simulation due to a large number of unknowns and strong nonlinear effects, making uncertainty assessment of such systems even more challenging. The developed FROST method for multicomponent systems relies on the theory of gas injection processes ([Orr, F. M. Jr. Theory of gas injection processes]) and analytical solutions that it provides. In numerical examples in 1- and 2-D we apply FROST to three- and four-component oil-gas systems subject to the stochastic porosity or/and permeability fields, and we show that FROST can provide accurate and efficient estimates of the probability distribution of different components in these types of compositional systems.

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CP4

Adaptive Numerical Homogenization: a Novel Approach for Simulation of Fluid Flow in Highly Heterogeneous Porous Media

Many real-life applications are involving fluid flow through porous media. In most of the cases, the porous medium is heterogeneous and has highly oscillatory characteristics. This makes the development of efficient numerical simulation methods a challenging task. In general, standard numerical methods will either fail or become inefficient due to the presence of the rapidly changing characteristics, which requires then a mesh that if fine enough to remain accurate at the smallest scales. In this context, multi scale techniques are a good compromise between accuracy and computational complexity. Here we present a numerical scheme for approximating the solution of effective (homogenized) models at the macro scale. Based on the mixed finite element formulation, this scheme is using the classical homogenization theory to derive effective parameters, but without assuming any periodicity in the medium characteristics. In addition, it uses an error estimator to perform a local mesh refinement. The main idea is to localize the computation of the effective parameters in order to improve the accuracy of the solution, but without affecting the efficiency. We first use some well-known examples to illustrate the behavior of the adaptive scheme and to analyze the error. Finally, we discuss the applicability of this approach to other problems, like the reactive flow and transport in porous media.

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CP4

Honmogenization Wavelet Reconstruction for Approximate Solution of Elliptic Partial Differential Equations

A multiscale methodology will be presented that treats discontinuous rapidly varying coefficients in elliptic partial differential equations. A wavelet transform based on coefficients conditioned by homogenization methods is central to the methodology. Analytic solution of local problems is used to produce a recursive algorithm for the average values on a nested dyadic mesh. In turn the details in the wavelet transform are used to reconstruct the solution on the same dyadic mesh. The result is an algorithm that produces approximate solutions on all scales involves in the mesh. Results will be presented for porous media equations in two dimensions. Simulations of the Cahn-Hilliard equation will also be discussed.

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CP4

Approximating Permeability Density Functions for Flow and Transport in Obstructed Porous Media

Changes in pore scale geometry cascade into changes in the critical core scale coefficients, porosity and permeability, as well as transport parameters. With numerical upscaling, we move information from pore scale to core scale. In this talk, we describe the use of a Markov Chain Monte Carlo (MCMC) method to generate realistic obstructions to pore scale flow. We can then build large classes of obstructed pore scale geometries, which are used in generating the permeability density functions for a given class of obstructions, and for the upscaled parameters. But the MCMC method requires three tuning parameters. How should these numbers be chosen? We discuss this question and how we can improve upon heuristic-based human choices.

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CP5

Isogeometric Analysis of a Coupled Stokes-Biot System

Understanding the interaction of a free flow and a deformable porous medium is essential for geomechanical applications such as Enhanced Geothermal Systems and the controlled extraction of oil and gas from fractured reservoirs. To study this interaction we developed a coupled model. In the model, the free flow is described by the Stokes equations, the porous formation is described by Biot's equations, and the fluid flow in the formation is described by Darcy's law. Both the free flow region and the formation are saturated with fluid. One of the challenges addressed in this contribution is the choice and implementation of suitable coupling conditions on the shared interface of the free flow and the poroelastic medium. To fully couple the Stokes equations to Biot's equations, both stress and flow conditions are prescribed. The slip encountered by the fluid flowing along the saturated formation is enforced by the Beavers-Joseph-Saffman condition. Furthermore, the Darcy flux over the interface is driven by a pressure jump condition. We apply isogeometric analysis (IGA) to the problem. IGA employs splines instead of the Lagrange basis functions used in traditional FEA. The controllable continuity property of splines allows for high accuracy with relatively few degrees of freedom. The numerical model is shown to fully couple a free flow and a saturated deformable porous medium in one- and two-dimensional cases and for various geometries.

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CP5

Semi-infinite Fracture Driven by Herschel-Bulkley Fluid

Hydraulic fracturing, a well-known industrial process, is often applied to enhance oil and gas recovery. Under this process, fractures are generated by an injection of highly pressurized fluids, which typically exhibit shear-thinning rheology and yield stress. The global fracture propagation is quite complex, as it is influenced by various processes occurring near the fracture tip. To gain a mechanistic insight into the fracture propagation, we consider the near-tip region of a hydraulic fracture with Herschel-Bulkley (HB) fluid propagating in permeable linear elastic rock. The mathematical model consists of the elasticity equation, the lubrication equation, and the propagation criterion for the semi-infinite plane strain fracture to obtain the fracture opening. The solution is influenced by the competing processes related to rock toughness, fluid properties, and leak-off. The effects of these phenomena prevail at different length scales, and the corresponding limiting behaviors can be described via analytical solutions. For a HB fluid, an additional limiting solution, related to fluid yield stress, is obtained and its region of dominance is investigated. The general problem is solved numerically by using Newtons method and Simpsons rule to discretize the governing integral equation. Numerical results demonstrate that the yield stress influences the solution at larger distances from the tip and the solution follows the behavior of a power-law fluid ahead of this zone.

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CP5

Approximation and Wavelet-based Modelling in Poroelasticity

In geothermal research, the aspect of poroelasticity is important to consider. It describes the interaction between solids deformation and fluid flow. Its mathematical model and equations are dated back to Biot. We regard the quasistatic equations of poroelasticity (QEP) with the unknown displacement u and pore pressure p.

$$-\frac{\lambda+\mu}{\mu}\nabla_x(\nabla_x\cdot u)-\nabla_x^2 u+\alpha\nabla_x p=f,$$

$$\partial_t(c_0\mu p+\alpha(\nabla_x\cdot u))-\nabla_x^2 p=h.$$

Fundamental solutions were derived by [A.H.D. Cheng, E. Detournay: On singular integral equations and fundamental solutions of poroelasticity, Int.J.Solid.Struct.(1998)], where one problem are singularities.
Based on [C. Blick, W. Freeden, H. Nutz: Feature extraction of geological signatures by multiscale gravimetry, Int.J.Geomath.(2017)], we regularize the fundamental solutions concerning a parameter τ (scaling parameter) with a Taylor approximation and construct wavelets by subtracting two of them with a different scale.
By the convolution of given data u and p e.g. from the method of fundamental solutions (cf. [M. Augustin, A Method of Fundamental Solutions in Poroelasticity to Model the Stress Field in Geothermal Reservoirs,PhD Thesis(2015)]) with the wavelets, we want to decorrelate these data and extract more details of u and p. Another way to do can be to approximate given data with these regularized fundamental solutions.

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CP5

System Reduction for Fractured Porous Media through a Machine-learning Approach that Identifies Main Flow Pathways

High-fidelity flow and transport simulation on large discrete fracture networks (DFN) are computationally expensive. This makes uncertainty quantification studies of quantities of interest such as travel time through the network computationally intractable, since multiple runs of the DFN model are required to get good bounds on the uncertainty of the predictions. In this context, we present a system-reduction technique for DFNs using supervised machine-learning via a Random Forest Classifier. The in-sample errors (in terms of precision and recall scores) of the trained classifier are found to be very accurate indicators of the out-of-sample errors, thus exhibiting that the classifier generalizes well to test data. Moreover, this system-reduction technique yields sub-networks as small as 12% of the full DFN that still recover transport characteristics of the full network such as the peak dosage and tailing behaviour for late times. Most importantly, the sub-networks do not get disconnected, and their size can be controlled by a single dimensionless parameter. The computational efficiency gained by this technique depends on the size of the sub-network, but large reductions in computational time can be expected for small sub-networks, yielding as much as 90% computational savings for sub-networks that are as small as 10-12% of the full network.

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CP6

Iterative Solvers for Poromechanics with Large Deformation

In this work we propose convergent iterative solvers based on the L-scheme and Newtons method for a nonlinear Biot model. More precisely, the mechanical deformation follows the Saint Venant-Kirchoff model and the fluid compressibility in the fluid equation is assumed to be nonlinear. We use the Newton method and the L-scheme for linearizing the equations. Monolithic and fixed-stress type splitting approaches are proposed. We use mixed finite elements for the flow equation, (continuous) Galerkin finite elements for the mechanics and Backward Euler for the time discretization. The stability of each scheme is illustrated by numerical experiments and it confirm the theoretical predictions under small deformations.

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CP6

Enriched Galerkin Methods for Matrix Acidizing in Fractured Carbonate Reservoirs

Matrix acidizing is a technique to improve permeability and enhance production especially for carbonate reservoirs, which involves injecting acid to dissolve minerals to create highly conductive channels known as wormholes. Since carbonate reservoirs are often naturally fractured, we present a pressure diffraction formulation with adaptive enriched

Galerkin (EG) methods for simulating acidizing in fractured carbonate reservoirs. The fracture is treated as a diffusive zone. A phase-field variable is defined as an indicator to distinguish fractures and un-fractured rock matrix, which varies from 0 (fracture) to 1 (un-fractured matrix). A weighted pressure diffraction equation is derived to model the flow in both fractures and matrix through phase field. We adopt a two-scale continuum model for the acid transport. The coupled flow and reactive transport system is spatially discretized by EG methods. Our simulation results can reproduce different dissolution patterns of laboratory experiments. Simulation results show that the fracture system controls the dissolution pattern since the wormhole growth is a self-feeding process. This diffusive approach can circumvent substantial permeability contrasts between fractures and un-fractured matrix and allow complicated fracture network. EG methods have less numerical dispersion and grid orientation effects than standard finite difference methods. Computational mesh is adaptively refined to track wormholes and saves computational cost.

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CP6

A Pore-scale Study of the Transport of Inertial Particles in Porous Media

We study the transport of inertial particles in a water-saturated porous medium. We consider particles as a dispersed phase in water phase and analyse the compressible multiphase flow problem at the pore scale. The interaction between phases is restricted to Stokes drag. We show that the inhomogeneities in the flow created by the water flow in the tortuous paths generate regions of preferential accumulation or dispersion of particles. More specifically, strain-dominated regions tend to favor accumulation, whereas vorticity-dominated regions favor dispersion. The possibility of flow diversion due to particle accumulation is analysed and quantified in terms of the Stokes number.

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CP6

Improving Reservoir Simulator Performance through Ensemble Based Robust Optimization

Reservoir simulator performance is considerably impacted by the choice of preconditioners used in linear iterative solvers, time stepping parameters and number of processors used for parallel computing. Typically, the solution of the linear system takes up to 60-70% of the total simulation time. For a well-tuned reservoir simulator, this quickly increases to 80-90% on parallel simulations. Most linear solvers and preconditioners popular for reservoir simulation use many parameters which can be tuned to improve performance but also impact simulation accuracy. Often these parameters are either manually adjusted by trial-and-error or set to their default values, which are far from optimal. This makes the selection of preconditioners and the combination of solver parameters an important and complex task for minimizing model runtime.
The focus of this work is on the application of ensemble-based optimization techniques to improve reservoir simulator performance without adversely impacting simulation accuracy. We use the Stochastic Simplex Approximate Gradient method to optimize solver parameters and select preconditioners (from CPR and 5 different variants of ILU) within the OPM FLOW simulator on a large scale reservoir model. We show that we can on average improve the simulation performance by 30% over an ensemble of 25 model realizations. Furthermore, we describe a workflow for optimizing solver CPU time and highlight the practical value achieved with multiple experiments.

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CP7

Efficient Numerical Ice-sheet Simulations over Long Time Spans

The full-Stokes models to palaeo-ice sheet simulations have previously been highly impractical due to the requirement on the mesh resolution close to the grounding-line. We propose and implement a new sub-grid method for grounding-line migration in full Stokes equations with equidistant mesh. The beauty of this work is to avoid remeshing when the Grounding-line moves from one steady state to another. A new boundary condition is introduced to accommodate the discontinuity in the physical and numerical model. The method is implemented in Elmer/ICE that solves the full Stokes equation with the finite element method. The convergence of the sub-grid method is examined as the mesh is refining and the results are compared with MISMIP benchmark.

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CP7

An Efficient Non-intrusive Reduced Order Model for Approximation of Shallow Water Flows

The Shallow Water Equations (SWE) are widely adopted to study various flow regimes from dam breaks and riverine flows to atmospheric processes. For multi-query and fast replay applications like optimal design or risk assessment, a fully resolved two-dimensional shallow water model poses a significant computational challenge. Proper Orthogonal Decomposition (POD)-based reduction techniques are a popular choice in which, the governing equations are projected onto the space of reduced basis modes to develop a reduced model. We present a non-intrusive approach which replaces the projected reduced model with a multidimensional radial basis function (RBF) interpolant. The RBF interpolant is constructed from a collection of adaptively scaled radial basis kernels and allows for efficient computation of the time evolution of the POD coefficients. This method avoids the stability of the POD/Galerkin reduced model and is also independent of the governing equations. Some results involving practical riverine flows, flow in estuaries and large-scale geophysical flows are presented. The accuracy, computational expense, and robustness of the method are evaluated in comparison to a traditional nonlinear POD strategy.

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CP7

Targeted Re-investigation of Paleoclimate Records using Information Theory

Deep polar ice cores provide us with long, detailed accounts of Earths ancient climate system: tens to hundreds of thousands of years worth of perspective and clues about temperature, accumulation rates, volcanic activity, and more. But this length and precision come at a high cost. Collection of an ice core is very expensive and extraction of proxy data from it is time consuming—as well as susceptible to both human and machine error. Ensuring the accuracy of these data is as challenging as it is important. Many of these cores are only fully sampled one time and most are unique in the time period and region that they "observe," making comparisons and statistical tests challenging and outliers difficult to identify. However, recent advances in information theory and ice-core measurement technology have provided us the means to begin tackling this problem. Here we demonstrate that estimates of the Shannon entropy rate of the water-isotope data from the West Antarctica Ice Sheet Divide ice core, calculated using permutation entropy techniques, identify regions of the core that merit further investigation. To date this approach has flagged regions containing missing ice, data-post processing errors, instrumentation irregularities, signatures of geothermal heating and identified several intervals in the data that may be of direct relevance to paleoclimate interpretationincluding periods of abrupt climate change.

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CP7

A Multilayer Shallow-Water Model with Variable Density

In this work we present a multilayer shallow-water model with variable density. This model should be suited to simulate highly stratified ocean currents where the effects of salinity and temperature are relevant, such as the Strait of Gibraltar. The model consists on a system of hyperbolic equations with non-conservative products that takes into account the pressure variations due to the salinity fluctuations in a stratified fluid. The system is approximated by a path-conservative scheme. The numerical scheme is second order accurate and well-balanced for the stationary solutions corresponding to water at rest. Some numerical results will be presented.

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CP8

'Streamline' Flux-form Semi-Lagrangian Methods for Scalar Transport

The development of efficient and accurate methods for the scalar transport problem in high-resolution GCMs remains an elusive task, with contemporary Eulerian TVD-type methods plagued by restrictive CFL conditions on timestep size. The expense associated with such schemes limits the development and use of complex BGC and pollutant-transport models, which typically require the integration of large numbers of distinct tracer variables. In this work, a new 'streamline' flux-form semi-Lagrangian method is in-

troduced, designed to support large time steps, high-order accuracy and efficient multi-tracer computation. This new scheme is based on a finite-volume type ‘flux-splitting’ approach, in which cell-face fluxes are split into a combination of face-centred mass-fluxes and upwind tracer values; computed by integration along streamlines emanating from local quadrature points. The performance of this new method is evaluated using the Coastal Ocean Model for Prediction Across Scales (COMPAS) a multi-resolution coastal and regional ocean modelling framework based on unstructured meshes. A family of numerical schemes are presented, exploring strategies to obtain high-order accuracy in space and time.

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CP8

Conservative Explicit Local Time-stepping Schemes for the Shallow Water Equations

We present explicit local time-stepping schemes of second and third order accuracy for the shallow water equations. The system is discretized in space by a C-grid staggering method, namely the TRiSK scheme adopted in MPAS-Ocean, a global ocean model with the capability of resolving multiple resolutions within a single simulation. The time integration is designed based on the strong stability preserving Runge-Kutta methods but with different time step sizes in different regions of the domain restricted by respective local CFL conditions. The proposed local time-stepping schemes preserve all important properties in the discrete sense, such as exact conservation of the mass and potential vorticity and conservation of the total energy within time-truncation errors. Extensive numerical tests are presented to illustrate the performance of the proposed algorithms.

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CP8

Multiparameter Full-Waveform Inversion with Near-Interface Sources using Staggered-grid Finite Differences

As imaging targets in exploration seismology become increasingly complex, more advanced imaging algorithms such as full-waveform inversion (FWI) are required. To solve the FWI problem via iterative methods, the gradient of the misfit function is calculated using the solution of the forward partial differential equation (PDE) and its corresponding adjoint. For many acquisition scenarios, the receivers, which are sources in the adjoint problem, are positioned close to or even on boundaries or material interfaces. Most finite difference methods lack rigorous imposition of boundary and interface conditions, accurate treatment of near-interface sources, and a simple procedure for obtaining the discrete adjoint. We use the well-known staggered-grid technique that facilitates accurate wave propagation in the interior of the domain. By requiring that the difference operators satisfy a summation-by-parts formula, we also achieve rigorous imposition of boundary and interface conditions and high-order accurate treatment of singular sources. Moreover, the fully discrete adjoint operator is immediately available and approximates the adjoint PDE to high-order. We prove the effectiveness of the method with 1D numerical examples in which we estimate density, bulk modulus and a source time function from a transmission experiment.

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CP8

The Multiscale Perturbation Method for Elliptic Equations

In the formulation of multiscale methods for second order elliptic equations that are based on domain decomposition procedures, typically the computational domain is decomposed into subdomains, and for each subdomain a set of multiscale basis functions is numerically constructed. Consider the application of such a method to solve a multiphase flow problem where through an operator splitting algorithm, the velocity-pressure and transport equations are solved sequentially. From one time step to the next the multiscale basis functions should be recomputed, because of the coupling of the underlying PDEs. Instead of recomputing all multiscale basis function every time step of a numerical solution, we propose the Multiscale Perturbation Method (MPM). In MPM an approximate solution of velocity and pressure for a new time is obtained by combining regular perturbation theory with multiscale basis functions computed in a earlier time. A novel parallel preconditioner is then used to obtain an improvement on the result obtained from the naive approach. An efficient parallel algorithm is implemented in multi-core machines and the method also fits well in GPU clusters. Numerical experiments, where the perturbation theory results are compared with direct fine grid solutions, are presented and discussed.

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CP8

A Scalable Parallel Implementation of Double Porosity / Permeability Model

Natural geomaterials such as fissured rocks and aggregated soils often exhibit a pore size distribution with two dominant pore scales. An accurate description of flow of fluids in these materials can be achieved using the four-field double porosity/permeability (DPP) model. The problems arise in subsurface modeling are typically large-scale in nature, and hence one cannot solve the practical problems arising from the DPP model on a standard desktop or by employing direct solvers; as such a computation will be prohibitively expensive. In this talk, we discuss two four-field composable block solver methodologies to solve the discrete systems that arise from finite element (FE) discretizations of the DPP model. Utilizing PETScs composable solver features and Firedrake Projects FE libraries, we show that the proposed solvers can be easily implemented in a parallel setting. Moreover, we demonstrate that the composable solvers can be employed under a wide variety of mixed FE discretizations (e.g., classical mixed formulation, stabilized mixed CG formulation, and stabilized mixed DG formulation). Finally, we show that the proposed composable solvers are scalable in both the algorithmic and parallel senses using the recently proposed Time-Accuracy-Size (TAS) performance spectrum.

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CP8

Finite-3lement Approximation for Practical Simulation of Oil-water Systems

Reservoir simulation – a computer model of fluid flow inside a reservoir – is an important tool used by oil-and-gas companies in practically all stages of a reservoir's lifespan. The majority of commercial reservoir simulators traditionally have relied on a low-order finite-volume discretization of the model equations, which despite its speed and relative accuracy, is not without certain drawbacks. Chief amongst them are the need for a specialized, material-property dependent grid (known as K-orthogonal), and the low approximation order of the transport equations. In this presentation we will discuss the application of finite elements, and specifically mixed finite element and discontinuous Galerkin methods, to the problem of reservoir simulation. We will focus on oil-water systems, as we aim to present a fairly complete formulation for practical simulations – including all relevant physics such as gravity, fluid compressibility, capillary pressure, etc. – while still keeping the setting simple enough as to emphasize the important features, and current challenges, of the proposed numerical algorithm. We will, however, comment on the advances needed to extend the algorithm discussed to a full-fledged three-phase miscible (black-oil) formulation.

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CP9

A Data Assimilation Procedure for Calibrating Relative Permeability using Data of Multiple Types

Comprehensive models for flow in subsurface formations typically include many parameters and functions that must be inferred from observed data. Additional complexity arises when these parameters are state-dependent functions, e.g., phase relative permeability curves k_{rp}, which depend on phase saturation S_p. Such functions can be measured experimentally at the core (cm) scale, but the applicability of the resulting curves at grid-block scales (10–100 m) may be questionable. In this work we develop a novel mathematical approach for constructing $k_{rp}(S_p)$ curves, in a point-by-point manner (i.e., a specific functional form is not assumed), using a data assimilation procedure. This is accomplished by formulating an appropriate regularized optimization problem, which we solve using an adjoint-gradient method supported by the automatic differentiation technique. Results for a number of examples, including those where the goal is to determine regional (e.g., well-block) $k_{rp}(S_p)$ curves, as well as cases in which both relative permeability and the absolute permeability field are uncertain, are presented. The inclusion of both production and seismic data is also considered.

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CP9

Sparse Level Set based Ensemble Smoother for History Matching of Reservoirs

We propose a novel shape reconstruction technique called SELE which denotes Sparsity-Ensemble-Level-set optimisation implementing a coupling of a Level-set-Ensemble Smoother Multiple Data Assimilation (ES-MDA) with compressed sensing (CS). Due to the ill-determined nature of history matching, several realisations may match quantitatively to the true model but vary qualitatively in the nature of permeability replicates.SELE solves this ill-posed inverse problem by using a sparsity promoting ES-MDA approach. An initial over-complete learned dictionary is created using an unsupervised learning algorithm, K-SVD. We combine this K-SVD with a greedy orthogonal, matching pursuit algorithm (OMP) for the parametrisation of the petrophysical properties (permeability/ or porosity fields). During the history matching step, we generate the ensemble state which consists of these sparse coefficients coupled with the level set representation of these properties. The analysed sparse coefficients are then mapped back to spatial fields using this K-SVD dictionary. We show the efficiency of our algorithm with numerical examples and quantify the SELE shape reconstruction by using a structural similarity index metric (SSIM). The proposed method is optimal in enforcing prior structural information over the history matched realisations, reduction in computational complexity during the Kalman gain inversion and faster arrival at the minimum of the cost function.

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CP9

Uncertainty Quantification and Reduction by Data Assimilation Techniques in Land Subsidence Modeling

Any modelling activity of real-world processes implies uncertainties and approximations that affect the solution quality and the model reliability. In predicting land subsidence above producing hydrocarbon fields, uncertainty typically affects the estimate of the model geomechanical parameters, which are fundamental for an accurate result. The large amount of currently available surface measurements, e.g., from GPS or InSAR, can be useful to improve the reliability of the numerical solution. In this project, Ensemble Smoother (ES) and Multiple Data Assimilation (MDA) algorithms are implemented and combined with a state-of-art geomechanical non-linear Finite Element (FE) model with the aim to evaluate which, when and how monitoring information can improve subsidence prediction reliability. Two synthetic reservoir models are built with different input data sets, in order to study the effects of including various types of records. Numerical tests show that Data Assimilation approaches can be a powerful tool to improve the effectiveness and reliability of numerical models for land subsidence prediction. In particular, such methods allow quantifying and reducing the model uncertainties, with the identification of a more representative constitutive law for the rock behavior.

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CP9

Projected Gaussian Filtering with Sampled Covariance Updating

We develop a methodology for large-scale, nonlinear filtering suitable for numerical weather prediction (NWP). The aim of filtering or data assimilation is to use observational data and prior knowledge to form the best initial state estimate for a forecast model. Improving the starting point used to launch a forecast model improves the model performance leading to more accurate weather prediction. The method we will discuss introduces a new paradigm for data assimilation. The proposed method, which we will call the assumed Gaussian reduced (AGR) filter, provides limited updating for decomposed covariances. The method is a type of generalized Gaussian filter utilizing efficient quadrature to evaluate non-linear Gaussian integrals. We use the dominant singular value of the covariances as search directions in order to directly update the square root factorization of the covariances. Search directions corresponding to smaller singular values are attenuated and thus truncated for the covariance update. Thus, the dominant component of the optimal filter is captured and can be very low order in practice. In this manner we limit the computational cost as well as storage requirements of the filter. Additionally the method is model agnostic and scalable. We will demonstrate the effectiveness of our method with a fluids model example and provide comparison to the ensemble Kalman filter which is commonly used in NWP applications.

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CP9

Solution of Density Driven Groundwater Flow with Uncertain Porosity and Permeability Coefficients

In many countries, groundwater is the strategic reserve, which is used as drinking water and as an irrigation resource. Therefore, accurate modeling of the pollution of the soil and groundwater aquifer is highly important. As a model, we consider a density-driven groundwater flow problem with uncertain porosity and permeability. This problem may arise in geothermal reservoir simulation, natural saline-disposal basins, modeling of contaminant plumes and subsurface flow. This strongly non-linear problem describes how salt or polluted water streams down building 'fingers". The solving process requires a very fine unstructured mesh and, therefore, high computational resources. Consequently, we run the parallel multigrid solver UG4 (https://github.com/UG4/ughub.wiki.git) on Shaheen II supercomputer. The parallelization is done in both - the physical space and the stochastic space. The novelty of this work is the estimation of risks that the pollution will achieve a specific critical concentration. Additionally, we demonstrate how the multigrid UG4 solver can be run in a black-box fashion for testing different scenarios in the density-driven flow. We solve Elder's problem in 2D and 3D domains, where unknown porosity and permeability are modeled by random fields. For approximations in the stochastic space, we use the generalized polynomial chaos expansion.

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CP10

Monolithic and Splitting Based Solution Schemes for Nonlinear Quasi-static Thermo-poroelasticity

This work is concerned with an iterative solution procedure for coupled thermo-poroelasticity. The thermo-poroelastic model problem we consider is formulated as a three-field system of PDEs, consisting of an energy balance equation, a mass balance equation and a momentum balance equation, where the primary variables are temperature, fluid pressure, and elastic displacement. Due to the presence of a nonlinear convective transport term in the energy balance equation, it is convenient to have access to both the pressure and temperature gradients. Hence, we introduce these as two additional variables and extend the original three-field model to a five-field model. Based on this formulation, we propose six different iterative algorithms, where we at each iteration either split the problem into several subproblems, or solve monolithically a linearized system. These methods are based on the well-known fixed stress splitting algorithm from poroelasticity, extended to also include thermal effects, and also capable of resolving the nonlinearity in the model. We also provide a convergence proof for the algorithms, and validate our results through numerical experiments.

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CP10

Fully Implicit Multidimensional Hybrid Upwind Scheme for Coupled Flow and Transport

Robust and accurate fully implicit finite-volume schemes applied to Darcy-scale multiphase flow and transport in porous media are highly desirable. Recently, a smooth approximation of the saturation-dependent flux coefficients based on Implicit Hybrid Upwinding (IHU) has been proposed to improve the nonlinear convergence in fully implicit simulations with buoyancy. Here, we design a truly multidimensional extension of this approach that retains the simplicity and robustness of IHU while reducing the sensitivity of the results to the orientation of the computational (Cartesian) grid. This is achieved with the introduction of an adaptive, local coupling between the fluxes that takes the flow pattern into account. We analyze the mathematical properties of the proposed methodology to show that the scheme is monotone in the presence of competing viscous and buoyancy forces and yields saturations remaining between physical bounds. Finally, we demonstrate the efficiency and accuracy of the scheme on challenging two-dimensional two-phase examples with buoyancy, with an emphasis on the reduction of the grid orientation effect.

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CP10

A Study on Iterative Schemes for Fully Coupled Reactive Transport and Flow in Variably Saturated Porous Media

Fully coupled flow and reactive transport represent a classical example of non-linear coupled equations on a porous medium. We model the transportation of a surfactant, dissolved into the water phase, in a variably saturated domain. An efficient linearisation scheme is needed due to the non-linearity of the system. We study three different schemes: the Newton method, the modified Picard, and the L-scheme [List, Radu, A study on iterative methods for solving Richards' equation, 2015]. We implement fully implicit and sequential solvers, defining also a new sequential implicit algorithm which appears to be the best approach in terms of the number of iterations. Such scheme, which is a modified variant of the classical splitting iterative scheme, presents equally accurate results but requires fewer iteration than the common formulations. We observe also that the L-scheme is the only convergent scheme in case of discontinuous initial conditions, highly non-linear expressions and complex domain configurations involving multilayers [Seus et al., A linear domain decomposition method for partially saturated flow in porous median, 2017].

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CP10

A Domain Decomposition Projection Method for the Navier-Stokes Equations Based on the Multiscale Robin Coupled Method

Solving the Navier-Stokes equations for a large number of unknowns is a difficult task, usually done in parallel, limited by convergence and speedup issues. We propose a new domain decomposition projection method based on the Multiscale Robin Coupled method (MRCM), that allows for the independent computation of local problems, which are finally coupled by the solution of a much smaller interface problem. Results show that accurate solutions are obtained compared to the undecomposed case.

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CP10

Linearization and Domain Decomposition Methods for Two-phase Flow in Porous Media

In this work, we discuss the mathematical model of two-phase flow in porous media including dynamic capillarity and static hysteresis, where the domain is composed of two regions with possibly different parameterizations leading to discontinuities in the coefficient values at the interface. These nonlinear differential equations within the subdomains are coupled by the continuity of the flux and the pressures at the interface. Based on this, we discretize the system in time by the implicit θ-scheme and introduce two iterative schemes for the semi-discrete equations, which combine a stabilized linearization iteration of fixed-point type (L-scheme) and a non-overlapping domain decomposition method with Robin type transmission conditions. The proposed methods are independent of the concrete space discretization and avoid the use of derivatives as in Newton based iterations. In the subsequent analysis, we prove for both schemes the existence and uniqueness of solutions and rigorously show the convergence of the sequence of iterative solutions towards the solution of the semi-discrete equations under some mild constraints on the time step independently of the initial guesses. Finally, we present several numerical studies in two spatial dimensions to validate the stability, robustness and efficiency of the developed methods. The results confirm our theoretical analysis, and clearly demonstrate the practical advantages of the second scheme over the first.

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CP10

Sequential-Implicit Newton Method for Reservoir Simulation

In this work, we are interested in improving the efficiency of sequential-implicit fixed-point methods by wrapping them with a full Newton scheme. The focus here is on geomechanics and compositional reservoir simulation problems. The new method, called the Sequential Implicit Newton (SIN) method, is constructed by using the sequential-implicit fixed point method as a preconditioner to Newton's method. The SIN method uses the same sequential-implicit scheme as the fixed-point method, but after each sequential iteration, a Newton update is computed. Wrapping a Newton loop around the traditional sequential-implicit scheme leads to significant improvements in the convergence rate. Our numerical experiments show that the SIN approach improves the overall convergence rate for all the nonlinear multiphysics problems considered. For specific cases where there is strong nonlinear coupling between the subproblems, we see up to two orders of magnitude decrease in the number of sequential iterations when using SIN compared with the fixed-iteration scheme.

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MS1

Face-based Discretization of Two-phase Discrete Fracture Matrix Models with Interface Solver

We consider in this work, the two-phase Darcy discrete fracture-matrix model from [Brenner et al., 2018] with nonlinear matrix fracture transmission conditions. This type of model accounts accurately for gravity segregation in the fracture, for discontinuous capillary pressure curves at the matrix-fracture interfaces, and for fractures acting either as drains or barriers. This model is shown to be more accurate than alternative hybrid-dimensional two-phase Darcy flow models based either on continuous phase pressures at the interfaces assuming fractures acting as drains [Bogdanov et al., 2003], or on elimination at the linear level of the interface unknowns [Karimi-Fard et al., 2004]. However, keeping the nonlinear interface equations increases the difficulty to solve the nonlinear and linear systems at each time step and at each Newton iteration. These issues come from the highly contrasted permeabilities and capillary pressures at interfaces and from the vanishing phase mobility in single phase zones combined with the absence of porous volume at the interface leading to singular systems. To treat this issue, we investigate the possibility to eliminate the interfacial unknowns at the nonlinear level through a rigorous analysis of the local interfacial nonlinear problem obtained from the nonlinear two-phase flux conservation at a given interface. Its implementation requires to adapt the discretization strategies using face and cell based discretizations.

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MS1

Block Preconditioners for Mixed-dimensional Flow Problems in Fractured Porous Media

We are interested in the mixed-dimensional approach to modeling fractured porous media, where fractures and their intersections are represented as lower-dimensional structures and the mortar method is used for flow coupling between the matrix and fractures. The advantages of the model are immediate in handling complex geometries and large aspect ratios. However, the model has set new numerical challenges and developing a robust linear solver is still necessary. Our goal is to efficiently solve the single-phase flow problem in fractured porous media. We consider a stable mixed finite element discretization of the problem, which results in a parameter-dependent linear system. For this, we develop block preconditioners based on the well-posedness of the discretization choice. The preconditioned iterative method demonstrate robustness with regards to physical and discretization parameters. The analytical results are verified on several examples of fracture network configurations, and notable results in reduction of number of iterations and computational time are obtained.

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MS1

Unified Formulation for Polytopic Discontinuous Galerkin Approximation of Flows in Fractured Porous Media

We propose a formulation based on discontinuous Galerkin (DG) methods in their generalization to polytopic grids for the simulation of flows in fractured porous media. Our method is very flexible from the geometrical point of view, being able to handle meshes made of arbitrarily shaped elements, with edges/faces that may be in arbitrary number (potentially unlimited) and whose measure may be arbitrarily small. Our approach is then very well suited to tame the geometrical complexity featured by most of applications in the computational geoscience field. More precisely, we adopt a model for single-phase flows where fractures are treated as a $(d-1)$-dimensional interfaces between d-dimensional subdomains, $d = 2, 3$. In the model, the flow in the porous medium (bulk) is assumed to be governed by Darcy's law and a suitable reduced version of the law is formulated on the surfaces modelling the fractures. The two problems are then coupled through physically consistent conditions. We focus on the numerical approximation of the coupled bulk-fractures problem, presenting and analysing, in the unified setting of [D. N. Arnold et al., Unified analysis of discontinuous Galerkin methods for elliptic problems, 2001/02], all the possible combinations of primal-primal, mixed-primal, primal-mixed and mixed-mixed formulations for the bulk and fracture problems, respectively. Finally, the validity of the theoretical analysis is assessed through numerical experiments.

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MS1

Local and Semi-local Modeling and Discretization Principles for Fractured Porous Media

Reduced-order models for flow in fractured porous media fall within the broader class of mixed-dimensional partial differential equations. Within the latter, it is natural to introduce the notions of local and semi-local constitutive laws. We show how most existing work for flow in fractured porous media can be understood as utilizing local constitutive laws. In contrast, it is is necessary to consider semi-local constitutive laws for most problems involving material deformations. Semi-local constitutive laws can also be understood as important for flows in certain industrial materials with thin layers. We show the conditions for well posedness of models with semi-local constitutive laws, and provide new discretization methods tailored for this problem.

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MS1

Modeling the Flow in Complex Fracture Networks in Porous Materials via an Optimization Approach on Non Conforming Meshes

One of the major difficulties in the numerical simulation of flow in fractured porous media is related to geometrical complexity. In fact, a typical field of application is the simulation of flow in the subsoil, which can be characterized as a porous material crossed by a large number of fractures. Fractures are thin regions with properties that are significantly different from the surrounding medium. As the generation of a computational mesh capable of an explicit representation of both the scale of fracture thickness and of the bulk domain would be excessively expensive, fractures are typically reduced to planar interfaces of co-dimension one. Nevertheless, as fractures can have random spatial orientations, the resulting fracture network is usually very complex and presenting again geometrical features at different length scales. This drives the necessity of exploring unconventional simulation techniques capable of using meshes that do not require to match the geometry of the domain. This work presents the latest developments of a PDE-constrained optimization approach for the simulation of flow in complex fracture networks in a porous matrix. The method allows to mesh each fracture independently from each other, and also independently from the mesh of the matrix. The matching at the interfaces is achieved by minimizing a properly chosen functional. The resulting method is extremely flexible and robust, thus providing a viable option for simulations on large scales.

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MS2

Construction and Analysis of HDG Methods for Two-phase Flows

We develop a high-order hybridized discontinuous Galerkin (HDG) method for a linear degenerate elliptic equation arising from a two-phase mixture of mantle convection or glacier dynamics. We show that the proposed HDG method is well-posed by using an energy approach. We derive a priori error estimates for the method on simplicial meshes in both two- and three-dimensions. The error analysis shows that the convergence rates are optimal for both the scaled pressure and the scaled velocity for non-degenerate problems and are sub-optimal by half order for degenerate ones. Several numerical results are presented to confirm the theoretical estimates. Degenerate problems with low regularity solutions are also studied, and numerical results show that high-order methods are beneficial in terms of accuracy.

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MS2

A Combined GDM-ELLAM-MMOC (GEM) Scheme for Advection Dominated PDEs

We propose a numerical scheme which combines the Eulerian Lagrangian Localised Adjoint Method (ELLAM) and the Modified Method of Characteristics (MMOC) for time-dependent advection-dominated PDEs. The combined scheme, so-called GEM scheme, takes the advantages of both the ELLAM scheme (mass conservation) and the MMOC scheme (easier computations), while at the same time avoids their disadvantages (respectively, harder tracking around the injection regions, and loss of mass). We present a precise analysis of mass conservation properties for these three schemes and numerical results illustrating the advantages of the GEM scheme. A convergence result for the MMOC scheme, motivated by our previous work [Cheng, Droniou, and Le,"Convergence analysis of a family of ELLAM schemes for a fully coupled model of miscible displacement in porous media"] on the convergence analysis of a family of ELLAM schemes for miscible displacement, is also provided. This can be extended to obtain the convergence of GEM scheme.

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MS2

Advances in DiSk++: A Generic Programming Framework for the Implementation of Discontinuous Skeletal Methods

Discontinuous Skeletal (DiSk) methods present several attractive features: dimension-independent construction, arbitrary polynomial order, support for meshes with polytopal cells and non-matching interfaces. Positioning unknowns at mesh faces is also a natural way to express locally the balance properties satisfied by the boundary-value problem. A recent example of DiSk method is the Hybrid high-order method [1]. Generic programming (GP) offers a valuable tool to implement DiSk methods [2]: thanks to templates, it is possible to avoid assumptions on the spatial dimension of the problem and on the kind of mesh. Templated code resembles pseudocode: the compiler will take care of giving the correct meaning to each basic operation. The resulting code is efficient despite its generality: GP, since it is a static technique, allows abstractions that do not penalize the performance at runtime. With DiSk++ [3], a C++ template library, we replicated the mathematical flexibility of DiSk methods in software, obtaining a "write once, run on any kind of mesh' framework. In this talk we describe the GP and data structures behind DiSk++ and we discuss the recent advances of the library. [1] D. Di Pietro, A. Ern, A hybrid high-order locking-free method for linear elasticity on general meshes [2] M. Cicuttin, D. Di Pietro, A. Ern, Implementation of Discontinuous Skeletal methods on arbitrary-dimensional, polytopal meshes using generic programming [3] https://github.com/wareHHOuse/diskpp

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MS2

Multiderivative Time-stepping for HDG

In this talk, we consider the numerical treatment of evolution equations of form

$$w_t + Q(w) = 0,$$

where Q can of course be a differential operator. Convection-diffusion equation, the Navier-Stokes equations and many more fall into this rather general framework. Here, we focus on the discretization of the time-derivative using a multi-derivative approach. This means that, unlike in classical one-step methods, not only $Q(w)$ is taken into account, but also $\dot{Q}(w) := Q'(w)Q(w)$, $\ddot{Q}(w)$, ... For the equations we have in mind, we favour implicit methods to remove a (possibly severe) CFL condition. We discuss several possibilities of implementing *implicit* multiderivative solvers into an existing HDG (hybridized discontinuous Galerkin) solver and show weaknesses and strengths of the approaches. In particular, we show why a standard Cauchy-Kovalewskaya-approach can fail, and we present a uniformly stable fix.

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MS2

A Posteriori Error Estimates for Hybrid Discontinuous Galerkin Methods for Elliptic Problems

Recently, various hybrid discontinuous Galerkin (HDG) methods have been introduced and developed. These are locally conservative and important for certain class of problems, e.g., Darcy flows in porous media and convection diffusion equations. In this work, two types of a posteriori error estimates for HDG methods are analyzed by introducing suitable estimators. The first one is a residual-based error estimator. This estimator is simple and fully computable, but this does not cover the linear approximation of the hybrid discontinuous Galerkin method with continuous traces. The second is a flux reconstruction based error estimator. This estimator exploits the flux reconstruction which provides a a guaranteed type estimator for all polynomial approximations. These two error estimators are also reliable and efficient, and they can achieve high-order accuracy for both smooth and non-smooth solutions by using adaptive algorithms. Performances of these estimators are presented using several numerical examples.

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MS3

Full Waveform Inversion by Model Extension

The main issue inherent to full waveform inversion (FWI) is its inability to correctly recover the Earths subsurface seismic parameters from inaccurate starting models. This behavior is due to the presence of local minima in the FWI objective function. To overcome this problem, we propose a new objective function in which we modify the nonlinear modeling operator of the FWI problem by adding a correcting term that ensures phase matching between predicted and observed data. This additional term is computed by demigrating an extended model variable, and its contribution is gradually removed during the optimization process while ensuring convergence to the true solution. Since the proposed objective function is quadratic with respect to the extended model variable, we make use of the variable projection method. We refer to this technique as full waveform inversion by model extension (FWIME). We illustrate its potential on two synthetic examples for which FWI fails to retrieve the correct solution. First, by inverting data generated in a borehole setup. Then, by inverting diving waves recorded with a standard surface acquisition geometry

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MS3

Seismic Inversion and Imaging via Model Order Reduction

We introduce a framework for seismic inversion and imaging based on model order reduction. The reduced order model (ROM) is a projection of the wave equation propagator on the subspace of time domain wavefield snapshots. Even though neither the propagator nor the wavefields are known in the bulk, the projection can be computed just from the surface seismic data. Once the ROM is computed, its use is trifold. First, the ROM can be used as a nonlinear preconditioner for full waveform inversion. Instead of minimizing the least squares data misfit we propose to minimize the ROM misfit. Such objective is more convex and thus optimization is less prone to cycle skipping, slow convergence, etc. Second, the projected propagator can be backprojected to obtain an image of subsurface reflectors. ROM computation is highly nonlinear unlike the conventional linear migration (Kirchhoff, RTM). This allows to untangle the interactions between the reflectors. Consecutively, the images are almost completely free from multiple reflection artifacts. Third, the ROM can be used to generate the Born data, i.e. the data that the measurements would produce if wave propagation obeyed Born approximation instead of the wave equation. Obviously, such data only contains primary reflections and the multiples are removed. Thus, existing linear inversion methods can be applied to Born data to obtain reconstructions directly.

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MS3

Dual Formulations of Wavefield Reconstruction Inversion

Wavefield reconstruction inversion (WRI) is based on the combination of data misfit and PDE-residual penalty terms, and it aims at the reconstruction of the optimal property model and field pair. A full-space optimization would require the storage of field variables for every frequency or time sample (and every source). Remedies via variable projection are well studied, but they entail the solution of a modified wave equation, which is costly both in frequency and time domain. Here, we explore an efficient alternative to WRI, where properties are complemented, instead, by elements of the dual data space. The starting point of our proposal is the denoising reformulation of WRI: the PDE compliance is optimized under the constraint of a given data fit. Since the field variable can be eliminated from the associated saddle-point problem, we obtain a new objective functional of only properties and Lagrange multipliers. Its evaluation, and gradient computation, involves the solution of the original wave equation, which is amenable to time-domain discretization. The optimization scheme of choice can now leverage on affordable storage of the iterates.

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MS3

Dimension Reduction for Extended Space Approaches to Seismic Velocity Inversion

Modification of seismic velocity inversion (model estimation by data fitting) via search space extension can improve the inversion robustness by enlarging the domain of convexity for suitable objective functions about the global best-fit model, but make an aleady very large-dimensional problem even larger. The resulting increase in computational complexity has hindered application of extended space methods to the resolution of 3D earth structure. This talk will explain how the structure of extended space methods can be leveraged to drastically reduce their computational cost. Extended inversion via numerical optimization produces a sequence of extended model estimates approaching the (conventional) reduced search space. Thus the extended search domain is naturally a neighborhood of the reduced search space, the extent of which can be progressively shrunk as the iteration proceeds. Together with low-to-high frequency continuation, a long-established technique in reduced space inversion, this dynamic redefinition of the extended search domain can result in orders-of-magnitude reduction in computational complexity, to an iteration-independent multiple of the per-iteration cost for reduced space methods. In some cases this reduction may be sufficient to make extended inversion a feasible method for imaging the 3D earth.

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MS3

Central Difference Time-lapse Full Waveform Inversion

Estimating earth velocity models from surface seismic data can be formulated as a nonlinear inverse problem. Adjoint linearized gradient optimization methods are often used due to the computational cost of solving the wave equation. These full waveform inversion (FWI) methods can be applied to repeated seismic surveys in order to estimate time-lapse (4D) changes in the subsurface caused by natural or man-made processes. However, reliable results are difficult to obtain when the time-lapse signal is weak or obscured by non-repeatable noise and inversion errors. We propose a two-step "central difference' method by which forward- and reverse-bootstrap 4D inversion results are averaged to attenuate model errors. A test example is shown for the SEAM 4D seismic dataset. Spatially *uncorrelated* errors in the velocity estimates tend to cancel when averaged since they have similar statistical error distributions. Spatially *correlated* errors due to data residuals from the first (baseline) inversion are further diminished during the second (monitor) inversion. Interestingly, the reverse-bootstrap implementation (i.e. monitor inversion before baseline inversion) can regenerate the forward-bootstrap errors with a phase reversal; thus, the central difference summation can also mitigate such artifacts. The proposed central difference 4D FWI method can provide more accurate time-lapse velocity model estimates for reasonable computational costs, compared to other methods.

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MS4

The Impacts of Initialisation Errors on Ice-sheet

Forecasting

Abstract not available.

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MS4

Automatic Code Generation for Seismic Imaging using Finite Differences and the Adjoint-State Method

Abstract not available.

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MS4

Instability of Adjoint Pseudo-Acoustic Anisotropic Wave Equations

We discover that the adjoint system of the second-order pseudo-acoustic anisotropic wave equations that we have implemented in previous work has unstable solutions and propose two possible alternative systems. The unstable solutions have magnitude that grows linearly with time and does not propagate spatially. This is not the kind of numerical instability that occurs when the propagation timestep does not satisfy the CFL condition. This instability is inherent to this particular type of wave equations. In fact, there is a family of unstable wave equations that all describe the same kinematics. The key to stability for this type of pseudo-acoustic anisotropic wave equations is not whether the system is self-adjoint but whether it reduces to the scalar wave equation in isotropic media. The first proposed system is self-adjoint and obtained by splitting the medium parameter matrix while the second system is a generalization of the original system with all non-zero coefficients. To use in waveform inversion, both of these systems involve a change of variables and are computationally more expensive than the original system. Instead, one can use the time-reversed forward wave equations to compute the gradients. Our numerical experiments indicate that in terms of convergence, the difference between the correct and incorrect adjoints is minimal.

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MS4

Efficient Computation of Derivatives for Solving Optimization Problems in R and Python using Swig-generated Interfaces to Adol-C

Abstract not available.

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MS5

Finite Volume and Finite Element Methods for Shallow Water Flows on Surfaces

Shallow water models of geophysical flows must be adapted to geometrical characteristics in the presence of a general bottom topography with non-negligible slopes and curvatures, such as a mountain landscape. We study a shallow water model defined intrinsically on the bottom surface from a mathematical and numerical point of view. The equations are characterized by non-autonomous flux functions and source terms embodying only the geometric information. We extend an existing intrinsic first order Finite Volume scheme to 2nd order via the Discontinuous Galerkin method. We also explore continuous P1-Galerkin approximations based on traditional stabilization and entropy-viscosity regularization. Our goal is to identify fully intrinsic discrete operators that are robust, accurate and that explicitly maintain the symmetries of the geometrical formulation of SWE. We compare the schemes in terms of accuracy, stability, and robustness for advection-dominated problems on simple surfaces as well as the full shallow water system.

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MS5

A Hierarchical Solver for Extruded Meshes with Applications to Ice Sheet Modeling

A hierarchical solver is proposed for solving sparse ill-conditioned linear systems in parallel. The solver is based on a modification of the LoRaSp method, but employs a deferred-compression technique, which provably reduces the approximation error and significantly improves efficiency. Moreover, the deferred-compression technique introduces minimal overhead and does not affect parallelism. As a result, the new solver achieves linear computational complexity under mild assumptions and excellent parallel scalability. To demonstrate the performance of the

new solver, we focus on applying it to solve sparse linear systems arising from ice sheet modeling. The strong anisotropic phenomena associated with the thin structure of ice sheets creates serious challenges for existing solvers. To address the anisotropy, we additionally developed a customized partitioning scheme for the solver, which captures the strong-coupling direction accurately in ice sheet modeling. In general, an algebraic partitioning can be computed with existing software packages, and thus the new solver is generalizable for solving other sparse linear systems.

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MS5

A Locally Conservative Enriched Galerkin for Coupling Flow and Transport

Accurate viscosity/density-dependent flow and transport model is a crucial key to successful water resources management in coastal areas and on islands. However, traditional modeling approaches without special treatment may not be able to resolve accurate sharp moving fronts and corresponding groundwater flow velocities due to the numerical instabilities. In this presentation, we employ the enriched Galerkin finite element methods (EG), which enriches a classical continuous Galerkin finite element methods with piecewise constant functions to ensure local and global mass conservation. EG has the same bilinear forms as the discontinuous Galerkin (DG) finite element methods, but EG has fewer degrees of freedom in comparison with DG and a fast effective solver for elliptic problems are provided. Moreover, dynamic mesh adaptivity approaches are employed to save computational cost for realistic large-scale problems. An efficient Krylov solver with preconditioner is provided. We will present numerical results for existing benchmark example to show efficiency and effectiveness of the proposed method in viscosity/density-driven flow modeling.

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MS5

The use of Entropy Production for Non-dilute Flow and Transport Models

Recent advances have been made for simulating non-dilute transport in porous media using the thermodynamically constrained averaging theory (TCAT). TCAT is a method for formulating models that provides a firm connection between the microscale and the macroscale. Conservation equations and thermodynamic relations are combined to from an entropy inequality which is then used to posit closure relations to formulate a closed model. As a fluid becomes non-dilute, mechanical dispersion is reduced due to the gradients of the mass fraction, density, viscosity and activity. This results in shaper fronts in both space and time. To achieve a grid independent solution, the system must be highly resolved which can be computationally expensive. While low-order methods may be used for simple simulations of one-dimensional laboratory experiments, advanced numerical methods may be required to solve large scale systems with complex geometries. In this work, the entropy viscosity method is used to solve the TCAT non-dilute transport model. The entropy viscosity method is an approach for hyperbolic equations that utilizes a local entropy production rate to balance artificial diffusion and anti-diffusion. Traditionally, an ad-hoc entropy function is used, however we utilize the simplified entropy inequality, derived when formulating TCAT models, for the local entropy production function, thus using the physical model to aide in the numerical approximation.

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MS5

Using Bayesian Networks for Sensitivity Analysis of Complex Biogeochemical Models

Sensitivity analysis is a vital tool in numerical modeling to identify important parameters and processes that contribute to the overall uncertainty in model outputs. Conventional methods of sensitivity analysis focus on identifying important parameters of a deterministic model structure, despite of the uncertain nature of model structure and complex dependencies between uncertain model structures and model parameters. In this study, we developed a new method of sensitivity analysis to quantify the relative importance of uncertain model processes that contain multiple uncertain parameters. The method is based on the concepts of Bayesian networks (BNs) to account for hierarchical uncertainty structure. We derive new sets of sensitivity indices following the methodology of variance-based global sensitivity analysis with the Bayesian inference. The framework is capable of representing the detailed uncertainty information of a complex model system using BNs, and affords flexible grouping of different uncertain inputs given their characteristics and dependency structures. We implemented the method on a real-world biogeochemical model at the groundwater-surface water interface within the Hanford Sites 300 Area. Our new sensitivity analysis framework based on BNs offers substantial flexibility for investigating the importance of uncertainty sources in a hierarchical order, and it is expected to be applicable to a wide range of multi-physics models for complex systems.

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MS6

High-performance Computing for the Geodynamo

The Earth's magnetic field is primarily created by a dynamo operating in the Earth's fluid outer core, some 3000 km underneath our feet, termed the geodynamo. Direct and indirect observations of the temporal variability of the geomagnetic field are based on paleomagnetic measurements, historical navigation data, magnetic observatory time series, and more recently, satellite measurements. This highly heterogeneous catalog (in terms of temporal and spatial coverage) points to a very dynamic field, which can eventually reverse polarity (with the magnetic North becoming South, and vice-versa). In this talk we will describe the standard approaches followed to model the geodynamo, and the methodological developments undertaken over the past 10 years which aim at bringing together numerical models of the geodynamo and observations of its dynamics. I will review the computational approaches followed for both the forward and inverse problems, and discuss avenues for future research (including sparse spectral methods and parallel in time approaches). Of course, development for development is pointless, and I will argue that extremely interesting questions require extremely efficient simulations, in particular those questions connected with geomagnetic reversals, arguably the most fascinating (and most computationally demanding) feature of the Earth's magnetic field.

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MS6

Linking Compositional Properties and Epeirogenic Movement in Mantle Flow Models

Abstract not available.

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MS6

High-resolution Design and Simulation of Nonlinear Flow in Modern Subduction Systems

Wadati-Benioff zone seismicity and seismic tomography indicate modern subduction zones are characterized by discontinuous slabs, with significant lateral variations in plate curvature both within and between subduction zones. In addition, rock deformation experiments indicate that olivine, the dominant constituent of the asthenosphere, deforms by dislocation creep, which can lead to highly nonlinear viscosity. Despite the importance of accurately representing the observed geometry, few open source software packages are available to construct sophisticated, high-resolution, model design for geodynamic models of modern subduction systems. Here I present TECT_Mod3D, an open source C/C++ program that constructs high-resolution configurations of modern plate boundaries with multiple intersecting plates. The three-dimensional output from TECT_Mod3D can be directly input to finite-element codes that solve the Stokes' flow, with the coupled workflow allowing for the solution of complex flow dynamics in natural subduction systems on Earth. The incorporation of the geometric complexity requires high-resolution, parallel computing, and adequate solvers to resolve the resulting non-linear, three-dimensional flow. Simulation results from the coupled workflow are shown for several case studies on Earth, with model grids spanning 100 to 200 million mesh nodes, a local resolution of 2-3 km, and 20,000 to 100,000 CPU hours per flow simulation.

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MS6

Workflow Management Challenges for Exascale Seismology

Modern numerical methods in combination with GPU-accelerated high-performance computing (HPC) have enabled unprecedented simulations of seismic wave propagation. In a complementary development, adjoint-state methods accommodate the full nonlinearity of 3D wave propagation in iterative seismic inversions. In earthquake seismology, seismic imaging based on spectral-element and adjoint methods has enabled massive data assimilation for the construction of 3D (an)elastic Earth models. These methods account for the full physics of wave excitation and propagation by numerically solving the anelastic, anisotropic equations of motion, and require the execution of complex computational procedures that challenge the most advanced HPC systems. Current research is petascale; future research will require exascale capabilities. There are successful applications of Full-Waveform Inversion (FWI) both on regional and continental scales, and recently a global model based on FWI with data from 1,480 earthquakes has been produced. In this presentation, I will discuss our latest results.

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MS7

On Accurate Semi-discrete Schemes for Multiphase Flow in Porous Media

In this work, we present conservative numerical schemes for simulating multiphase-flow in highly heterogeneous porous media, which allows changes of the porosity field in space. The global methodology combines stabilized mixed-hybrid finite elements for the flow subsystem (velocity and pressure) with different semi-discrete central schemes, that are then integrated in time by Strong Stability Preserving Runge-Kutta (SSPRK) schemes. We also comment on the use of this methodology as a block for coupling multiphase flows with geomechanics.

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MS7

Computational Modeling of Naturally Fractured Reservoirs with Geomechanical Coupling

Formulations and numerical approximations are presented for the simulation of discrete fracture networks including geomechanics effects in two and three dimensions. The constitutive modeling is developed in two steps; first, for the reservoir flow, the fracture is represented by a one/two dimensional flow coupled with a two/three dimensional Darcy flow; second, for the geomechanics response, the fracture opening is computed using the Barton and Bandis (BB) (1990) model with an associative elastoplastic constitutive model for reservoir rock. The implementation has two modules. The reservoir module uses H(div) approximation with MHM (Multiscale Hybrid Mixed) multiscale reduction yielding fluxes and pressure fields. For the geomechanical module, we use of a hybridized H1 approximation where the normal stress defined on the fractures act as a Lagrange multiplier to impose the fracture opening. The use of a Lagrange multiplier improves the numerical stability when applying the BB constitutive law. The approximate solution is obtained in a staggered way by iterating between the two modules. The information exchange between the reservoir module and geomechanics module is performed by a datastructure associated with numerical integration points that are shared between both modules. The formulations are implemented using the NeoPZ programming environment that is freely available on github https://github.com/labmec/neopz.git

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MS7

High Order HDG for Two Phase Flow and Miscible Displacement

Accurate and reliable numerical simulations are important for assessing the performance and cost of enhanced oil recovery techniques. To that end, we present a hybridizable discontinuous Galerkin method which generates high fidelity simulations of flow and transport in porous media. The proposed method is high-order accurate, conserves mass locally, and the number of globally coupled degrees of freedom is significantly reduced compared to standard discontinuous Galerkin methods. To further reduce the computational cost of our method, we outline the operator splitting technique that is utilized. We consider the miscible displacement problem as well as immiscible two-phase flow at the reservoir scale. Numerical experiments are provided that show that the method converges optimally and is robust for highly heterogeneous porous media in 2D and 3D.

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MS7

High-order Discontinuous Galerkin Methods for Flows in Porous Media: High-fidelity Viscous Fingering Computations on Fully Unstructured Meshes

Viscous fingering phenomena occur naturally in a number of important porous media flow applications. When a flow is displaced in a porous medium under an adverse mobility ratio, finger-like structures naturally occur as the result of flow instability. Their impact can be significant in a number of subsurface engineering applications, such as carbon sequestration and enhanced oil recovery. Reservoir simulators currently used in petroleum engineering applications rely on low-order numerical formulations (of finite difference or finite volume type). These formulations, although robust and efficient, do not possess the fidelity necessary to attack viscous fingering instability problems, and are furthermore very sensitive to mesh orientation. A new method is proposed in this talk to address these issues: It is based on a discontinuous Galerkin discretization of the porous media flow equations and leads to arbitrarily high-order discretizations on fully unstructured meshes. The combination of these two features is essential to provide a viable strategy to high-fidelity computations of viscous fingering in practical engineering scenarios. Numerical examples in the context of carbon sequestration and reservoir engineering problems will be presented.

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MS7

Implicit Weno for Two-phase Flow

We define a third order finite volume implisit WENO scheme in two space dimensions for application to two-phase flow in porous media. The keys to high order accuracy are to use WENO reconstruction in space (which handles shocks and steep fronts) combined with a high-order time stepping scheme. The solution is approximated by its averages over the mesh elements at the current time level and two future time levels; therefore, it uses two unknowns per grid block per variable, independent of the spatial dimension. This makes the scheme fairly computationally efficient, both because reconstructions make use of local information that can fit in cache memory, and because the global system has about as small a number of degrees of freedom as possible. The scheme is simple to implement, high order accurate, maintains local mass conservation, applies to general computational meshes, and appears to be robust. Preliminary computational tests show the potential of the scheme to handle advection-diffusion-reaction processes on unstructured meshes to high order accuracy using relatively long time steps. The scheme can be viewed as a generalization of standard cell-centered finite volume (or finite difference) methods. It achieves high order in both space and time, and it incorporates WENO slope limiting.

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MS8

Deep Multiscale Model Learning

The objective of this work is to design novel multi-layer neural network architectures for multiscale simulations of flows taking into account the observed data and physical modeling concepts. Our approaches use deep learning concepts combined with local multiscale model reduction methodologies to predict flow dynamics. Using reduced-order model concepts is important for constructing robust deep learning architectures since the reduced-order models provide fewer degrees of freedom. The solution (e.g., pressures and saturations) at the time instant $n+1$ depends on the solution at the time instant n and input parameters, such as permeability fields, forcing terms, and initial conditions. One can regard the solution as a multi-layer network, where each layer, in general, is a nonlinear forward map and the number of layers relates to the internal time steps. In each layer, our reduced-order models will provide a forward map, which will be modified (trained) using available data. Because of the lack of available data, the training will be supplemented with computational data as needed and the interpolation between data-rich and data-deficient models. We will also use deep learning algorithms to train the elements of the reduced model discrete system. We will present main ingredients of our approach and numerical results. Numerical results show that using deep learning and multiscale models, we can improve the forward models, which are conditioned to the available data.

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MS8

Physics and Data Science for Geoscience Applications

Next to data sets from elementary particle physics and astronomy, geoscience data sets are the largest and most complex ones in all of science and engineering. This makes most geoscientific applications of data driven methods reliant on specialized HPC resources. Paradoxically, it also leads to a situation of data paucity when applying the modern machine learning based image recognition and analysis techniques that have been so successful on natural images (millions of seismic images are not available). Faithful physics based models can assist by providing training data, parametric models with fewer free parameters, or basic physical constraints on data science models. We will present examples of the successful combination of physics and data science models in seismic imaging and interpretation, in petrophysical log analysis and geomodeling, and in the domain of Digital Rocks where the analysis of scanned images is beginning to supplement and replace traditional core analysis. It is not surprising that many decades of physics based modeling in geoscience will not be quickly replaced by physics-agnostic data driven models but that the two categories of methodologies reinforce each other.

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MS8

VelocityGAN: Subsurface Velocity Image Estimation using Conditional Adversarial Networks

Acoustic- and elastic-waveform inversion is an important and widely used method to reconstruct subsurface velocity image. Waveform inversion is a typical non-linear and ill-posed inverse problem. Existing physics-driven computational methods for solving waveform inversion suffer from the cycle skipping and local minima issues, and not to mention solving waveform inversion is computationally expensive. In this work, we developed a real-time data-driven technique, VelocityGAN, to accurately reconstruct subsurface velocities. Our VelocityGAN is an end-to-end framework which can generate high-quality velocity images directly from the raw seismic waveform data. A series of numerical experiments are conducted on the synthetic seismic reflection data to evaluate the effectiveness and efficiency of VelocityGAN. We not only compare it with existing physics-driven approaches but also choose some deep learning frameworks as our data-driven baselines. The experiment results show that VelocityGAN outperforms the physics-driven waveform inversion methods and achieves the state-of-the-art performance among data-driven baselines.

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MS8

Modeling Flow and Transport in Fracture Networks using Machine Learning and Graphs

Simulating flow and transport in fractured porous media frequently involves solving numerical discretizations of partial differential equations with a large number of degrees of freedom using discrete fracture network (DFN) models. Uncertainty in the properties of the fracture network that controls flow and transport requires a large number of DFN simulations to statistically describe quantities of interest. However, the computational cost of solving more than a few realizations of a large DFN can be intractable. As a means of circumventing this problem, we utilize machine learning in combination with a graph-based model of flow and transport. The graph-based approach significantly reduces the number of degrees of freedom, and hence the computational cost of the model. The use of machine learning enables the correction of biases introduced in the reduction from a refined mesh to a coarse graph. We demonstrate the efficacy of this approach in comparison with high-fidelity DFN models.

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MS8

Information-theoretic Approaches to Multiscale Learning

We employ an information-theoretic approach that allows for seamless integration of multi-resolution data into multiscale simulations to upscale/downscale hydraulic conductivity of heterogeneous porous formations. Available data (at either the fine- or the coarse-scale) are used to inform models at the opposite scale by setting a probabilistic equivalence between the fine and the coarse scale, with closures (parameters and/or constitutive laws) that are learnt via minimization of observables error and mutual information across scales. We investigate how this can guide us to formulate scaling laws and we explore means to accelerate scaling of dynamic processes and to reduce data requirements.

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MS9

Numerical Modeling of Fracture Reactivation in a Three-dimensional Domain Based on a Coulomb Friction Law

Deformation of fractures due to anthropogenic injection of fluids in underground reservoirs is a concern in applications such as CO2 storage, enhanced oil recovery, and geothermal energy. We will investigate the reactivation of natural fractures numerically based on a discrete-fracture-matrix model, where the fractures are resolved by the mesh. The mathematical model results in a strongly coupled, nonlinear variational inequality problem, where the slip of fractures is described by a Coulomb type friction law. For the discretization we use a hybrid scheme where the displacements are given in terms of degrees of freedom per element and additional the surface traction can be easily obtained per face by a finite-volume type scheme. By doing so, we can directly impose the inequality constraint on each face. Motivated by enhanced geothermal systems, a 3D fracture network under injection is considered as model problem.

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MS9

Efficient and Reliable Adaptive Simulations in Large Scale DFNs

In the talk the issue of reliable and efficient flow simulations in Discrete Fracture Networks is tackled. The stochastic generation of DFNs introduces fractures sampled from given distributions for position, orientation, dimension, and hydrogeological properties. Among the several numerical difficulties of these simulations, the mesh generation takes a relevant rule. Recently, a new approach has been proposed, based on a reformulation of the flow problem as a PDE-constrained optimization problem and capable to circumvent these difficulties. The new approach has proved to allow for very general Uncertainty Quantification analyses, also in the case of geometrical stochasticity; moreover, a tailored parallel approach has been derived and very high parallel efficiency has been obtained allowing very large scale simulations. For this recasting of the flow problem, reliable a posteriori error estimates have been derived and their application to the flow simulation in realistic DFNs yield a large improvement of the quality and reliability of the solution. The automatic choice of a suitable computing mesh can be useful to ensure, for a fixed level of accuracy, the same precision in the large number of simulations needed in Uncertainty quantification analyses, reducing the effect on the UQ analysis of numerical noise in the solution.

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MS9

Preconditioning Techniques for Mimetic Discretizations of Flow in Fractured Porous Media

The numerical simulation of flow in fractured porous media may be carried out using hybrid-dimensional discretisations where fractures are modelled as a network of one-codimensional planar manifolds (usually called discrete fracture network) immersed in the bulk domain. Proper interface conditions ensure the appropriate mass and pressure balance between the two components. In the last years, we have investigated the use of mimetic finite differences techniques for the flow in the bulk coupled with a finite volume description for the flow in the fractures. This numerical model gives rise to a saddle point problem which, particularly for 3D simulations, may require the use of iterative solution techniques. The heterogeneity of the flow parameters and the presence of the fractures may make the linear system poorly conditioned. Thus the use of appropriate preconditioning techniques is mandatory. In this talk, we will illustrate some results on the analysis of the spectral properties of the matrix governing the discrete problem as well as numerical experimentations of different type of preconditioners.

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MS9

Octree-refined Continuum Representation of Discrete Fracture Networks: Evaluation of Equivalent Permeability Expressions and Applications in Multiphysics Simulations

Equivalent continuum models (ECM) are attractive counterparts to discrete fracture networks (DFN) because they can be used in a variety of multiphysics applications that include both fracture and matrix flow. However, their accuracy is limited by their ability to equivalently represent the properties of the underlying fracture network. In this work, we present a system of methods to generate an octree-refined continuum mesh that preserves the characteristics of the input DFN and allows for high resolution meshing around the areas of interest (i.e. fractures) at low computational cost. We construct the octree-refined mesh using a DFN, as generated by dfnWorks, as input, where the refinement level is controlled by the user and the finest level corresponds to the fracture locations. For cells that are intersected by fractures in the DFN, we explicitly calculate the intersection area of each intersecting fracture, which results in a highly accurate scheme to resolve the equivalent porosities and permeabilities on the continuum mesh. We verify our methods using analytical solutions for transport and heat transfer through a single fracture and present comparisons between the ECM and DFN, which show good agreement. We also present more complicated examples using large numbers of fractures, which show that the method scales appropriately to represent more complex natural systems.

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MS10

Precice – a Comprehensive Coupling Library for Large-scale Surface-coupled Multi-physics Problems

Many simulation problems in geoscience require coupling of different types of equations such as free flow and porous media flow. In cases where the coupling happens across a surface, domain-decomposition like, so-called partitioned approaches can be applied. They allow us to compose the overall simulation environment from separate existing and specialized solvers for each sub-system. The coupling library preCICE provides all functional components required for partitioned surface-coupled simulations: (i) fully parallel inter-code communication, (ii) data mapping between non-matching grids, (iii) acceleration methods for implicit coupling iterations, and (iv) consistent time stepping approaches. We shortly present these functional components and show results for their robustness and efficiency for various coupled scenarios. In addition, we give examples for the adaption of existing open and closed-source solvers in order to be coupled to other components via preCICE. Once adapted to coupling via preCICE, a simulation software components can be freely combined with each other without further code changes or enhancements. preCICE is available as open source software at www.github.com/precice/.

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MS10

Revisiting Coupling Approaches for Surface-subsurface Flow

A number of different strategies have been proposed over the last decades for coupling surface and subsurface flow at the catchment scale. The guiding principles are typically continuity of pressure and fluxes at the soil-atmosphere interface, leading to conservation of mass but not momentum. Approaches range from monolithic fully coupled solves to iterative and time-split techniques. Here we attempt to recast standard techniques in a common framework and identify the specific approximations that define each formulation. This allows us to analyze the sources of coupling errors and the ensuing stability constraints with specific attention to the distinct time scales of the surface and subsurface processes. We use test problems from the recent intercomparison project to assess the different approaches and classify existing models in terms of this framework. We also identify opportunities for improved accuracy and efficiency by looking at the interactions in space and time between the different model components.

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MS10

Error Analysis for Coupled Time-dependent Navier-Stokes and Darcy Flows

The coupling of free flow and porous media flow arises in several fields, such as energy, environment and biomedicine. Existence and uniqueness of a weak solution for the coupled time-dependent Navier-Stokes and Darcy equations are proved. Interface conditions include the continuity of fluxes, the balance of forces and the Beavers-Joseph-Saffman condition. The literature on coupling steady-state Stokes and Darcy is vast. There are very few papers on the time-dependent case. We propose and analyze a numerical scheme of arbitrary order. for solving the time-dependent Navier-Stokes equations coupled with Darcy equations. The nonlinear reaction term is time-lagged. The proof of the existence of the numerical solution relies on the construction of an operator that relates discrete functions from the Darcy subdomain to functions from the Navier-Stokes subdomain. Optimal error estimates are derived and verified computationally.

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MS10

Modeling, Analysis, and Implementation of a Coupled 3D Shallow Water–Darcy/Richards System

The interaction between free and subsurface flows (the latter either saturated or unsaturated) is important for many applications, e.g. infiltration of overland water into the soil during rainfall, contaminant propagation into the subsurface, sedimentation processes, interaction of seas, lakes, rivers, or wetlands with groundwater aquifers. Mathematical models for such coupled surface/subsurface flows generally express the conservation of mass and momentum in the coupled system. These models usually pose substantial challenges on various levels: Analytical – due to differences in PDE system types in the subdomains giving rise to well-posedness and stability issues, numerical and computational – arising from the growing algorithmic complexity and increased performance and parallel scalability demands. We propose a coupled surface/subsurface flow model that relies on hydrostatic equations with free surface in the free flow domain and on the Darcy/Richards model in the subsurface part. The model is discretized using the local discontinuous Galerkin method and implemented within the fully-vectorized MATLAB / GNU Octave toolbox FESTUNG. An energy stability analysis for the coupled system is provided.

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MS10

Complex Interfaces Between Free Flow and Porous Media Flow

Systems of coupled free flow and porous-medium flow appear ubiquitously in nature and in technical applications. Examples for interface-driven transport and exchange processes include soil evaporation, fuel cell water management or food drying. A pore-scale description of these systems (e.g. by means of DNS) tends to be unfeasible due to the highly complex geometry of the porous material. Averaged REV-scale approaches often fail to describe the region close to the interface to the free flow in sufficient detail, thereby neglecting pore-scale effects like local saturation distribution patterns that can strongly affect the global behavior of the coupled system. Here, we propose a novel hybrid model that is able to capture pore-scale effects at the interface in ample detail while maintaining a comparatively low computational effort which allows the simulation of rather realistic scenarios. The key feature of this approach is a pore-network model which represents the transition region between the porous matrix and the free flow. The model comprises three computational domains: the free-flow region where the (Navier-) Stokes equations are solved, the transition zone described by the pore-network model and a bulk porous domain accounted for by Darcys or Forchheimers law. Appropriate coupling conditions ensure the continuity of mass, momentum and energy fluxes as well as thermodynamic consistency between the respective subdomains.

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MS11

Effects of Spatiotemporal Averaging on Predictions of Reactive Transport in Porous Media

The typical temporal resolution used in modern simulations significantly exceeds characteristic time scales at which the system is driven. This is especially so when systems are simulated over time-scales that are much longer than the typical temporal scales of forcing factors. We investigate the impact of space-time upscaling on reactive transport in porous media driven by time-dependent boundary conditions whose characteristic time scale is much smaller than that at which transport is studied or observed at the macroscopic level. The focus is on transport of a reactive solute undergoing diffusion, advection and heterogeneous reaction on the solid grains boundaries. We first introduce a concept of spatiotemporal upscaling in the context of homogenization by multiple-scale expansions, and demonstrate the impact of time-dependent forcings and boundary conditions on macroscopic reactive transport. We then derive the macroscopic equation as well as the corresponding applicability conditions based on the order of magnitude of the Péclet and Damköhler dimensionless numbers. Finally, we demonstrate that the dynamics at the continuum scale is strongly influenced by the interplay between signal frequency at the boundary and transport processes at the pore level.

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MS11

On a Two-scale Phase Field Model for Reactive Transport

Evolving interfaces at the pore scale may appear in dissolution and precipitation in a porous medium. More precisely, ions transported by a fluid can precipitate at pore walls, and, conversely, the precipitate attached to the grains can dissolve, increasing the ion concentration in the fluid. Such processes can alter the pore structure and hence impact the flow through the porous medium. Commonly, the corresponding mathematical models are conservation laws defined on evolving domains formulated in terms of free boundaries. The latter are representing the apriori unknown location of the precipitate-fluid interface. We here propose a phase field formulation that allows formulating the relevant conservation laws on a stationary domain. The evolving interface is replaced by a diffuse transition layer of non-zero width. We first show that this model converges to the original sharp-interface model when the width of the diffuse transition zone approaches zero. Then we employ homogenization techniques to upscale the pore scale phase field formulation to the Darcy scale. In doing so, the phase field variable appears in the cell problems. The resulting two-scale model relies on solving the phase field locally in the periodic cell problems, with effective flow rates obtained through a phase-field dependent permeability. Finally, we investigate numerically the behavior of the model with respect to the scale separation factor and the width of the diffuse interface.

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MS11

Immersed Boundary Method for Dissolving Interfaces

Abstract not available.

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MS11

Two-phase Flow in Porous Media: An Upscaling Approach

Classical models for two-phase flow in porous media are based on a capillary pressure - saturation relationship.

However, it is known for a long time that this relation is just an approximation as measurements show hysteresis effects. In this talk we will present a novel upscaling approach for two-phase flow in porous media. We start with a thermodynamically consistent diffuse interface model, as no artificial additional conditions are necessary to model the arising topological changes. As it turns out, this problem contains not only multiple length scales, but also multiple time scales which have to be identified. By separating the different spatial and temporal scales, we derive equations which allow us to explain the hysteresis effects and show the connection between the capillary pressure and the microscopic droplet topology.

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MS11

Reactive Transport in Porous Media: A Two-scale Level Set Approach

We consider porous media applications that contain an evolving solid phase due to heterogeneous reactions. At the pore scale, we consider transport equations for the species' concentrations while taking the processes of convection and diffusion into account. The interface between the solid and the fluid is characterized by means of a level-set. We determine a macroscopic model description applying two-scale asymptotic expansion in a level set framework. A micro-macro model emerges that comprises several levels of couplings: Macroscopic equations describing transport at the scale of the porous medium (macro scale) include averaged time- and space-dependent coefficient functions. These functions are explicitly computed by means of auxiliary cell problems (micro scale). Finally, the geometry on which the cell problems are defined is time- and space dependent and determined by means of the level-set equation. Here, information from the transport equation's solutions enters (micro-macro scale). For evaluation purposes, we complement our theoretical results with numerical computations. For the level set equation a upwind scheme by Rouy and Tourinis applied. (Extended) Finite Element Methods are used for the evaluation of the cell problems and the transport equation. Ultimately, we investigate the dissolution of an array of calcite grains in the micro-macro context.

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MS12

Stable Mixed Finite Elements for Linear Elasticity with Thin Inclusions

Mechanics of a composite material is modeled by representing thin inclusions as lower-dimensional manifolds. By successively applying this dimensional reduction to junctions and intersections within the material, a geometry of hierarchically connected manifolds is formed which we refer to as mixed-dimensional. The governing equations with respect to linear elasticity are then defined on this mixed-dimensional geometry. The resulting system of partial differential equations is also referred to as mixed-dimensional, since functions defined on domains of multiple dimensionalities are considered in a fully coupled manner. With the use of a semi-discrete differential operator, we obtain the mixed formulation of this system of equations in a variational setting. This system is then analyzed and shown to be well-posed with respect to appropriately weighted norms. We propose a numerical discretization scheme using well-known mixed finite elements in all dimensions. The scheme conserves linear momentum locally while relaxing the symmetry condition on the stress tensor. A priori analysis of the discretized system show the method to be stable and convergent, which is confirmed by numerical experiments.

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MS12

Derivation of Effective Models for Reactive Diffusion Processes Through Thin Heterogeneous Layers

We deal with the mathematical modeling of reactive transport through a thin heterogeneous membrane. The aim is the rigorous derivation of homogenized models, where the thin layer is replaced by a lower dimensional interface, and the transport processes through the membrane are described by effective interface transmission conditions. In the microscopic model, we consider a system of reaction-diffusion equations in a domain consisting of two bulk regions separated by a thin layer Ω_ϵ^M with a periodic structure. The thickness of the layer and the period within the layer are of order ϵ. The equations in the layer depend on the scaling parameter ϵ. We consider different strengths of diffusion and two different types of interface conditions between the bulk-domains and the thin layer: Continuous transmission conditions and nonlinear Neumann-boundary conditions. The aim is the derivation of homogenized models for $\epsilon \to 0$, when the layer reduces to an interface Σ separating the two bulk-regions. The crucial point is the derivation of the effective transmission conditions across Σ. One has to deal with the coupling between the bulk-domains and the thin layer, the heterogeneous structure within the layer, the singular limit, when the thin layer reduces to an interface, and the nonlinear reaction-kinetics. To overcome these difficulties, we use the method of two-scale convergence and the unfolding operator in thin domains.

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MS12

The Mathematical Structure of Coupled 1D-3D Models

Coupled 1D-3D flow models are used in a variety of applications, e.g., to model blood flow through vascularised tissue, to model the flow of water and nutrients through soil embedded with a root system, or to model flow between aquifer and well. As the blood vessels, roots or wells typically have miniscule radii compared to the domain of interest, it would be computationally intractable to resolve them as 3D objects in a mesh. Instead, it is natural to view these inclusions as 1D line sources present in a 3D domain. The result is a mixed dimensional model in which the 3D and 1D elliptic equations are coupled together. While computationally favourable, this model reduction has one drawback: The high dimensional gap of the problem induces singularities in the solution. In this talk, we present a splitting theorem for the problem, where the solution is split into an explicit, logarithmic term capturing the singularity, and a smooth correction term w. Besides revealing the mathematical structure of the solution, this splitting technique can be used to significantly improve the approximation properties of the problem. We conclude by showing the results of a generalized finite element method, in which optimal convergence rates are obtained on uniform meshes, i.e., without needing to refine the mesh around the inclusions.

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MS12

Basis Construction in Finite Element Exterior Calculus, Revisited

We give a systematic and self-contained account of the construction of geometrically decomposed bases and degrees of freedom in finite element exterior calculus. In particular, we elaborate upon a previously overlooked basis for one of the families of finite element spaces, which is of interest for implementations. Moreover, we give details for the construction of isomorphisms and duality pairings between finite element spaces. These structural results show, for example, how to transfer linear dependencies between canonical spanning sets, or give a new derivation of the degrees of freedom. Our finite lement spaces are defined over arbitrary triangulations.

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MS12

Hybrid Cellular Automata / PDE Modeling for Self-organisation of Soil Microaggregate Structures

The understanding of soil processes and functions requires a concept of the formation and consolidation of soil structural elements at the microscale taking into account the major driving forces. We present an approach to model the interplay between prototypic building units of soils (e.g. quartz, goethite and illite) on the scale of μm, forming soil microaggregates. The mechanistic model accounts for reactive transport of solutes and charges, the development of biomass and glueing agents, fluid phases, and in particular solid restructuring [1,2]. Interaction rules within and between the phases are prescribed using a cellular automaton method (CAM) and PDE systems (reaction-diffusion type and Nernst-Planck equations). These result in a structural self organization of the phases on a computational domain evolving in time. A fully implicit local discontinuous Galerkin (LDG) method is applied. We study structure formation as a function of the size and shape of the solid particles, and of the effect of attraction and repulsion. The resulting microaggregate structures are investigated quantitatively by morphological analysis. [1] Ray, Rupp, Prechtel (2017): Discrete-continuum multiscale model for transport, biomass development and solid restructuring in porous media; Adv. Water Resour. 107, 393-404 [2] Rupp, Totsche, Prechtel, Ray (2018): Discrete-continuum multiphase model for structure formation in soils including electrostatic effects; Front. Environ. Sci. 6:96

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MS13

Wasserstein Metric-driven Bayesian Inversion with Applications to Wave Propagation Problems

The trace-by-trace quadratic Wasserstein metric pioneered by Yang et al. has emerged as a useful technique for wave motion dominated inverse problems. In this talk we consider its application to full wave inversion using high order energy stable summation-by-parts finite difference methods. We also discuss a Bayesian framework based on a new exponential likelihood function driven by the quadratic Wasserstein metric. Compared to conventional Bayesian models based on Gaussian likelihood functions driven by the least-squares norm (L2 norm), the new framework features several advantages. The new framework does not rely on the likelihood of the measurement noise and hence can treat complicated noise structures such as combined additive and multiplicative noise. Secondly, unlike the normal likelihood function, the Wasserstein-based exponential likelihood function does not usually generate multiple local extrema. As a result, the new framework features better convergence to correct posteriors when a Markov Chain Monte Carlo sampling algorithm is employed. We apply the new framework to a class of signal processing problems, that is, the inverse uncertainty quantification of waveforms, and demonstrate its advantages compared to Bayesian models with normal likelihood functions. This work is joint with G. Kreiss, G. Ludvigsson, M. Motamed and Y. Yang.

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MS13

Resolution Analysis in Seismic Imaging using the Kronecker-factored Hessian

Advanced techniques such as reverse-time migration and full waveform inversion (FWI) have led to a step change in the resolving capability of seismic imaging. Much attention has been given to the development of these algorithms to produce high-resolution models of subsurface properties; however, essential tools for rigorous resolution and uncertainty analysis remain underdeveloped. Resolution analyses in FWI, either via resolution operators or posterior model covariances (in Bayesian formulations), are challenging as they involve the Hessian. The immense computational cost associated with computing and storing the Hessian has thus precluded extensive research on the topic. We propose a novel approach that decomposes the Hessian as a sum of Kronecker products while retaining its block, banded-diagonal structure. The factor matrices obtained from the decomposition act as directional blurring filters when applied to a model perturbation. We exploit this property to compute directional resolution lengths (and relative strengths) within the discrete model space. Applications of the method are presented for acoustic FWI. The computational cost associated with approximating the Hessian is comparable to a single FWI iteration. The approximation to the full Hessian can be stored with minimal overhead due to the compact representation in terms of the factor matrices.

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MS13

Optimal Transport for Full Waveform Inversion: A Graph Space Approach

Optimal transport has been proposed for seismic imaging based on the full waveform (full waveform inversion - FWI) to design more convex misfit functions. The main difficulty to adapt optimal transport to FWI is the non-positivity of seismic data. In a recent paper [Metivier et al, 2018], we have illustrated that straightforward adaptations based on affine scaling of the data, or on the use of the W1 distance might not be appropriated as the convexity property of the optimal transport distance is lost. On this basis, we have proposed a novel strategy based on the comparison of the discrete graph of the data, instead of the data itself. This preserves the convexity and leads to the comparison of positive measures with equal mass. In this presentation, we further explore this method. We show that the numerical computation of the optimal transport distance between discrete graph amounts to the solution of a linear sum assignment problem for which efficient algorithms exist. We demonstrate that the optimal transport distance between discrete graphs can be interpreted as a generalization of standard L_p distances. We illustrate the interest of the approach for a realistic synthetic experiment. The robustness with respect to the initial model design is enhanced compared to least-squares or W1 distance approaches. The computational cost increase is limited to few tens of percent of the computational cost associated with least-squares FWI.

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MS13

Optimal Transport for Full Waveform Inversion: Tackling the Nonlinearity

Full Waveform Inversion (FWI) has been achieving impressive results together with the improvement of the computation power and hardware. However, using the least-square (L2) norm for inversion, nowadays we still fail at the same place as pointed out by Tarantola in 1980s. Compared with Least Square Reverse Time Migration (LSRTM), FWI is a nonlinear inverse problem while LSRTM is a linear inverse problem. If we use the same algorithm/framework for both FWI and LSRTM, one of the two is going to fail since they are two different types of problems. We proposed that the L2 norm is not ideal for the nonlinear inverse problem, not only in Geophysics but many other applied fields. In another word, we need to seriously consider what component of the model parameter we desire before design an algorithm or choose an objective function in optimization. This talk serves as an introduction for the whole mini-symposium "Optimal transport for imaging in geosciences".

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MS14

Accurately utilizing Particle-in-cell Methods for Adaptively Refined Finite-element Models of Mantle Convection and Lithosphere Dynamics

Particle-in-cell methods have a long history in modeling of mantle convection, lithospheric deformation and crustal dynamics. They are primarily used to track thermal or chemical properties, the history of a rock, or the amount of volatiles or partial melt present in a region. However, their efficient and accurate parallel implementation - in particular combined with adaptively refined, dynamically changing, high-order accurate finite-element meshes - is complicated due to the complex communication and frequent reassignment of particles to cells. Here, we present algorithms for a flexible, scalable and accurate particle-in-cell method for massively parallel models with dynamically changing unstructured meshes and high-order accurate finite-elements. We discuss the complexity of these algorithms and present weak and strong scaling tests. We also discuss load-balancing strategies such as balanced repartitioning of particles in adaptive meshes, and present a new benchmark that allows us to quantify sources of errors in the solution of a (pseudo) time-dependent incompressible Stokes flow. This benchmark allows us to determine under which conditions a hybrid particle-in-cell finite-element method can reach the designed convergence rate of high-order finite-element methods in time-dependent flow. We provide a reference implementation of these algorithms in ASPECT (aspect.geodynamics.org), an open-source community code for geodynamic modeling studies.

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MS14

A Comparison of IMEX Time Integrators for the Simulation of Thermal Convection in an Annulus

Numerical simulations of outer core thermal convection of the Earth have been an essential tool in understanding the dynamics of magnetic field generation which surrounds the Earth. Efficient numerical strategies to solve this system of governing equations are of interest in the community of deep Earth research. This work focuses on the time domain integration techniques for solving such problems. We solve for a thermal convection problem in a 2D annulus. The governing equations contain both numerically stiff (diffusive) and non-stiff (advective) components. A common practice is to treat the diffusive part implicitly and the advective part explicitly so as to alleviate the timestep restriction which happens when we use a purely explicit method. These are known as the IMEX time integrators. We focus on these IMEX methods and analyze their performance when applied to this problem. We consider two families of IMEX methods, the multi-step methods and the multi-stage IMEX Runge-Kutta methods (IMEXRK). We do a systematic survey of input parameters namely the Rayleigh number (Ra) and the Prandtl number (Pr), which control the thermal forcing and the ratio of momentum to thermal diffusivities respectively. As the Reynolds number increases, few of the IMEXRK methods perform better than multi-step methods. However, in most cases multi-step methods of a given order outperform IMEXRK methods of the same order.

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MS14

More Than Gradients: Dynamical Attribution in Ocean Science using Adjoint Models

Numerical models are indispensable for improving our understanding of the general circulation of the ocean, elucidating the leading controls governing its variability, and quantifying its role in the global climate system. Sensitivity analysis is a ubiquitous approach for gaining basic insights into the systems response to perturbations of uncertain forcings or parameters. To do so in a comprehensive manner for very high-dimensional spaces of uncertain control variables, adjoint models are powerful arguably indispensable tools. Here we showcase the application of a scalable adjoint of a state-of-the-art ocean general circulation model, obtained via algorithmic differentiation, to problems of central importance in ocean and climate research. Applications presented here focus on the Atlantic Meridional Overturning Circulation (AMOC) as represented in global ocean model simulations. We show how linearized reconstructions, based upon the time-evolving adjoint state, i.e., the dual of the model state, provide critical quantitative understanding of governing mechanisms underlying this climate metric, as a formal target quantity of interest. Such reconstructions can be conducted with negligible computational cost, once the time-evolving adjoint state has been computed and stored. The work demonstrates that adjoint models have merits far beyond their application in gradient-based optimization.

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MS14

Towards Mantle Convection Simulations in the Exa-scale Era: Real World Models

Mantle convection simulations require an extreme fine spatial resolution to represent details at different scales. The long-term study of the processes makes the simulations additionally challenging. Hence, the enormous computational power that will be available on future exa-scale computer is of special interest for such simulations. The Terra-Neo project has the ambitious goal to construct a next generation mantle circulation framework able to truly exploit the capabilities of this new generation of supercomputers. In this talk, we investigate a two-scale approach for efficient matrix-free finite element simulations. We apply this technique to geodynamical problems to demonstrate its efficiency in classical benchmark settings as well as for high-resolution models with lateral viscosity variations. In addition, we study the scalability of the solver on up to 47 250 processes when solving linear systems with more than 10^{12} DOF. In a further step, we extend our benchmark study for the time-space solver. The temperature evolution starting millions years in the past is considered in a forward problem by imposing plate velocity data that are derived by a plate re-construction model on the Earth's surface. Present day temperature obtained from a tomographic model of seismic wave speeds within the Earth is compared to the temperature of the simulation.

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MS14

Improved Newton Linearization for L^1-Norm-type Minimization with Application to Viscoplastic Fluid Solvers

We target highly nonlinear applications in CS&E that are modelled by optimization problems with Hessians exhibiting a problematic (near) null space upon linearization with Newton's method. The null space is caused by a projector-type coefficient in the Hessian, which is created by terms in the objective functional that resemble the L^1-norm. This occurs, e.g., in nonlinear incompressible Stokes flow in Earth's mantle with plastic yielding rheology, which effectively limits stresses in the mantle by weakening the viscosity depending on the strain rate. Another example is total variation regularization for inverse problems. Using a standard Newton linearization for such applications is known to produce severe Newton step length reductions due to backtracking line search and stagnating nonlinear convergence. Additionally, these effects become increasingly prevalent as the mesh is refined. We analyze issues with the standard Newton linearization in an abstract setting and propose an improved linearization, which can be applied straightforwardly to Stokes flow with yielding and total variation regularization. Finally, numerical experiments compare the standard and improved Newton linearizations in practice. When we employ our improved linearization within our inexact Newton-Krylov method, a fast and highly robust nonlinear solver is attained that exhibits mesh-independent convergence and scales to large numbers of cores with high parallel efficiency.

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MS15

A Conforming Mixed Finite Element Method for the Navier–Stokes/Darcy–Forchheimer Coupled Problem

In this work we present and analyse a mixed finite element method for the coupling of fluid flow with porous media flow. The flows are governed by the Navier–Stokes and the Darcy–Forchheimer equations, respectively, and the corresponding transmission conditions are given by mass conservation, balance of normal forces, and the Beavers–Joseph–Saffman law. We consider the standard mixed formulation in the Navier–Stokes domain and the dual-mixed one in the Darcy–Forchheimer region, which yields the introduction of the trace of the porous medium pressure as a suitable Lagrange multiplier. The well-posedness of the problem is achieved by combining a fixed-point strategy, classical results on nonlinear monotone operators and the well-known Schauder and Banach fixed-point theorems. As for the associated Galerkin scheme we employ Bernardi–Raugel and Raviart–Thomas elements for the velocities, and piecewise constant elements for the pressures and the Lagrange multiplier, whereas its existence and uniqueness of solution is established similarly to its continuous counterpart, using in this case the Brouwer and Banach fixed-point theorems, respectively. We show stability, convergence, and a priori error estimates for the associated Galerkin scheme. Finally, we report some numerical examples confirming the predicted rates of convergence, and illustrating the performance of the method.

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MS15

Time-accurate, Doubly-adaptive Artificial Compression Methods for Prediction of Fluid Motion

Abstract not available.

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MS15

Efficient Solution of Coupled Flow and Porous Me-

dia Problems by Monolithic Multigrid Methods

The interaction between fluid flow and porous medium models is an attractive topic due to its wide range of applications. It consists of a complicated multi-physics problem which can be described by a coupled model based on the Stokes equations to model the free flow and Darcy equation or Biot's model to describe the saturated rigid or deformable porous medium. Such coupled system is completed by appropriate interface conditions. The numerical simulation of this problem is a challenging task due mainly to the solution of the large linear systems arising from its discretization, since this is the most consuming part in real simulations. In this work, a monolithic multigrid method is proposed as an efficient solver for the linear discrete system obtained by a finite volume discretization of the problem on staggered grids. A novelty in our modeling approach is that a special discretization at or near the points in the interface, which combines the approximation of the governing equations and the considered interface conditions, is proposed. This results to be the key for the successful application to the monolithic algorithm. The efficiency and robustness of the proposed method are confirmed in numerical experiments with typically small values of the physical coefficients.

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MS15

Effective Model for Crystal Precipitation and Dissolution in a Porous Medium with Perforated Solid Matrix

This talks presents an upscaled model for crystal precipitation and dissolution in a saturated porous medium with a perforated solid matrix. We model the solid matrix itself at the pore-scale as a porous medium. Hence, at the pore-scale we consider a Darcy-Stokes system, where the Beavers-Joseph boundary condition at the corresponding interface is proposed. By asymptotic expansions we derive an upscaled model describing the process via Darcy's law, a transport equation and corresponding effective coefficients given by the evolution of the microstructure. Moreover, weak solvability of the upscaled model is investigated.

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MS16

Enhanced Galerkin using Serendipity Spaces on Quadrilaterals for Miscible Displacement

Computational meshes must be designed to follow geologic layering of natural subsurface porous media. It is well known that standard serendipity and mixed finite elements lose accuracy on quadrilaterals. We develop new direct serendipity and mixed elements that remain accurate on quadrilateral meshes, because they contain the full space of polynmomials locally on each element. That is, polynomialls are included directly in the finite element space, but two supplemental functions must be added to allow the elements to be joined continuously. The serendipity spaces have a minimal number of degrees of freedom, and they can be constructed explicitly. A de Rham sequence then implies the existence of direct mixed finite element spaces that can be constructed explicitly without the need for any mappings from reference elements. We use these new elements to design an enhanced Galerkin method for miscible displacement and two-phase flow in porous media. In the latter case, we solve the pressure equation using direct mixed finite elements. The methods are locally conservative and use a minimal number of degrees of freedom. Theoretical and numerical results for these methods are given.

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MS16

Conservative Multirate Multiscale Method for Multiphase Flow in Heterogeneous Porous Media

We propose a conservative multirate multiscale method, which allows for simulation of multiphase flow in heterogeneous media adaptively in time and space. Motivated by the co-existence of fast and slow processes, the multirate method constructs an adaptive conservative time discretization scheme which imposes different time steps in different sub-domains. Yet, these sub-domains are consistently integrated with a conservative flux partitioning strategy. On the other hand, to resolve the challenge of imposing fine-scale spatial grids, to heterogeneous fine-scale properties, we integrated our multirate approach with the multiscale finite volume method. The multiscale method allows for the construction of coarse-scale systems while the fine-scale heterogeneity is being captured by using local basis functions. To this end, we develop a sequential simulation approach where we solve the pressure equation with the multiscale technique and then advance the phase saturation adaptively by solving the transport equation using multirate approach. Preliminary numerical results show that the proposed adaptive strategy yields efficient and accurate solutions. In the talk, we will illustrate the numerical procedure and the latest developments.

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MS16

Comparison of Implicit Discontinuous Galerkin and Weno Schemes on Stratigraphic and Unstructured Grids

Higher-order methods have only been applied to a limited extent in simulation of real petroleum assets. Possible reasons are complex grid formats (unstructured, polyhedral cells, large aspect ratios) and need for implicit time discretization. I this talk, we outline how weighted essentially non-oscillating (WENO) methods and discontinuous Galerkin (dG) methods can be adapted to the needs of reservoir simulation. We discuss some implementation details and highlight advantages and shortcomings of the two methods on a number of test cases, including models representing real reservoirs.

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MS16

New Finite Element Solvers for Poroelasticity in the 2-field Approach

This talk first presents results from our recent efforts for reviving the 2-field (fluid pressure and solid displacement) approach for numerically solving poroelasticity problems on quadrilateral meshes. The Darcy equation is solved for fluid pressure by the weak Galerkin finite element methods, which establish the discrete weak gradient and numerical velocity in the Arbogast-Correa spaces. The elasticity equation is solved for solid displacement by renovated Bernardi-Raugel elements, which were originally designed for Stokes problems. These two types of solvers are coupled through the implicit Euler temporal discretization to solve poroelasticity. Numerical experiments on two widely tested benchmarks will be presented to demonstrate the new solvers are locking-free. Then we will discuss extension to 3-dim and implementation in deal.II. This is a joint work with Graham Harper, Simon Tavener, and Zhuoran Wang, all at Colorado State University.

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MS16

MIN3P-HPC: A High Performance Code for Subsurface Flow and Reactive Transport Simulation

This research presents a novel multi-point flux approximation (MPFA) method with multi-point spatial weighting and the implementation of this method into the process-based model MIN3P-THCm, which was designed for the investigation of subsurface flow and reactive transport in variably saturated media. A flexible parallelization scheme based on domain decomposition and thread acceleration was implemented, allowing the use of OpenMP, MPI and hybrid MPI-OpenMP for computing resources ranging from desktop PCs to supercomputers. A series of numerical experiments have been conducted to evaluate the performance of the implemented numerical methods in terms of accuracy, monotonicity and convergence behavior. Specifically, non-physical oscillation problems at wetting fronts are investigated. The proposed MPFA method with multi-point upstream weighting avoids spurious oscillations and generates accurate results for the challenging sharp wetting front problems. Furthermore, the numerical accuracy was verified against analytical solutions for 2D and 3D solute transport, and was also verified against the structured grid version of MIN3P-HPC and by comparison with third-party software using different cell types. Parallel efficiency of OpenMP, MPI and hybrid MPI-OpenMP versions were examined through a series of solute transport and reactive transport cases. The results demonstrate the versatility and enhanced performance of MIN3P-HPC for subsurface flow and reactive transport simulations.

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MS17

Bayesian Transmissivity Estimation using Continually Refined Local Surrogate Models within Parallel MCMC

We use Bayesian methods to characterize the posterior distribution over transmissivity given discrete observations of contaminant concentration. Hydrological models used to predict subsurface flow depend the transmissivity field, which parameterizes subsurface properties and cannot be observed directly. Bayes rule defines a posterior distribution over the transmissivity given the observations and the model. Ideally, Markov chain Monte Carlo (MCMC) characterizes the posterior distribution. However, evaluating the nonlinear hydrological model requires an expensive numerical PDE solve and repeatedly evaluating the model within MCMC is computationally intractable. Our scheme exploits regularity in the posterior density to construct a local regression approximation from pointwise density evaluations during MCMC sampling. Continually refining the approximation leads to an asymptotically exact characterization of the posterior. We balance the decay rate of the bias introduced by the regression model with that of the variance in the MCMC estimate to guide an ideal refinement strategy, given a finite number of MCMC steps. We achieve further computational savings using parallel MCMC chains to construct a single surrogate model, which is shared across all chains.

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MS17

Robust Parameter Estimation using Inverse Modeling and Advanced Machine Learning Techniques

The high cost and complex logistics of using ship-based surveys for bathymetry, i.e., depth imaging, have encouraged the use of various types of indirect measurements for waterbody high-resolution bathymetry. However, estimating bathymetry from indirect measurements is usually an ill-posed inverse problem and can be computationally challenging as most of the inversion techniques require iterative calls to complex forward models to compute Jacobians and subsequent inversion of relatively large matrices. In this work, we use a fully connected deep neural network and a convolutional neural network algorithm to estimate bathymetry using indirect measurements. Also, we extend these techniques to a Bayesian setting to quantify estimation uncertainty robustly. We show that these neural nets can perform the inversion operation much faster than traditional inversion methods. The improvement and performance of these methodologies are illustrated by applying them to depth imaging problems for two synthetic test cases.

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MS17

Ensemble Pattern-learning for Calibration of Subsurface Flow Models with Complex Geologic Facies Descriptions

Modern geostatistical techniques enable grid-based multiple-point statistical simulation of complex patterns from a training image (TI). Conditioning the simulated models on nonlinear flow and pressure data is challenging. We introduce a novel pattern-based facies model calibration method to integrate dynamic flow response data while honoring the discrete statistical patterns in the TI. To this end, sparsity-promoting parameterization (using k-SVD) is first used for model calibration to identify a continuous solution in the first step of the algorithm. Because of the approximation involved in continuous parameterization, in the second step the solution is mapped onto to the TI, which is treated as a geological feasibility constraint. To implement the mapping, a local search template is used to scan the TI to find and store local discrete spatial patterns with smallest distances from those in the continuous solution. Unsupervised ensemble learning is then employed to assign most likely facies types to each grid cell using the collected patterns that intersect with a given cell. The resulting discrete solution serves as a regularization term in the next continuous model calibration step in the next iteration. The process is repeated until the discrete solution provides an acceptable match to the data. Numerical experiments are presented to evaluate the performance of the proposed approach for model calibration in complex discrete systems.

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MS17

Global Sensitivity Analysis and Parameter Estimation for Nearshore Wave Models

Coastal engineers use a variety of numerical models for simulating wave transformation and wind wave growth in the nearshore zone. These models depend on a large number of input parameters, ranging from real-time data fields such as wind velocity to tuning parameters such as grid size. Global sensitivity analysis (GSA) of the models sheds light on the relationship between these parameters and the model output fields. We carry out GSA by computing total Sobol' indices for each parameter-output pairing for wave models including STWAVE, the ERDC-CHL steady-state, spectral wave model. We interpret the results to provide guidance for model calibration and simplification as well as parameter inference and uncertainty quantification.

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MS17

Quantifying Uncertainties in Large-scale Bayesian Linear Inverse Problems using Krylov Subspace Methods

For linear inverse problems with a large number of unknown parameters, uncertainty quantification remains a challenging task. In this work, we use Krylov subspace methods to approximate the posterior covariance matrix and describe efficient methods for exploring the posterior distribution. Assuming that Krylov methods (e.g., based on the generalized Golub-Kahan bidiagonalization) have been used to compute an estimate of the solution, we get an approximation of the posterior covariance matrix for "free.' We provide theoretical results that quantify the accuracy of the approximation and of the resulting posterior distribution. Then, we describe efficient methods that use the approximation to compute measures of uncertainty, including the Kullback-Liebler divergence. We present two methods that use preconditioned Lanczos methods to efficiently generate samples from the posterior distribution. Numerical examples from seismic tomography demonstrate the effectiveness of the described approaches.

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MS18

Seismic Velocity Analysis: What is the Need for a Non-physical Extended Space to Derive a Proper Solution?

Migration velocity analysis is a technique to derive optimal macro velocity models associated to focused seismic images. A macro velocity model is needed to convert the seismic data, recorded in the time domain, to images expressed in the depth domain. The conversion can be obtained by applying the migration operator to the observed data. Recent techniques have indicated the benefit of using the inverse operator instead of the migration (adjoint) operator. Here, we discuss the need for extending the model space as an artificial intermediate solution to be able to converge towards the proper solution. Currently, the extension is expensive in terms of memory allocation and is a limiting factor for the extension to 3d. The need for the extension is thus a relevant question for the applicability of migration velocity analysis schemes.

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MS18

Extending the Search Space of Full Waveform Inversion (FWI) by Alternating Direction Method of Multipliers (ADMM)

Full Waveform Inversion (FWI) is a wave equation-constrained optimization problem which seeks to estimate the earth parameters embedded in the coefficients of the wave equation from a sparse recording of its solution, the seismic wavefield. The wave equation is a non-linear function of the wavefield and earth parameters. However, when the wavefield is known, the wave equation becomes a linear function of the earth parameters and vice versa. This property makes FWI be a bi-convex optimization problem which can be solved efficiently with the alternating direction method of multipliers (ADMM). ADMM breaks down FWI into two linear subproblems: wavefield reconstruction and model parameter estimation. The wavefield reconstruction subproblem extends the search space of FWI by relaxing the wave equation, while it injects the observed data as priors into the optimization. Then, the earth parameters are estimated by minimizing wave equation errors (i.e., source residuals). Compared to a classical reduced variable-projection approach, realistic synthetic examples show how our method pushes the reconstructed wavefield toward the true wavefield, hence making FWI more resilient to cycle skipping. Moreover, we show that, unlike an alternating-direction penalty method, the augmented Lagrangian embedded in ADMM allows for the convergence toward an accurate minimizer when a fixed penalty parameter is used. We also show that bi-convexity applies to acoustic and elastic multiparameter FWI.

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On the Parametrization of Slope Tomography: Its Implication on the Velocity-position Coupling

Seismic tomography seeks to reconstruct the subsurface parameters, mainly wavespeeds. In reflection/diffraction tomography, an additional parameter class is inherently introduced: the scattering positions. The underlying inverse problem is awkward due to the ill-famed velocity-position coupling. We review different optimization strategies in the frame of slope tomography, namely tomographic approaches based on locally coherent seismic events associated with reflection/diffraction from small reflector segments/diffractors. The latter are described by their two-way traveltimes and slopes, the horizontal component of slowness vector at the source and receiver positions). Three plausible inversion strategies exist to address this multi-

variate problem: the first consists of alternating between scattering position and wavespeed updates to bypass the coupling issue. The second jointly updates both sought parameters with the risk of ill-posedness. The third one relies on the projection of the model subspace spanned by scattering positions onto the model subspace spanned by velocities leading to a mono-variate reduced-space inversion. This projection is implemented in the adjoint-state method by using two focusing equations satisfied by two observables (traveltimes and one slope) as constraints. Assessing these strategies on synthetic and real cases shows that the reduced-space approach exhibits superior performance while not needing any scaling of the data and model spaces.

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MS18

Seeding Waveform Inversion from Bandwidth Extension

This talk considers the question of frequency extrapolation of bandlimited recordings of scattered waves. I will review a few known methods that have been shown to give meaningful results for seismic imaging, with the recent addition of deep learning with convolutional nets. Bandwidth extension is useful in that it can help seed the frequency sweeps for full waveform inversion. Joint work with Hongyu Sun and Yunyue Elita Li

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MS18

Reconstructed Full Waveform Inversion with Extended Source: Increasing Depth and Resolution

By including the source wavefield as an additional parameter to the search space, our extended parameter FWI adds the wave equation error as a penalty term to the original data misfit in conventional FWI (Lailly, 1983; Tarantola, 1984; Virieux and Operto, 2009) and formulates a joint optimization problem to minimize the data misfit subject to the wavefield being consistent with the wave equation in an L2 sense. We reconstruct the source wavefield and estimate the earth models in an alternating fashion. Time-domain derivation and implementation differentiate our extended parameter FWI from other previous works that are related to wavefield reconstruction inversion or source extension in the frequency domain (van Leeuwen and Hermann, 2013; Huang et al., 2016) and provides a more suitable solver for processing 3D large-scale production data sets. By expanding the search space, extended parameter FWI reconstructs the forward modeled data to better fit the field data and avoid cycle skips. It takes advantages of reflected waves from wavefield reconstruction and produces deeper model improvement with a proper choice of penalty parameter that needs to be updated as well.

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MS19

Numerical Analysis of a System of Variational Inequalities for Biofilm Growth at Porescale

We consider a model of biofilm growth and nutrient consumption in porous media at the pore-scale. There are constraints on the volume of the biofilm, thus the model is a coupled system of parabolic variational inequalities. Additional difficulties come from the accumulation of the biofilm near the walls of the pore-scale. We approximate the system by finite element method in space and backward Euler in time, and we use semi-smooth Newton method to solve the constrained problem with a nonlinear complementarity constraint. Our results include solvability of the model as well as the proof of convergence, which we verify with numerical experiments. Qualitatively, our upscaled results compare favorably with experiments.

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MS19

FSI with Multi-layered Poroelastic Tissue

We present a novel multi-layered poroelastic structure model consisting of the classical Biot model for 3D poroelastic structures coupled to a reduced, Biot-membrane model based by the recent work by Mikelic and Tambaca. The multi-layered poroelastic stucture is coupled to the flow of an incompressible, viscous fluid. The Biot membrane serves as a fluid-structure interface with mass. Two-way coupling is considered both between the fluid and the poroelastic structure, and between the two structures. An advection-reaction-diffusion model is added to the FSI problem to describe drug uptake by the vascular tissue treated with endovascular prosthesis called stent. Preliminary results on analysis and numerical results related to the blood flow through poroelastic arteries treated with stents will be presented. This is a joint work with Y. Wang (postdoc, Math, UC Berkeley), J. Tambaca (Math, U Zagreb, Croatia), T. Desai (Bioengineering, UCSF), and M. Bukac (Applied Math, Notre Dame).

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MS19

A Multiscale Formulation of Multiphase Flow at the Pore Scale

Multiphase flow in porous media is relevant to several applications ranging from geologic CO2 storage, geothermal energy, and hydrocarbon recovery to manufacturing of fuel cells and batteries. In order to optimize design and operational controls in these systems it is necessary to consider processes at the pore (nm-μm) scale. While computational models provide an attractive means for achieving fluid-structure optimization, traditional direct numerical simulations (DNS) are prohibitively expensive. In this work, we present a multiscale formulation for single- and two-phase flow at the pore scale aimed at accelerating simulations. The approach produces approximate solutions that are highly accurate and enables adaptivity by localizing computations to the two-phase interface. This obviates calculations in the single-phase regions ahead and behind a displacement front, reducing the degrees of freedom of a 3D problem to that of a 2D surface. Prediction errors can be estimated and reduced through an iterative strategy, which is not feasible in other approximate techniques such as pore-network modeling (PNM). The multiscale method is amenable to scalable parallelism and multiphysics (or hybrid) computations.

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MS19

Phase Field Models for Multi-phase Pore-scale Processes with Microstructural Evolution

Combined flow and reactive transport processes are frequently encountered in porous media applications. We are mostly interested in precipitation/dissolution processes that occur for the multiphase flow of incompressible and immiscible fluids on the pore scale. In this case the flow on the pore scale is characterized by the dynamics of various (fluid-fluid/solid-fluid) interfaces. In the lecture we will first review standard sharp-interface approaches. Based on these we present several phase field models that combine the Navier-Stokes equations with evolution equations for artificial order parameters for the phases. The new diffuse interface models are validated by analysing the sharp interface limit using tools of asymptotic analysis. In particular we ensure the thermodynamical consistency by identifying appropriate free energy functionals. The lecture will conclude with several numerical simulations on the pore scale as well as an ansatz towards up-scaling to the Darcy scale. This is joint work with Carina Bringedal, Rainer Helmig and Iuliu Sorin Pop.

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MS19

Level Set-Immersed Boundary Method for Pore-scale Simulations of Precipitation-dissolution Processes in Porous Media

Flow and reactive transport problems at the pore-scale often involve complex geometries. Grid based methods (e.g. finite volume, finite element, etc.) are a vital tool for studying such problems. Cartesian grids are one of the most attractive options as they possess simple discretization stencil and are usually straightforward to generate at virtually no computational cost. The Immersed Boundary Method (IBM), a Cartesian based methodology, maintains most of the useful features of structured grids, while it exhibits a great resilience in dealing with complex geometries. These features make it increasingly more attractive to model transport in porous media as the cost of grid generation reduces greatly. Moreover, in most reactive transport processes, the geometry evolves due to solid dissolution or precipitation. The successful implementation of the IBM strongly depends on the accurate tracking of the reactive interface (i.e. solid-liquid interface). In this work, we have developed a novel, high order Level Set-Immersed Boundary Method framework, which is able to accurately model flow and reactive transport with geometry changes at the pore-scale. The accuracy test shows at least second order of accuracy in L_1, L_2 and L_∞ norms of error. We have also tested the method for several transport and flow scenarios, including dissolution and precipitation processes in porous media.

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MS20

Reliable and Fast Solving of Small-strain Plasticity Problems with a Nonsmooth Multigrid Method

We present a new approach for solving small-strain plasticity problems called the *Truncated Nonsmooth Newton Multigrid Method* (TNNMG). It is based on the primal form of the plasticity problem, where the unknowns are the *displacement* and the *plastic strain*. Time discretization results in a sequence of convex minimization problems. It works both for smooth and nonsmooth yield laws, as well as for various linear and nonlinear hardening rules. TNNMG is designed to minimize such convex functionals with block-separable nonlinearities by combining local nonlinear smoothing steps and global linear multi grid corrections. TNNMG has been proven to be *globally convergent*, and is extremely fast in practice: With this method we can compute a complete plasticity time step in less time than one classical predictor–corrector step. In the presentation the TNNMG method will be explained and applied to rate-independent small-strain plasticity theory. Several numerical simulations will be given for *Tresca* and *Von Mises* yield laws as well as for different hardening rules. The efficiency of the algorithm will be compared to the predictor–corrector approach.

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MS20

Numerical Formulations and Applications for Geomaterial Cap Plasticity Models

Cap plasticity models have been developed to model the instability and failure of wellbores, the sand production of oil reservoirs, and the subsidence of ground surfaces. For example, the compaction of carbonate reservoirs with soft rocks often induces large plastic deformation due to the collapse of rock pores. Poroelasticity or poroelastoplasticity without cap models will not able to predict the subsidence of ground surfaces due to the compaction of reservoirs with soft rocks or clays. Following the compaction of reservoirs and failure of rock formations, the porosity and permeability of formations undergo changing. These bring a challenge for reservoir simulations because of high nonlinearity of coupled geomechanics and fluid flow fields. In this presentation, we briefly review cap plasticity models and focus on a fully coupled, fully implicit, and fully consistent finite element formulation for coupled geomechanics and fluid flow problems with cap models and nonlinear flow models. Two numerical examples, the damage of multiple horizontal wellbores and the subsidence of ground surface due to the depletion of reservoirs with soft rocks are presented. Finally, computational issues for cap plasticity models are also discussed.

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MS20

Numerical Methods for Fault Slip Computation in Poroelastic Media

The role of fluid pressure in natural and induced seismicity is a highly debated topic: changes in fluid pressure can indeed destabilize critically stressed preexisting faults. In particular the injection of fluid in the subsurface has been linked to an increase in the occurrence of small to moderate earthquakes. The risk of fault slip can be quantified by the so called slip tendency, the ratio between tangential and effective normal stress, which should not exceed the Coulomb friction coefficient. The governing equations for this problem form a highly nonlinear coupled system of PDEs, whose numerical approximation poses some challenges. First of all, there is a two-way coupling between the mechanical and fluid-dynamic problem, which can be handled by means of iterative splittings such as the fixed stress. Moreover, in realistic cases, the problem is posed in complex geometries, usually in layered sedimentary basins cut by multiple faults: this motivates our interest in the application of XFEM to both the mechanical and fluid problems. Finally, we focus on the problem of frictional contact: the partitioning of the fault into stuck and slipping part changes in time according to slip tendency, which in turn depends of stress and displacement which are affected by slip. In this work we choose to impose the interface conditions on the fault by means of Nitsche penalization and formulate a control problem to compute slip on the fault.

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MS20

Numerical Simulation of a Poroelastic Model with Random Coefficients using Polynomial Chaos and High-order Polyhedral Methods

We present several results on the Biot model with random coefficients for poroelastic simulations. First, we provide a physically admissible set for the random poroelastic coefficients, accounting for the dependence between the constrained specific storage coefficient and the other random model coefficients. The well-posedness of the resulting stochastic Biot model is then established at the continuous level. The stochastic discretization of the displacement and pressure fields uses non-intrusive Polynomial Chaos (PC) expansions. We rely on sparse pseudo spectral projection methods to compute the PC expansion coefficients of the random fields through an ensemble of deterministic model simulations. Our deterministic solver is based on the coupled Hybrid High-Order\discontinuous Galerkin method which supports general polyhedral meshes and arbitrary approximation orders. An injection problem and a traction test case are considered to investigate numerically the PC convergence with the sparse grid level. Finally, a sensitivity analysis is also performed in order to rank the importance of the different uncertain model coefficients on the displacement and pressure fields.

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MS20

Challenges in Modelling the Anisotropic Poroelastoplastic Behaviour of Fractured Rocks as Homogenized Media

In subsurface engineering applications, fractures are represented as thin inclusions embedded in an elastic matrix, and the fracture space is filled with elastic (possibly plastic) material. In the subsurface, fractures are present at different scales. While the large-scale fractures are represented explicitly, the fine-scale ones are incorporated into the constitutive model by upscaling the relevant rock matrix properties. The aim of this talk is twofold. Firstly, constitutive models of poroelastoplasticity for fractured materials as homogenized media are revisited. Here, we focus on the limitations of such models, and discuss challenges and opportunities towards more mathematically consistent constitutive models. In this context, we introduce reduced models for both flow and mechanics for the thin inclusions, which are obtained through vertical integration. In the second part of the talk, a mixed-dimensional formulation of the equations of flow and mechanics for deformable fractured porous media is proposed. This model is based on a novel semi-local approach, which consists on the partition of both the tangential stress/flux and tractions/normal fluxes into two terms, namely in-plane gradients and out-of-plane half-jumps. Construction of discretization schemes for semi-local constitutive models is then discussed. We conclude by presenting model validation results for flow in fractured media.

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MS21

Constraint Energy Minimizing Generalized Multiscale Finite Element Method

In this talk, we will present the recently developed constraint energy minimizing generalized multiscale finite element method and the resulting nonlinear upscaling method. The method is able to identify the number of local basis functions as well as the size of oversampling regions needed to ensure accurate capturing of long channelized effects. We will present the method and applications. The research is partially supported by the Hong Kong RGC General Research Fund (Projects: 14304217 and 14317516) and the CUHK Direct Grant for Research (2017-18).

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MS21

Adaptive Multiscale Methods for Multiphase Simulation of Complex Reservoir Models

Many multiscale methods for solving elliptic/parabolic flow equations can be written in operator form using a restriction and a prolongation operator defined over a coarse partition of an underlying fine grid. The restriction operator constructs a reduced system of flow equations on the coarse partition and the prolongation operator maps pressure unknowns from the coarse partition onto the original simulation grid. In the talk, we demonstrate that applying a sequence of such operator pairs that adapt to geological structures, well paths, and dynamic changes in primary variables gives significantly faster convergence than applying a single operator pair associated with a fixed partition.

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MS21

Generalized Rough Polyharmonic Splines for Numerical Homogenization

In this talk, we will introduce the so-called Generalized Rough Polyharmonic Splines (GRPS). The GRPS basis is associated with a set of measurement functions on the coarse level. By choosing proper measurement functions, the GRPS approximation space have quasi-optimal convergence rate as well as quasi-optimal localization property. This method has been applied to the numerical homogenization and also the optimal control of of multiscale PDEs.

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MS21

A Novel Transient Diffuse Source Algorithm for Multiscale Simulation in Porous Media

A novel upscaling approach was previously introduced using pressure transient concepts which allowed us to distinguish between well-connected, weakly connected and disconnected pay in the local upscaling region. The current work applies these same concepts to multiscale multiphase simulation using diffuse source basis functions which generate high resolution velocity fields that capture the subgrid heterogeneity and multiphase flow effects including rock and fluid compressibility. The local flow field generated for coarse transmissibility calculation is based on transients approaching pseudo steady state as opposed to steady state or pseudo steady state. Transients allow us to assess the impact of localization and degree of local connectivity on overall multiscale simulation performance. The concept of diffusive time of flight together with transient basis functions allow us to assess the error in localization for a particular local flow problem. The upscaling step draws upon its similarity to pressure transient well testing concepts to set up local flow problems to obtain coarse transmissibilities. After solving for flow on the coarse scale, superposition allows us to downscale the coarse flow, generating a fine scale velocity field. The downscaled flow may be utilized for solving transport on the fine grid. The approach is tested on the SPE10 synthetic reservoir model and a high resolution carbonate geologic model.

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MS21

Upscaling as Acceleration of Optimization and Inversion for Field Development

Supporting oil and gas field development decisions is the main objective of reservoir modeling and simulation. In this talk, we approach upscaling from the point of view of model reduction for accelerating decision support under deep subsurface uncertainty at multiple scales. Recent advances and further research are discussed.

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MS22

A Scalable Multigrid Reduction Framework for Coupled Multiphase Poromechanics

Simulation of multiphase poromechanics involves solving a multi-physics problem in which multiphase flow is tightly coupled with poromechanical deformation. To capture this dynamic interplay, fully implicit methods, also known as monolithic approaches, are usually preferred. The main bottleneck of this strategy is the cost of solving the linear systems resulting from discretization of the problem. Because of the strong coupling present in the continuous problem, efficient techniques such as algebraic multigrid (AMG) cannot be directly applied to the discrete linear systems. In this work, we present our efforts in developing an algebraic framework based on multigrid reduction that is suited for tightly coupled systems of PDEs. Using this framework, the decoupling between the equations is done algebraically through defining appropriate interpolation and restriction operators. One can then employ existing solvers for each of the decoupled blocks or design a new solver based on knowledge of the physics. We will demonstrate the applicability of our framework for multiphase flow coupled with poromechanics. We show that the framework is flexible to accommodate a wide range of scenarios, as well as efficient and scalable for large problems.

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MS22

System-AMG as a Framework for the Full Linear Solution Process in Fully Implicit Reservoir Simulations

Algebraic Multigrid (AMG) methods are known to be a highly efficient linear solver approach for problems based on elliptic PDEs. However, in reservoir simulation approaches we are concerned with coupled problems for different types of physical unknowns with different backgrounds. This needs to be accounted for in the design of a robust and efficient linear solver approach. This talk will discuss recent developments of how AMG can be applied for the solution of full coupled systems. This starts with basic Black-Oil problems but also accounts for coupled thermal and/or geomechanical applications. In all these cases it is necessary to ensure that AMG finds those matrix properties that it aims at exploiting them in the construction of its hierarchy of levels. Moreover, it is necessary to exploit the AMG hierarchy for all types of unknowns where this is appropriate. By being applied to the original linear problem, System-AMG can exploit all inherited information from the complex physics. On the one hand it applies matrix manipulations that aim at ensuring the applicability of the multigrid process in the second stage. On the other hand it adjusts the components of the AMG process to ensure that they fit with the given type of problem. This only requires a minimal set of physical information in addition to the matrix, but it ensures a robust and efficient applicability of the System-AMG solver.

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MS22

Inexact Newton Method for General Purpose Reservoir Simulation

Inexact Newton Methods are widely used to solve systems of non-linear equations. The convergence of these methods is controlled by the relative linear tolerance, that is also called the forcing term. A very small forcing term may lead to oversolving the Newton equation. Practical reservoir simulation uses inexact Newton methods with fixed forcing term, usually in the order of 1e-3 or 1e-4. Variable forcing terms for a given inexact Newton step have proved to be quite successful in reducing the degree of oversolving in various practical applications. The cumulative number of linear iterations reduces but the number of nonlinear iterations usually increases. We first present a review of existing inexact Newton methods with various forcing term estimates and then propose improved alternate estimates. Our estimates reduce the total linear iterations while only resulting in few extra Newton iterations. We show successful applications of fully-coupled three-phase and multicomponent multiphase models in isothermal and thermal reservoir simulation using Constrained Pressure Residual preconditioner with Generalized Minimal Residual method as the linear solver.

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MS22

Block Preconditioners for Non-isothermal Flow through Porous Media

In oil and gas reservoir simulation, the standard preconditioner is a two-stage process which involves solving a restricted pressure system with AMG. Initially designed for isothermal models, this approach is often used in the thermal case. However, it does not incorporate heat diffusion or the effects of temperature changes on fluid flow through viscosity and density. We seek to develop preconditioners which consider this cross-coupling between pressure and temperature. In order to study the effects of both pressure and temperature on fluid and heat flow, we first consider a model of non-isothermal single phase flow through porous media. For this model, we develop a block preconditioner with an efficient Schur complement approximation. Then, we extend this method for multiphase flow as a two-stage preconditioner. We present a numerical comparison of different preconditioning approaches.

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MS22

Projected Infinite-dimensional Solutions as Embarrassingly Parallel Strong Linear Preconditioners

The solution to an algebraic system that arises from the consistent discretization of advection-diffusion-reaction operators is closely related to the projection of the operators solution onto the discrete domain. In recent work, estimates for the discrete solution were obtained by a prolongation-solution-projection process, where the approximate solution stage is embarrassingly parallel and requires optimal computation. In previous work, these estimates were conservative in the sense of support, and were applied in order to localize computation. In this work, approximate solutions are obtained to be sharp and are used as physical preconditioners. Two schemes are presented including a combinative preconditioning application. Numerical results show strong preconditioning qualities as well as low application costs and high parallel scalability.

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MS23

A Simulation Pipeline for the Simulation of Earthquakes and Resulting Tsunamis

We present the two software packages SeisSol and sam(oa)^2 for earthquake and tsunami simulation, respectively. Together, they realise a pipeline for simulating earthquake-tsunami events. SeisSol allows to simulate subduction-zone earthquakes using complex topography and fault geometry with realistic initial data. sam(oa)^2 allows to simulate tsunamis using time-dependent displacement data obtained from respective earthquake simultions and with accurate inundation. Focus of the talk will be aspects of software and performance optimisation.

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MS23

Development of Runge-Kutta Discontinuous Galerkin Methods for Well-balanced Tsunami Inundation

Tsunami simulations are most often based on non-linear shallow water theory – a two-dimensional representation of conservation laws for mass and momentum. Corresponding discretization methods require local discrete conservation properties – a reason for the attractiveness of discontinuous Galerkin (DG) methods in this application field. DG methods are well suited for non-uniform polygonal meshes (in our case adaptive triangular meshes), and in combination with strong stability preserving Runge-Kutta time integrators they allow for accurate and robust tsunami simulations. For an integrated propagation and inundation simulation, where the propagation phase is generally spatially large scale and ocean wide, and the inundation phase is small scale and local at the coast, adaptive mesh refinement is used. Furthermore, since the water depth approaches zero, a numerically badly scaled problem needs to be solved. We developed limiting strategies for accurate and stability preserving inundation computations. We demonstrate the capability of our method with several well-known test cases as well as realistic historic and recent tsunami events.

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MS23

Multilayer Non-hydrostatic Shallow-water Models for Tsunami Simulations

Abstract not available.

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MS23

Uncertainty Quantification Techniques for Tsunamis

Abstract not available.

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MS23

Efficient Tsunami Modeling on Adaptive Grids with Graphics Processing Units (GPUs)

Solving the shallow water equations (SWE) efficiently is critical to the study of natural hazards induced by tsunami and storm surge, since it provides more response time in an early warning system and allows more runs to be done for probabilistic assessment. Using Adaptive Mesh Refinement (AMR) speeds up the process by reducing computational demands, while accelerating the code using the GPU does so through using faster hardware. Combining both, we present an efficient CUDA implementation of GeoClaw, an open source finite volume numerical scheme on adaptive grids for SWE with varying topography. The utilization of the GPU Streaming Processors is measured to be up to 80%, which is significant since the computation power of the GPU is often hard to efficiently utilized due to the complexity of both its hardware and the programming model. Numerical experiments on an artificial and a realistic transoceanic tsunami show the validity and efficiency of the code. The GPU implementation, when running on a single GPU, is 3 to 5 times faster than the original model running in parallel on a 16-core CPU. With the code, the Japan 2011 Tohoku tsunami can be fully simulated for 13 hours in under 7 minutes wall-clock time, using a single NVIDIA K20 GPU. This is done with AMR that adequately resolves the waves propagating across the ocean, and with 60-meter resolution near Crescent City, CA, producing good agreement of simulation results with observed tide gauge records in this harbor.

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MS24

Numerical Modelling of High Temperature Geothermal Systems with a Soil-atmosphere Boundary Condition

The interaction between the flow in the porous medium and the atmosphere plays an important role in geothermal flows. Since the coupling between the porous medium and surface flows is not computationally realistic at the space and time scales of a geothermal flow, the objective is rather to model the soil-atmosphere interaction using an advanced boundary condition that accounts for the matter (mole) and energy balance at the interface. Such model should take into account the vaporization of the liquid phase in the atmosphere, the convective molar and energy transfer, a liquid outflow condition at seepage surfaces, as well as the heat radiation and the precipitation influx. The model is formulated using complementary constraints both for the soil-atmosphere boundary condition and the gas liquid equilibrium. It is discretized in space using the Vertex Approximate Gradient (VAG) scheme introduced for the discretization of multiphase Darcy flows by Eymard et al. in 2012. It is consistent on general meshes and very efficient on simplectic meshes thanks to its nodal feature. Moreover it has the advantage to avoid the mixing of rock-types at nodal control volumes. The discrete nonlinear systems obtained after Euler implicit time integration are solved at each time step using a Newton-min algorithm. The model and its discretization are applied to numerical modelling of the Bouillante high-energy geothermal field located in Guadeloupe.

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MS24

Analysing Spatial Scaling Effects in Mineral Reaction Rates in Porous Media with a Hybrid Numerical Model

Mineral reaction rates in porous media, i.e. precipitation and dissolution, usually exhibit spatial scaling effects. There is a tendency for apparent reaction rates to decrease as one moves from the pore scale through the laboratory scale to the field scale. Mathematical models at the Darcy scale are often incapable of capturing pore-scale reactive-transport processes. Geochemical reaction rates are known to be much lower in the field than when measured in the lab. Understanding and quantifying these scaling effects is one of the central challenges in the field of subsurface reactive transport. In a recently granted research project, we aim to circumvent this problem without compromising accuracy by developing a hybrid model which spatially couples micro- and macroscale models. In particular, we want to use a microscale model in those parts of the model domain where it is necessary to guarantee accuracy and a macroscale model throughout the rest of the domain. In terms of computational effort, particular attention will be paid to the applicability of the model to laboratory-scale processes, which will be achieved by representing the microscale with pore-network models. In this talk, we will present first steps undertaken in the development of the hybrid model.

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MS24

New Numerical and Physical Developments in Chemical EOR Simulation

I will present the latest developments in a mechanistic chemical EOR simulator. Significant advances have been made in chemical EOR in recent years including the development of hybrid methods that combine surfactants, polymers, alkali, co-solvents, gas and heat in novel ways. New and improved chemical and physical property models have been developed to more accurately simulate these processes on a field scale. A new formulation was developed, implemented and tested in a higher-order finite-difference chemical compositional simulator with enhanced chemical and physical property models coupled with a general purpose geochemical model and a general energy balance. Because of the need to include a fully coupled gas phase, the formulation is for four-phase flow. The chemical EOR methods include surfactant-polymer flooding, alkali-surfactant-polymer flooding, low-tension gas flooding, alkaline-cosolvent-polymer flooding, hybrid thermal-chemical processes including the use of electrical heating, wettability alteration processes including low salinity and low-salinity polymer flooding and chemical imbibition processes for naturally fractured reservoirs. New models have been developed and validated for microemulsion viscosity, viscoelastic polymers, multiphase flow relative permeability as a function of trapping number and contact angle.

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MS24

Parametrization Technique for Reactive Multiphase Flow and Transport

We present a nonlinear formulation for modeling reactive-compositional transport in the presence of complex phase behavior related to dissolution and precipitation in multiphase systems. This formulation is based on the consistent element balance reduction of the overall composition. To predict a complex phase behavior in such systems, we include the chemical equilibrium constraints to the multiphase flash calculations. Using the Equilibrium Rate Annihilation matrix allows us to reduce the governing unknowns to the primary set only while the coupling between chemical and thermodynamic equilibrium is captured by a simultaneous solution of flash equations. An input in this thermodynamic computation is an element composition of the mixture when an output contains fractions of components in each phase, including solids. The simulation of general practical models is performed using the recently developed Operator-Based Linearization (OBL) technique proposed for compositional problems. In the modified version of the OBL, the nonlinear element based governing equations are formulated in terms of space and state-dependent operators. These operators are adaptively parameterized in terms of pressure and molar element compositions based on the solution of the extended multiphase flash.

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MS24

Numerical Simulation Approaches for Modeling Natural Gas Hydrate Systems in Geologic Media Subject to Geomechanical Stresses

Natural gas, primarily methane, has accumulated in clathrate form in geologic deposits around the globe where pressure and temperature conditions are within the phase envelope for gas hydrate stability. Discoveries of these accumulations in arctic and deep-water marine environments have driven research in technologies for producing these accumulations of methane hydrates as a potential future energy resource. Gas hydrate systems are complex involving coupled thermodynamic, hydrologic, and geomechanical (THM) processes, and in geologic environments the pore space could potentially be concurrently occupied with a number mobile and immobile phases. Numerical simulation plays a vital role, in conjunction with laboratory experiments and field trials in overcoming the technical challenges of developing viable commercial-scale production approaches. Most recently, scientists and engineers have realized the critical importance of understanding the geomechanical changes that occur during the production of gas hydrates from geologic reservoirs, and the modeling community has responded with the inclusion of geomechanical capabilities into modern gas hydrate reservoir simulators. An international code comparison study is currently underway that is considering a suite of gas hydrate problems that involve coupled THM processes. This paper compares current numerical simulation approaches being applied by the scientific community to understand production of gas hydrate reservoirs.

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MS25

Sparsity in Multichannel Blind Deconvolution via Focusing Constraints

We introduce focusing constraints that resolve the inherent indeterminacy of multichannel blind deconvolution (BD). They facilitate the blind recovery of the sparse Green's functions from the seismic records that are contaminated with a single arbitrary source. Unlike the traditional regularization methods, the focusing constraints seek a solution where the Green's functions are: "maximally white" - encoded as the energy focusing near zero lag of their temporal auto-correlations; and "maximally front-loaded" - encoded as the energy focusing near zero time. This talk also demonstrates the benefits of Focused Blind Deconvolution (FBD) in drill-bit noise imaging, processing vibroseis data and source-time-function estimation of the earthquakes.

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MS25

Shaping Regularization

Shaping regularization is a general framework for solving inverse problems with constraints on the estimated model. Shaping can be considered as an alternative to the conventional optimization framework. Its advantages include a convenience in formulating model constraints and a faster iterative convergence observed in applications. I discuss shaping regularization in the context of seismic inversion and present examples of shaping constraints for preserving edges and structures in the geologic models and sparsity in the transform domain.

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MS25

TV-regularized Extended LS RTM

With an unphysical model extension, extended least-squares reverse time migration (LSRTM) can fit seismic data despite errors in the velocity model. We exploit this property of E-LSRTM, constrain the inversion using a total-variation regularization, and extrapolate the frequency content in the seismic data from the recorded bandwidth to lower frequencies. The resulting low frequency seismic gathers are used to perform full waveform inversion in order to solve for a better initial model.

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MS25

Challenges and Opportunities of Sparsity-promoting FWI

The focus of this talk is on practical aspects of sparsity-promoting and total-variation (TV) regularization in seismic inversion, especially full-waveform inversion (FWI). We will look at specific examples of L_1/TV regularization and ways of achieving computational feasibility of associated algorithms in applications to large-scale inversion of structural earth models with billions degrees of freedom. Computational feasibility often does not correlate very well with the theoretical convergence properties of employed algorithms. In our presentation, we discuss practical ways of bringing the cost of L_1/TV-regularized FWI closer to that of FWI with smooth objective functions. We present an overview of some of the more popular approaches to non-smooth optimization including, among other things, smooth approximation of non-smooth objective functions, direct application of differentiable optimization in non-smooth problems, primal-dual and splitting methods, and convergence acceleration such as Nesterov's method. Theoretical convergence properties versus early resolution of important model attributes is key to our choice of algorithms. We discuss a trade-off between the computational speed and memory requirements in a recent implementation of the accelerated Alternating Direction Method of Multipliers (ADMM), and discuss the opportunity space associated with the proposed algorithm in areas of applied geophysics, machine learning, and big data analysis.

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MS25

Adaptive ADMM with Spectral Penalty Parameter Selection

The *alternating direction method of multipliers* (ADMM) is a versatile tool for solving a wide range of constrained optimization problems. However, its performance is highly sensitive to a penalty parameter, making ADMM often unreliable and hard to automate for a non-expert user. We tackle this weakness of ADMM by proposing a method that adaptively tunes the penalty parameter to achieve fast convergence. The keystone of our approach is to analyze the dual of the ADMM problem, which can be written without constraints. The resulting *adaptive ADMM* (AADMM) algorithm, inspired by the successful Barzilai-Borwein spectral method for gradient descent, yields fast convergence and relative insensitivity to the initial stepsize and problem scaling.

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MS26

Reflection Full-waveform Inversion with Sliced Wasserstein Distance

Given observed data, full-waveform inversion aims at retrieving a model such that the misfit under some principle is optimized. To obtain a plausible model, we generally begin with low frequency data to update the long-wavelength part and which is succeeded by higher frequency data to update the short-wavelength. When the observed data have limited offset such that the diving wave cannot propagate to deeper area in an estimated model, only the shallow part of macro-velocity model is plausible. The accumulative inaccuracy in macro-model will drive the update of short-wavelength into an implausible minimum if the conventional full-waveform kernel used. One remedy for this issue is reflection full-waveform inversion. However, reflection full-waveform inversion still suffers from cycle-skipping. One of strategies is to measure the misfit based on optimal transport. Instead of solving a multi-dimensional optimal transport problem with demanding computation for seismic gathers, sliced Wasserstein distance can determine a transport plan trace by trace in the transformed domain in which the information from other dimensions is considered implicitly. The slicing operator such as Radon transform can also condition the data to highlight the events associated with subsurface property.

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MS26

An Inversion Strategy Based on Optimal Transport and Time-windowing for Elastic Anisotropic FWI

Surface wave poses big challenges for onshore elastic full waveform inversion. Their strong energy and shallow penetration lead FWI, in the conventional least-squares approach, to interpret mainly surface waves and to update the shallow part of the shear-wave velocity. Their slow propagation (short wavelengths) generate cycle skipping, yielding updates in the wrong direction. Hierarchical strategies have been proposed to deal with onshore seismic data, based on the interpretation of early body waves first, before including the surface waves in a second step. Although this method alleviates some of the difficulties associated with the interpretation of onshore data, we illustrate its limitations in realistic environment including anisotropy on a 2D synthetic test representative of the Middle East geology. In this presentation, we propose an alternative strategy using an optimal transport misfit function. We show that using the 1-Wasserstein distance, the energies between body waves and surface waves are naturally balanced. We combine this approach with a hierarchical strategy based on a smooth Gaussian-time windowing. Still, with the same Middle East model, we show that we are able to interpret the entire seismograms and to recover the anisotropic structure of the subsurface. Our inversion strategy is robust and is valid for other geological complexity, which we confirm by applying the same method to another anisotropic synthetic dataset based on the SEAM II Foothhil model.

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MS26

An Optimal Transport Approach to Inversion of P-wave Receiver Functions

P-wave receiver functions are time series obtained after deconvolving the vertical from the radial (or transverse) component of the P-wave coda, thus removing the source and travel path information. Their analysis is widely used by seismologists to make quantitative inferences about the structure below a seismic station. As these observables are mainly sensitive to travel times of phases converted and reflected at seismic discontinuities, the resulting inverse problem is highly non-linear, the solution non-unique, and there are strong trade-offs between the depth of discontinuities and absolute velocities. To overcome this difficulty, we propose to measure the misfit between the predicted and observed data with an optimal transport distance instead of the conventional least-squares distance, a strategy that has shown its assets in the context of full waveform inversion. We test the optimal transport approach on the inversion of a radial P-wave receiver function. The resulting misfit function is minimized with a local optimization algorithm to constrain the receiver-side structure. The benefits of this methodology are studied in synthetic tests and with real data. We show that with its increased sensibility to time-shifts, the optimal transport distance reduces the number of local minima in the misfit function, which in the case of a linearized inversion, significantly reduces the dependency to the starting model, and results in a better convergence towards the solution model.

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MS26

Full Waveform Inversion with Unbalanced Optimal Transport

In this work, we consider the cycle-skipping problem in the full waveform inversion(FWI). A novel approach is presented to impose the optimal transport (OT) metric and unbalanced OT on the seismic inversion problem. We advocate the use of the quadratic Wasserstein norm with an encoding procedure to measure the transport cost and a penalty term for the mass creation/destroy in the unbalanced OT. This approach improves the convexity of the misfit function. The new solution uses an encoding scheme with the logistic function to emphasize the phase information in the inversion. In our implementation of the adjoint state method, the adjoint source is calculated trace-wise based on the 1D Wasserstein distance. It results in an efficient and robust algorithm with a computational complexity proportional to the number of shots and receivers, and the length of the seismic records. Consequently, there is no substantially added cost to the FWI when compared to the conventional least-squares norm implementation. We demonstrate the effectiveness of our solution by using the synthetic velocity models.

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MS26

The Wasserstein-Fisher-Rao Metric for Waveform Based Earthquake Location

In our previous work [Chen el al., J. Comput. Phys., 373(2018)], the quadratic Wasserstein metric is successfully applied to the earthquake location problem. However, the seismic wave signals need to be normalized since the quadratic Wasserstein metric requires mass conservation. This brings a critical difficulty. Since the amplitude of seismogram at receiver is a good reflection of the distance between the source and the receiver, merely normalizing the seismic wave signals will cause the objective optimization function to be insensitive to the distance between the source and the receiver. When there is high-intensity noise, the minimum objective optimization function will deviate a lot, which will lead to low accurate location results. To overcome the aforementioned difficulties, we apply the newly developed Wasserstein-Fisher-Rao (WFR) metric [Chizat et al., Found. Comput. Math., 18(2018)] to the earthquake location problem. This metric does not require the normalization of the seismic signals. Thus, the amplitude of seismograms can be considered as new constraints. The sensitivity of the objective optimization function to the distance between the source and the receiver is substantially improved. As a result, we can expect more accurate location results from the WFR metric based model compare to the quadratic Wasserstein metric based model under high-intensity noise.

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MS27

Real-time Decision Making for Geosteering

To improve oil recovery, it is important to optimize the directional steering during drilling in response to downhole measurements and considering the uncertainty of the geomodel. The continuity of the drilling operation requires geosteering decisions on minute scale thus setting strong constraints on the performance of the optimization methods. We present a systematic geosteering workflow for decision support under uncertainty. The uncertainty is captured in an earth model represented as an ensemble of geological realizations. The realizations are updated each time new real-time measurements become available. Thereafter, the up-to-date ensemble of realizations is used as input for an approximate discrete dynamic programming (ADDP) optimization. For selected objectives the algorithm optimizes the well path for the complete drilling trajectory for each realization separately (avoiding local minima), and then combines these results for a recommendation for the next decision. This omits modeling of learning over future time and can be interpreted as an assumption that perfect information becomes available after the next decision has been made. The ADDP algorithm solves a typical global optimization problem in less than a minute. We use numerical examples to demonstrate the methods flexibility with respect to optimization constraints and objective functions. The results indicate that the methodology systematically suggests good decisions for a complete drilling operation.

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MS27

Decision Making under Uncertanty - Field Development: Results, Challenges and Learnings

In this paper we present our results, challenges and learnings, over a two year time period wherein robust multi-objective optimization is being applied at a North Sea asset which is being currently developed. Four different problems were solved with different objectives. These problems were formulated based on the phases of planning and development at the asset. The optimization problems include drilling order and well trajectory optimization as the main objectives with reduction in water cut and reduction of gas production to minimize flaring as secondary objectives. We use the efficient stochastic gradient technique, StoSAG, to achieve optimization incorporating geological and petrophysical uncertainty. For some problems computational limitations introduced challenges while for other problems operational constraints introduced challenges for the optimization. Depending on the problems significant increases between 5% and 20% in the expected value of the objective function were achieved. For the multi-objective optimization cases we show that non-trivial optimal strategies are obtained which significantly reduce (40% decrease) gas production with minimal loss (less than 1%) in the economic objective. Our results illustrate the need for workflows which are flexible to optimize different types and parameterizations of variables that are encountered at different stages of the planning and development cycle at an operational asset.

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MS27

The Full Structure of Reservoir Management

Petroleum production modeling, data assimilation, and optimization techniques for reservoir management (RM) have advanced dramatically over the past decade. However, having advanced tools is not sufficient as good framing of RM problems, which clarifies relationships among uncertainty, information, and decisions, is crucial for high-quality decision making under uncertainty and is essential to optimizing the economics of oil and gas fields. Many RM problems involve sequential decisionsafter a decision has been made, additional information is gathered, which is further used to inform the next decision. Solving the full sequential decision making problem can be computationally intensive, or even prohibitive, especially when reservoir simulation models are involved. Closed-loop RM is a state-of-the-art approach to incorporating new information in sequential reservoir decision making. It is computationally feasible but often sub-optimal as it significantly simplifies the structure of sequential decision making by ignoring the evolution of uncertainty into the future. We will illustrate and discuss the full structure of sequential decision making using decision trees. A scaled-down model will be used to demonstrate the suboptimality of closed-loop RM and the value of using approximate dynamic programming to solve the full sequential reservoir decision making problem. We will then discuss the challenges that need to be addressed in future studies.

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MS27

Value of Sequential Information in Mud Weight Window Assessment

For safe and economic drilling operations, decision makers must study the risks of tight-hole or stuck-pipe with consequent loss of time and money, and risks of mud losses that can lead to blow out. Having an accurate mud weight window is extremely important in this context. We use PSI, a software developed by Sintef, to generate samples of the MWW in a shale formation. These samples are achieved by varying the inputs (wellbore data, formation conditions, and formation properties). We then run sensitivity analysis to study the effects of the input parameters. It turns out that Pore pressure (Pp) and UCS are the most sensitive, with largest main effects and interaction effect. We build a stochastic model (Gaussian process) for Pp and UCS, based on the available pre- drill information in the area, and we fit a surface for the MWW as a function of PP and UCS. We now study how gathering more data can improve our knowledge on MWW. This is done in a sequential framework, meaning that while we go down in the well and more information gets available, we decide if it is worthwhile to acquire all of them at the next stage, just some, or none. The calculations are based on the MWW predictions and the associated level of uncertainty we have obtained up to that depth. The value of this new information can be seen as a trade-off between drilling speed and costs / risks of possible accidents.

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MS27

Decision Analyses for Contaminant Remediation

Modeling flow and transport in aquifers presents a number of challenges including large datasets that contain limited information about the properties of the subsurface and complex models with a large number of parameters characterizing the properties of the subsurface and the hydrologic conditions (e.g., groundwater recharge, pumping, extraction). This leads to substantial uncertainty in predictions about quantities of interest (e.g., the concentration of a contaminant at points of compliance). We have developed a number of methods and tools to address these problems related to model calibration, uncertainty quantification, and decision support. The model calibration tools are capable of assimilating large calibration datasets (on the order of a million) a large number of model parameters (on the order of a million). The uncertainty quantification tools are highly-parallel and enable us to robustly quantify the uncertainties in model parameters (and therefore uncertainty in quantities of interest). The decision analyses utilize our recently developed Bayesian-Information-Gap Decision Theory. Having these capabilities in model analysis tools enables more informed decision making related to remediation of groundwater contaminants. The model analyses that we present are related to the Los Alamos National Laboratory (LANL) chromium site. The analyses are performed by using our open-source code MADS (Model Analysis & Decision Support; http://mads.lanl.gov).

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MS28

Coupling Virtual Element Methods and Finite Volume Schemes for Computational Geomechanics on General Meshes

The classical way to numerically solve a poroelastic model is to use one discretisation method for each conservation equation, usually with a finite element method for the mechanical part and a finite volume method for the fluid part. However, to capture specific properties of underground media such as heterogeneities, discontinuities and faults, meshing procedures commonly lead to badly shaped cellsfor finite element based modelling. To overcome this problem, we are interested in replacing the finite element method by the virtual element method (VEM), which works on general polyhedra and thus appears to be much more robust regarding the spatial discretisation. Indeed, [Andersen, Nilsen, Raynaud 2017] provided a first insight into VEM applied to the elastic problem in the context of geomechanical simulations. The originality of our work is to design and study a numerical scheme coupling VEM applied to the mechanical conservation equation with a finite volume method applied to the fluid conservation equation. A mathematical analysis of this original coupled scheme is provided, including existence and uniqueness results and a priori estimates, for the case of a two points finite volume scheme modelling of fluid flow. In addition, the coupling with more elaborate finite volume schemes such as multi point flux approximation schemes is investigated. The coupled scheme is illustrated by some computations on two or three dimensional grids coming from realistic cases.

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MS28

An Upscaled Model for Solute Transport in Fractured Media with Advective Trapping

Direct numerical simulations for prediction of transport processes in fractured rock is often computationally too expensive and upscaled models are used instead. In double porosity models, the transport is only described explicitly in the fracture continuum, while the rock matrix is described as a storage continuum. The mass transfer between these continua can be described by a multi rate mass transfer model. To have predictive models, it is crucial to relate the model parameters to the transport processes and to the properties and geometry of the fractured rock. Advection and diffusion have to be considered separately for this purpose. We discuss the formulation of a multi rate mass transfer model for advection dominated transport in the matrix blocks as a first step towards a predictive multi rate mass transfer model in a binary medium that captures advection and diffusion. Simple periodic patterns of spherical inclusions can be treated in a straight forward manner, as there are two transport times, which are clearly distinct. Already this simple binary structure with deviations from the periodic pattern leads to a broad distribution of transport times, which reveals a true multi rate mass transfer behavior. We discuss the parameterization of a multi rate mass transfer model with advective trapping for different geometry of the medium from simple patterns to complex networks and demonstrate the upscaled model with numerical test cases.

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MS28

Derivation of Effective Models for Unsaturated Flow in Fractured Porous Media

We consider a mathematical model for unsaturated flow in a porous medium containing a fracture. The flow in the fracture and in the matrix blocks is governed by the Richards equation. At the common interfaces, the models in each sub-domain (the matrix blocks and the fracture) are coupled by transmission conditions reflecting the continuity of the normal flux and of the pressure. After proving the existence of a solution for a fixed fracture width, we analyse the convergence towards effective models in the limit case when the fracture width goes to 0. Depending on the ratio of different parameters (porosity and permeability) in the sub-domains when compared tot the ratio of the fracture width and length, we derive different effective models. Numerical simulations confirm the theoretical upscaling results.

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MS28

Two-phase Flows in Porous Media with the Multiscale Robin Coupled Method

The Multiscale Robin Coupled Method (MRCM) is a domain decomposition method that has been developed to efficiently approximate velocity and pressure fields for single-phase flows in highly heterogeneous porous media. We propose the generalization of the MRCM for two-phase flows in fully saturated porous media, solving the coupled nonlinear system by operator splitting. The choice of parameters for the MRCM is thoroughly investigated, demonstrating its accuracy compared to other popular methods.

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MS28

Sparse Grid Approximation of Elliptic PDEs with Lognormal Diffusion Coefficient

This talk is concerned with efficient sparse grid approximations of u, solution of an elliptic PDE whose diffusion coefficient is modeled as a lognormal random field. In the first part, we build upon previous works available in the literature to establish a convergence result (in L^2 norm in probability) for the approximation of u by sparse collocation with Gauss-Hermite points. More specifically, we first link the error to the size of the multi-index set defining the sparse collocation and then derive a bound on the number of points in the associated sparse grid. The result of the analysis is an algebraic convergence rate of the approximation error with respect to both the size of the multi-index set and the number of points in the sparse grid; interestingly, the analysis gives also an explicit a-priori estimate of the optimal multi-index set. We validate the results by numerical tests in which we consider a family of random fields parameterized by a coefficient that sets the spatial smoothness of the field. As expected, the convergence rate for very rough fields turns out to be quite slow, even for optimized grids (be it the above-mentioned a-priori grids or the classical a-posteriori-adaptive grids). Thus, in the second part of the talk, we propose a remedy based on using the solution of the PDE on a smoothed version of the random field as control variate for a Monte Carlo sampling of u.

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MS29

Perturbative Theory of Flow-driven Deformation of Small Pores

An internal flow within a conduit with a soft boundary presents an example of a fluid–structure interaction (FSI). For example, such an FSI might arise from the flow-driven deformation of a small capillary in a deformable porous medium during hydraulic fracturing. Key synthetic experiments have shown that deformation leads to a nonlinear relationship between the volumetric flow rate and the pressure drop (unlike Poiseuilles law) at steady state. I will discuss our recent advances in deriving such relations via perturbative analysis of coupled flow–deformation problems. Specifically, the governing equations for vanishing Reynolds number (of either a Newtonian or a non-Newtonian) fluid flow can be coupled to the governing equations of an elastic rectangular plate (e.g., Kirchhoff–Love) or cylindrical shell (e.g., Donnell–Sanders). The perturbation expansion requires that a thin, slender geometry. Several mathematical predictions arise from this approach:

the flow rate–pressure drop relation, the cross-sectional deformation profile of the deformable conduit, and the scaling of the maximum displacement with the flow rate. These prediction are then verified through 3D two-way coupled direct numerical simulations of FSI using the commercial software suite ANSYS.

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MS29

Analytical, Numerical and Geometric Methods with Applications to Fractured Porous Media Modeling

In this work, we analyze the flow filtration process of slightly compressible fluids in porous media containing man made fractures with complex geometries. We model the coupled fracture-porous media system where the linear Darcy flow is considered in porous media and the nonlinear Forchheimer equation is used inside the fracture. We develop a model to examine the flow inside fractures with complex geometries and variable thickness. The fracture is represented as the normal variation of a surface immersed in $\mathbb{R}^3$. Using operators of Laplace Beltrami type and geometric identities, we model an equation that describes the flow in the fracture. A reduced model is obtained as a low dimensional BVP. We then couple the model with the porous media. Theoretical and numerical analysis have been performed to compare the solutions between the original geometric model and the reduced model in reservoirs containing fractures. We prove that the two solutions are close, and therefore, the reduced model can be effectively used in large scale simulators for long and thin fractures with complicated geometry.

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MS29

Fully Coupled Geomechanical and Dynamic Reservoir Simulations

Abstract not available.

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MS29

A Power Law Analysis of Non-Newtonian Fluid Flow through Porous Media

The flow of non-Newtonian fluids through porous media have frequently been modeled using power law assumptions. Previous workers have presented correct flow equations but their solutions are valid only for large flow behavior index and require long term data for validation. The analytical technique presented here requires no additional assumptions or limitations and may be applied to flow behavior index at any value. The technique can be used to successfully estimate the in situ flow behavior index (n), skin factor and effective mobility of the fluid. An estimate of permeability can also be obtained if the consistency parameter (H) is known from laboratory experiments. The new technique was applied to severa sets of published field data and two sets of simulated data. This study shows that previous established techniques had underestimated formation permeability by more than 40%.

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MS29

Approximate Analytical Solution to the Groundwater Flow in Unconfined Aquifers

Flows near wells in unconfined aquifers are commonly modeled by the Boussinesq equation or by the Porous Medium Equation (PME). In this talk we consider a recharge of an initially dry aquifer. For certain types of the initial and boundary conditions such problem for partial differential equation can be rewritten using similarity variables in a form of a boundary-value problem for an ordinary differential equation. We construct an approximate analytical solution to this problem. The approximate solution has a polynomial part and a singular part. One to model the behavior near the leading front and the other to represent the behavior near the well.

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MS30

Impact of Highly Transient Boundary Conditions on the Groundwater Flow Field and its Implication for Mixing

The influence of heterogeneity occurring in natural porous media on spreading, dilution and mixing processes has been widely recognized in the literature, while less attention has been dedicated to investigating the influence of highly transient boundary conditions on the transport of contaminants in the subsurface. In general, mixing in Darcy flows is inefficient, but it can be greatly enhanced by transient conditions, which are commonly encountered in the environment. This work focuses on the case where the boundary conditions of the problem are represented by two rivers and the hydraulic head fluctuates at multiple temporal scales due to seasonal and anthropogenic (i.e., water management) reasons. To study how such fluctuations may modify the topology of the groundwater flow field and thus transport processes, we modeled a cross-section of the aquifer at the Adige Valley (Italy) and prepared two transient models at hourly and daily time scales. Motivated by this case study, we additionally created different scenarios (e.g. different hydraulic conductivity of the riverbed or considering wet/dry conditions) and characterized the flow field considering various topological and kinematic indicators of mixing enhancement. Finally, we identify the most sensitive model parameters and provide suggestions for tailored field investigations.

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MS30

Uncertainty Quantification and Sensitivity Analysis in Reservoirs with Fractures

A fracture is a heterogeneity in a porous medium with small width relative to its length. Due to their small width and a lack of grid resolution, fractures are often modeled as lower dimensional surfaces within the reservoir. A parameter known as the transmissibility multiplier of the fracture is introduced into the model to account for the change in permeability across the fracture. Often, these transmissibilities are unknown and must be inferred from data such as pressure at the wells. In this work, we apply a recently developed method for parameter estimation in inverse problems called the consistent Bayesian approach [T.Butler, J. Jakeman, and T. Wildey, A consistent bayesian formulation for stochastic inverse problems based on push-forward measures, 2017] to reservoir models with fractures. The model under consideration is a two-phase flow model in which the phases are assumed to be oil and water. The inversion targets are the fracture transmissibilities and the observed data are pressure and water saturation measurements taken at the injection and production wells of the reservoir. We investigate how different well spot patterns and fracture geometries affect recovery of the transmissibilities. We also show how the recovered values of fracture transmissibilities can be used to predict unknown quantities of interest within the reservoir.

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MS30

Fast and Scalable Joint Subsurface Inversion using Hydrological-geophysical Datasets with a Parallel Black-box Fast Multipole Method

Subsurface properties such as permeability can be better characterized when using both hydrological and geophysical data sets, due to differences in e.g. sensitivity and the underlying physics. However, a large number of hydrological and geophysical measurements with fine model discretization, requires prohibitive computational costs for carrying-out simultaneous subsurface flow and transport modeling and geophysical forward model simulations, even in high-performance computing environments. In this work, we use a recently developed parallel Fast Multipole Method, PBBFMM3D, to solve the joint inverse problem efficiently by accelerating high-dimensional covariance matrix-vector products and reducing the number of forward model runs. The proposed joint inversion method only requires $\sim$O(100) hydrogeological and geophysical forward model runs, while delivering an inversion result that is close to the one obtained from an adjoint-based approach, which usually requires forward model runs proportional to the number of measurements.

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MS30

Accelerating Prediction under Uncertainty for Groundwater Problems

Making predictions under uncertainty for groundwater flow and transport often involves solving stochastic inverse problems that have high-dimensional spaces of input parameters. Furthermore, the solution spaces of underlying forward problems are also often high-dimensional. This high-dimensionality may cause the problem of making a prediction under uncertainty extremely computationally expensive and possibly infeasible with traditional methods. We combine methods to effectively reduce the dimension of input parameter spaces and to reduce the dimension of the PDE solution space to accelerate predictions under uncertainty that are suffering the curse of dimensionality. These methods include active subspaces, reduced basis approximations, and model order reduction. Additionally, adaptivity is incorporated to further increase accuracy without greatly increasing the computational costs.

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MS30

Emulating Mesoscale Physics in Subsurface Systems through Machine Learning

We demonstrate the use of machine learning in emulating, with uncertainties, complicated mesoscale physics for modeling subsurface flows. Real time predictions often require solving multi-scale physics based models. However, complex models with coupled multi-scale physics require a lot of computational resources. We describe a new framework to emulate the fine scale physics using machine learning and showcase its usefulness by providing an example from modeling fracture propagation that are prevalent in subsurface geology. Such an approach can be thought of as a data driven dimension reduction technique, we differ from current approaches by describing a physics informed probabilistic framework for the emulator.

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MS31

Model-order Reduction of Coupled Flow and Geomechanics in Unconventional Reservoirs

Global model reduction has been applied extensively in reservoir simulation to mitigate the high computational cost of multiphase flow but, its application to combined multiphysics, as in the case of flow and geomechanics, has been minimal. This work focuses on the development of accurate and fast simulation models for Ultra-Low Permeability (ULP) reservoirs, i.e., tight-sands and shales. We rely on projection-based Model-Order Reduction (MOR) techniques, namely POD-DEIM to reduce the ULPs computational burden. The usage of global basis is not convenient to tackle problems characterized by different regimes, i.e., depletion/build-up. Also having many snapshots to capture all these variations is unfeasible. We thus develop a strategy based on local POD basis to reduce one- and two-way coupled flow and geomechanics computations. Preliminary results focused on linear and nonlinear thermo-poroelasticity, show that our MOR algorithm provides substantial single and double digits speedups, up to 50X if we combine with multi-threading assembling and perform MOR on both physics.

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MS31

Numerical Upscaling of Perturbed Diffusion Problems

We consider elliptic partial differential equations with rapidly varying diffusion. In particular we study efficient solution techniques for problems where the diffusion is perturbed from a reference configuration. The goal is to develop an efficient numerical method for solving multiple perturbed problems by reusing local fine-scale computations. The proposed method is based on the Petrov–Galerkin Localized Orthogonal Decomposition (PG-LOD) method which is a generalized finite element method with multiscale shape functions in the trial space [Engwer, Målqvist, Henning, Peterseim, Efficient implementation of the Localized Orthogonal Decomposition method]. We focus on two types of perturbations. Firstly local defects which we treat by local recomputation of multiscale shape functions. Secondly we consider global mappings of a reference configuration, for which we apply the domain mapping method to map the problem back to a reference configuration. We analyze the proposed method for these problem classes and present several numerical examples.

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MS31

Nonlinear Nonlocal Multicontinua Upscaling Method

We are going to present a non-local upscaling methods for non-linear multiscale problems. This method is an extension of the recently developed non-local multicontinuum (NLMC) method. The main idea of this approach is to calculate some upscaling parameters or muliscale basis functions by solving a constrainted local problem. There are two approaches to handle the nonlinearity of the problem. The first approch is constructing the multiscale basis functions by solving a constrainted non-linear problem. Then the solution is approximated a linear span of these basis functions. This approach is easy to implement but it lacks the nonlinear interpolation. For the second approch, we will develope a nonlinear coarse scale model by calculating the upscaling parameter by solving a constrainted non-linear problem. We present some numerical result for both of the approches to demonstrate the performance of the method.

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MS31

Using Pore Scale Simulations to Improve Continuum Modeling of Straining of Particulate Suspensions in Porous and Fractured Media

Using pore scale simulations to improve continuum modeling of straining of particulate suspensions in porous and fractured media Porous and fractured materials are notorious for their geometrical complexity, that results in flow nonlinearities that are often difficult to upscale. This is especially true for complex fluids such as particulate suspensions. Depending on the size of particles, fluid properties such as density and viscosity, and possibly surface forces, the particles could flow with the fluid, or get captured either at the solid surface or get stuck in the narrow parts of the pore space (also known as straining). As particulates are also not necessarily permanently captured, this phenomenon is very difficult to correctly handle in continuum equations. In particular, continuum conservation laws predict particulate front moving through the medium that is not necessarily observed in simulations or experiments. We show how we use pore scale simulations of straining to improve the continuum scale model. This is joint work with Dr. Maryam Mirabolghasemi and Min Zhang.

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MS31

Darcy-Brinkman-Stokes Framework for Modeling of Reactive Dissolution

We present a framework for modeling of acid stimulation in the near-well region. The dissolution of rock material can lead to a situation when some of the simulation control volumes have values of porosity close to 1. One way to correctly deal with that is to perform a domain decomposition where micro-scale Stokes-type equations are used in the high-porous regions, while upscaled Darcy-type equations are employed elsewhere. Alternatively, to avoid the complications related to the tracking of the moving boundary between the two regions, a unified Darcy-Brinkman-Stokes (DBS) equation can be used. Based on the current flow parameters, DBS automatically switches from upscaled description to micro-scale model. To avoid the exhaustive computational costs, we apply an adaptive algorithm that comes down to a pure Darcy description when Brinkman correction is small. For chemical reactions, we propose a local nonlinear solver for the solid species balances so that they can be treated separately yet retaining the full coupling with the rest of the equations. We demonstrate simulation results for several models of practical interest, including modeling of dissolution in real core samples.

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MS32

Numerical Modeling of Fault Activation and Induced Seismicity in Gas Storage Reservoirs: The Netherlands Case

Subsurface withdrawal and/or injection of fluids has raised a growing alarm on the possible risk of induced/triggered seismicity. In case of conventional reservoirs, the seismicity can be connected to the possible re-activation of existing faults, caused by the variation of the natural stress regime induced by the mining operations. In this work, an original modelling approach is developed to investigate the conditions that are more likely to produce a fault reactivation in the typical geological setting of Dutch reservoirs used for gas storage purposes. The inception of fault motion is numerically simulated by a Lagrange multiplier-based formulation for prescribing the contact constraints in a geomechanical Finite-Element model. The numerical model proves mathematically stable and allows for locating the fault portions that can move and estimating the size of the activated area and the amount of expected slip. The influence of several different factors is analyzed, such as: (i) geometrical configuration, (ii) initial stress regime, (iii) rock mechanical properties, (iv) pore pressure distribution, and (v) presence of a salt caprock. The outcome of this research project will contribute to the definition of a safe operational bandwidth for gas storage activities in The Netherlands.

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MS32

Data Assimilation for State Estimation of Fault Behavior

Probabilistic forecasts of seismicity can benefit from assimilation of near-surface and indirect geophysical observations. A recent study using the Ensemble Kalman Filter (EnKF) demonstrates the effectiveness of data assimilation in seismic cycle models to improve state estimation of fault behavior in subduction zones. Likewise, data assimilation has the potential to improve the simulation of pre-existing fault behavior at a smaller scale, induced by industrial activity. As an alternative to the EnKF, we investigate the use of the Particle Filter. Identical twin experiments demonstrate the effectiveness of both methods in a perfect model test in a Seismo-Thermo-Mechanical (STM) model. With the aid of synthetic observations at a single point, located just below the surface, the data assimilation methods update five state variables: horizontal- and vertical velocity, normal- and shear stress, and pressure. In addition to constraining model uncertainties, data assimilation can also help to identify which observations provide the most valuable information for forecasting. As a first step towards such a value-of-information study, we compare the assimilation of (combinations of) different observation types. Depending on the choice of observations and ensemble generation, the methods are able to reproduce the stress and pressure at the observation location. We discuss the implications of the STM-model results for models of induced fault reactivation.

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MS32

Linking Oklahoma Seismicity and Saltwater Disposal with a Hydromechanical Rate and State Fric-

tion Model

The earthquake activity in Oklahoma and Kansas that began in 2008 reflects the most widespread instance of induced seismicity observed to date. We develop a reservoir model to calculate the hydrologic conditions associated with the activity of 902 saltwater disposal wells injecting into the Arbuckle aquifer. Estimates of basement fault stressing conditions inform a rate-and-state friction earthquake nucleation model to forecast the seismic response to injection. Our model replicates many salient features of the induced earthquake sequence, including the onset of seismicity, the timing of the peak seismicity rate, and the reduction in seismicity following decreased disposal activity. We present evidence for variable time lags between changes in injection and seismicity rates, consistent with the prediction from rate-and-state theory that seismicity rate transients occur over timescales inversely proportional to stressing rate. Given the efficacy of the hydromechanical model, as confirmed through a likelihood statistical test, the results of this study support broader integration of earthquake physics within seismic hazard analysis.

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MS32

An Embedded Discontinuity Model for the Simulation of Fracture Deformations in Enhanced Geothermal Reservoirs

Changes in reservoir temperature and pressure due to the injection and production of fluids can result in deformations in the subsurface. Induced stresses are of high importance particularly in geothermal reservoirs, which are subjected to long-term cold water injection. The strong coupling between pressure, temperature, and deformations can lead to the substantial slip and opening of natural and induced fractures, which in turn can significantly affect the hydraulic properties of the fractures. The objective of this study is to develop an efficient numerical method to model the interaction of fluid flow and heat transport in fractures and fracture deformations. We first present a mathematical formulation based on the Strong Discontinuity Approach (SDA) for mechanics and Embedded Discrete Fracture Model (EDFM) for flow and heat transport. We then introduce a series of mechanical tests that investigate the spatial convergence of the model and compare its accuracy with the Discrete Fracture Model (DFM). We finally consider a synthetic case of a geothermal reservoir and compare the performance of the SDA and DFM methods. Our results indicate super-linear spatial convergence and quadratic convergence in a damped Newton scheme for the proposed SDA algorithm. Numerical simulations confirm the applicability of the proposed method to modeling the coupling effects in subsurface applications.

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MS32

A Geomechanical Workflow for Simulation of Fault Reactivation: Numerical Issues and Applications

We develop a geomechanical workflow to solve different numerical and physical complexities connected to the simulation of fault reactivation. The workflow includes two different branches: Fault Slip Probability (FSP) and Fault Reactivation Modeling (FRM). FSP focusses on the quantification of the uncertainty of some variables on the slip tendency. FSP is used after a continuum geomechanical simulation where the faults are not explicitly present into the computational grid. This step is fundamental before shifting to fault reactivation modeling, because it allows the selection of the critical faults, avoiding large computational costs. FRM is devoted to the simulation of fault reactivation. An ad hoc mesher is developed in order to manage different types of fault intersections. The nodes of a single fault are split to generate two contact surfaces. The tractions between the two surfaces are then modeled by Lagrange multiplier in the finite element code. Different friction laws are implemented to simulate the evolution of fault slip after the failure. For instance, the rate-and-state friction law allows us to simulate both stick-slip deformation (earthquakes) and creeping (aseismic) fault slip. In addition, it allows to simulate the entire seismic cycle. In this presentation we show the applicability of the workflow both to simulate natural and human-induced earthquakes underlining some numerical issues and challenges.

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MS33

Advanced Simulation for Strongly Coupled Non-isothermal Flow and Geomechhanics for the Gas Hydrate Deposits

Coupled flow and geomechanics become an important topic for development of the gas hydrate deposits, considered as one of the potential future energy resources. Geological failure and substantial subsidence induced by dissociation of gas hydrates become problematic in production facilities and wellbore. In addition, depressurization, a typical method for gas production from the gas hydrates, in the deep oceanic deposits such as the Ulleung Basin causes significant compaction and large deformation. The field-wide simulation requires large-scale simulation, such as parallel computing. Thus, careful consideration of coupled flow and geomechanics is necessary for predicting behaviors of the gas hydrate deposits. We have been developing a reliable coupled flow-geomechanics simulator for development of gas hydrate deposits. This simulator is based on the fixed-stress sequential method, being unconditionally stable in two-way coupling. We focus on parallel computation, finite strain geomechanics for large deformation, fracturing induced by secondary hydrate formation, and wellbore stability. By using this developed advanced simulator, we will present the various numerical results including a specific field-scale simulation.

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MS33

Multiscale Preconditioning Strategies for Coupled Poromechanics

Present work focuses on accelerating the numerical solution of Biot's poroelasticity equations governing fluid flow and deformation in heterogeneous porous media. Spatial discretization employing finite elements for mechanics and finite volume for flow and backward implicit time integration lead to a sequence of block linear system to be solved at every time step. A two-stage preconditioning strategy is proposed to accelerate the convergence of a Krylov subspace solver. In the first (global) stage a set of multiscale basis functions for the displacement and pressure fields is used to construct a coarse-scale coupled system and interpolate the coarse solution onto the fine scale, effectively damping low-frequency error modes. The second (local) stage deals with high-frequency error modes via a block-triangular smoothing operator that decouples pressure and displacement unknowns through a fixed-stress approach. Several numerical examples are used to demonstrate the robustness and scalability of the proposed preconditioner.

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MS33

An Extended Fixed Stress Split for Nonlinear Coupling Between Flow, Transport and Geomechanics

In this talk we present some extensions of the fixed stress split scheme for flow in deformable porous media to the case of noninear coupling. Among the extensions we highlight the development of a new methodology for sequential coupling in the multi-phase flow case. Moreover we discuss generalization of the scheme to the case where the rock displays nonlinear plastic behavior ruled by an stress state different from Biot's effective stress.

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MS33

Coupling Geomechanics and Flow in Porous Media

Iterative methods for solving coupled flow and geomechanics have gained popularity in the last two decades for their simplicity and numerical efficiency. They are based on decoupling the equations using an intermediate sub-step; the flow, or the geomechanics, equations are solved first to obtain a solution for the other problem. This procedure is repeated at each time step until the solutions of the two problems converge to an acceptable tolerance. In this work, we consider a fixed- stress split algorithm to decouple the displacement equations from the flow equations for a large scale Biot system. The pressure flow equations are discretized by a mixed finite element method (MFEM) or enriched Galerkin (EG) and the elastic displacement equations arediscretized by a continuous (CG) or EG. A priori error estimates are derived with the expected order of accuracy provided the algorithm is sufficiently iterated at each time step. These error indicators are implemented in a large scale reservoir simulator (IPARS). A posteriori error estimators are also derived and implemented to help choose suitable mesh refinement. Numerical simulations are presented to confirm the theoretical results.

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MS33

A Generalized Framework to Couple Reservoir and Geomechanics Simulators for Full-field Poromechanics Modelling

We present a generalized framework to couple a standalone reservoir simulator and an external geomechanics tool in a highly efficient yet minimally intrusive manner. We target at full-fidelity applications where the existing reservoir and geomechanics models do not need to be simplified for coupling purposes. An API is developed to coordinate the simulation process and data exchange with a globally mass conservative mapping layer that interpolates and passes data through memory between the two simulators, allowing their meshes and local domains to be non-aligned. Through the API, pressures and fluid body forces are passed to the geomechanics system, while the porosity, pore compressibility, and permeability multipliers are passed back after the geomechanics solution to update the flow solution. By controlling the direction and frequency of the data exchange and convergence criteria, we can achieve one-way, two-way explicit and iterative coupling schemes. The coupled simulator is first validated by replicating results for a model problem from the literature. We then use a reservoir model with stress-dependent permeability to illustrate the significance of permeability coupling for stress-sensitive reservoirs. The third case is a synthetic, large scale, and highly heterogeneous reservoir model with both aligned and non-aligned meshes. It demonstrates good parallel scalability and excellent efficiency and accuracy in interpolating and exchanging data.

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MS34

A Non Linear Preconditioner for Coupling Transport with Chemistry in Porous Media

Coupling transport and chemistry in porous media is a challenging task of importance in various applications. Under a local chemical equilibrium assumption, it leads to a large non-linear system of advection-diffusion PDEs coupled with algebraic equations. We have previously proposed a coupled formulation that allows a separation of transport and chemistry at the software level, while keeping a tight numerical coupling between both subsystems. The coupled system, written as a fixed point problem, is solved by a Newton-Krylov method, with a block Jacobian computed from the individual sub-systems. The Krylov solvers can stagnate, and preconditioning is necessary to improve convergence. In this talk, we present an alternative formulation, based on eliminating some unknowns, that acts as a non linear preconditioner for accelerating the convergence of the method. We compare this formulation with linear preconditioners like block Gauss-Seidel or block Jacobi. It is observed that both linear and nonlinear convergence become independent of the mesh size. The methods are applied to the MoMaS benchmark.

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MS34

A Posteriori Error Estimates and Adaptive Stopping Criteria for Compositional Two-phase Flow with Nonlinear Complementarity Constraints

In this work we develop an a-posteriori-steered algorithm for a compositional two-phase flow with exchange of components between the phases in porous media. As a model problem, we choose the two-phase liquid-gas flow with appearance and disappearance of the gas phase. The discretization of our model is based on the backward Euler scheme in time and the finite volume scheme in space. The resulting nonlinear system is solved via an inexact semismooth Newton method. The key ingredient for the a posteriori analysis are the discretization, linearization, and algebraic flux reconstructions allowing to devise estimators for each error component. These enable to formulate criteria for stopping the iterative algebraic solver and the iterative linearization solver whenever the corresponding error components do not affect significantly the overall error. Numerical experiments are performed using the semismooth Newton-min algorithm as well as the semismooth Newton–Fischer–Burmeister algorithm in combination with the GMRES iterative linear solver to show the efficiency of the method.

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MS34

Modelling Coupled Phase Transitions in Gas Hydrate Geosystems

Gas hydrates are one of the most complex porous geosystems which are characterised by a large number of strongly coupled multiphysics processes. One of the main challenges in modelling gas hydrate geosystems is the complex phase transitions: methane hydrate $\longleftrightarrow$ gaseous methane $\longleftrightarrow$ dissolved methane. These phase transitions are strongly coupled through nonlinear source and sink terms and are extremely sensitive to local temperature, pressure, and salinity conditions. To handle these phase transitions in a consistent manner, we cast the phase transitions as nonlinear complementary constraints and develop a semi-smooth Newton scheme based on an active set strategy. Here we present our numerical scheme and show its robustness through field scale applications based on the highly dynamic geological setting of the Black Sea, where we analyze the hydrate destabilization due to rising sea temperatures and resulting and gas migration through the gas hydrate stability zone.

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MS34

Close-contact Melting in Ice - Modeling and Simulation of Phase-change in the Presence of a On-local Pressure Constraint

This work focuses on melting processes in the presence of contact forces. In ice these are relevant for understanding the development of cryoconite holes, or for determining the dynamics of thermal melting probes for ice in-situ exploration [Schüller K., Kowalski J., 2019: Melting probe technology for subsurface exploration of extraterrestrial ice - Critical refreezing length and the role of gravity, Icarus, 317, 1-9.]. The underlying multiphysics process is also referred to as close-contact melting. Its challenging aspect is the existence of two spatial scales, one associated with macro-scale conductive processes, and a second associated with the micro-scale melt film, which is subject to a nonlocal pressure constraint. A single computational model that resolves both scales directly is infeasible. We therefore propose an efficient hybrid approach coupled through a generalized boundary condition. At first, we will discuss the process's thermodynamic regime and describe how this gives rise to a two-scale mathematical model with constraints. We describe a numerical scheme for the microscale [Schüller K., Kowalski J., 2017: Spatially varying heat flux driven close-contact melting - A Lagrangian approach: International Journal of Heat and Mass Transfer, 115, Part B, 1276-1287.], and more recent work on a numerical coupling strategy that allows us to hybridize micro- and macro-scale. Finally, we will present and discuss simulation results.

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MS34

Stability Analysis and Solvers for Phase Transitions in Hydrate Formation

Gas Hydrate is an ice-like crystal which consists of a gas molecule inside the water cage which forms in the gas hydrate stability zone (GHSZ) of high enough pressure and low enough temperature conditions. We consider the methane hydrate formation associated with continuous supply of methane gas due to microbial activity or the methane fluxes from below the sediment. When the mass fraction of methane gas exceeds its maximum solubility which depends on the spatial variable at the specific temperature and pressure, any excessive methane gas would form methane hydrate in GHSZ. Outside GHSZ, the excessive methane gas would remain in the gas phase. The comprehensive model is very complex and difficult to analyze. Our (simplified) model is a conservation law of mass with challenges in the multivalued constraint graph and the nonsmooth space-dependent flux functional. In this presentation, we discuss the theoretical analysis of convergence of the numerical solution to this problem, with experiments which confirm the analysis. We also discuss the local phase behavior solver including extensions to the gas hydrate equilibria for the mixture of methane gas and air using the Peng-Robinson cubic equation of state.

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MS35

Edge-preserving FWI via Regularization by Denoising

The primary objective of Full Waveform Inversion (FWI) is to estimate high-resolution physical properties of geological structures by minimizing the data misfit between observed and modeled seismogram. In spite of its success, the application of FWI in areas with high-velocity contrast remains a challenging problem. Often, quadratic regularization methods are usually adopted to stabilize inverse problems. Unfortunately, edges and sharp discontinuities are not adequately preserved by quadratic regularization techniques. For models with high-velocity contrast where edges of the model were to be adequately reconstructed, an L1 norm regularization is needed. Here, we propose a regularization by denoising technique to extend the Full-Waveform Inversion formulation for models with high-velocity contrasts. One advantage of the regularization by denoising algorithm in FWI is easy to implement. The regularization by denoising technique only requires an image denoising engine to handle the structure of the inverse problems. Our image denoising engine is the primal-dual Total Variation regularization method. We present the BP/EAGE velocity model, where large velocity contrasts and complex salt bodies are present, to highlight the efficiency regularization by denoising technique.

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MS35

Use of a Deep-learning-based Geological Parameterization within the Context of Production Data

Assimilation

Geological parameterizations are highly useful in the context of oil and gas production data assimilation (this inverse problem is commonly referred to as history matching). Parameterizations are effective because they can maintain geological realism in posterior (history-matched) geomodels, in the sense of consistency with the underlying training image, while also providing low-dimensional model characterizations. Such low-dimensional representations are beneficial since only a small number of parameters (relative to the number of grid blocks in the model) must be determined during history matching. In this work we apply a parameterization called convolutional neural network-based principal component analysis (CNN-PCA). In this formulation, a convolutional neural network is trained to provide an explicit transform function that can post-process PCA models to geomodels that more closely honor the multipoint spatial statistics (e.g., patterns) that appear in the training image. The data assimilation framework is applied for several synthetic cases, with posterior models generated using a subspace randomized maximum likelihood method. Numerical results demonstrate that the CNN-PCA parameterization indeed provides geologically sensible posterior models, and that prediction uncertainty is reduced considerably through application of the overall procedure.

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MS35

Implementing Bound Constraints and Hybrid Total-variation+Tikhonov Regularization in Wavefield Reconstruction Inversion with the Aalternating Direction Method of Multiplier

Full waveform inversion (FWI) is a nonlinear waveform inversion which estimates subsurface parameters with a wavelength resolution. However, regularization is required to mitigate several sources of errors. Subsurface can be subdivided into blocky and smooth parts, whose different statistical properties require dedicated regularization. We tackle this issue by designing a new hybrid regularization, which combines Tikhonov and total-variation (TV) regularizers. Tikhonov regularization stabilizes the smooth-part reconstruction, while the TV one fosters reconstruction of lithological contrasts. Our Tikhonov-TV (TT) regularization with bound constraints is implemented in frequency-domain FWI. The bilinearity of the wave-equation makes TT-FWI be a bi-convex optimization problem, which can be solved efficiently with the alternating direction method of multipliers (ADMM) and operator splitting. Wavefield and subsurface parameter are estimated in an alternating way: first, wavefields, which best jointly fit in the l2 sense the observations and satisfy the wave equation, are estimated keeping the available subsurface model fixed. Then, we update the smooth and blocky components of the subsurface parameters by l2 minimization of source residuals, keeping wavefields fixed, this cycle being iterated until convergence. Synthetic examples will illustrate how TT-regularization and ADMM make FWI resilient to cycle skipping and noise while preserving its intrinsic resolution power.

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MS35

New Algorithms for Projections onto Intersections of Multiple Convex and Non-convex Sets and Application to Full-waveform Inversion

We present a new algorithm to compute projections onto the intersection of constraint sets, designed particularly for multiple sets because we exploit similarities between constraint sets.When we do not know projections onto the individual sets in closed form, as is the case for total-variation constraints, our algorithm does not need other optimization algorithms to solve sub-problems. This a significant advantage in terms of computational cost and number of tuning parameters and stopping conditions, compared to classical algorithms to compute projections onto the intersection, such as Dykstra's algorithm. The proposed algorithm is suitable for problems with a large number of model parameters such as full-waveform inversion because it exploits coarse and fine-grained parallelism, and we also present a multilevel accelerated version. The corresponding softwareis open-source and implemented in Julia. We present strategies to use projections onto multiple constraints to regularize full-waveform inversion for models with salt domes or sedimentary geology.

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MS35

Efficient Implementation of the L^1 Total-Variation Regularization for Large-scale problems

Full waveform inversion (FWI) solves an ill-posed inverse problem to provide high resolution models of the subsurface. L^1 type total-variation (TV) seminorm, with its generalizations, is considered a robust regularization method that seeks sparse representation of the model in a space spanned by piecewise constant functions. Split Bregman iterations [Goldstein and Osher, 2009] has been proven to be an efficient algorithm for solving L^1 type optimization problems in imaging sciences, in particular for TV regularization. While it is known to be an effective algorithm, its original splitting form leads to a heavily unbalanced distribution of the computational load. Its serial implementation cannot take advantage of multi-node clusters when solving large scale problems. In this work, we discuss a parallel implementation of the split Bregman method for generalized L^1 type TV regularization. The proposed algorithm makes use of a multiplex splitting technique and an overlapping domain decomposition that is inherently suitable for parallel computing.

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MS36

Unraveling Earthquake Dynamics through Large-scale Multi-physics Simulations

Abstract not available.

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MS36

High-order Discontinous Galerkin Methods for Coastal Hydrodynamics Applications

Abstract not available.

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MS36

3D Inelastic Wedge Failure and Along-strike Variations of Tsunami Generation in the Shallow Subduction Zone

Abstract not available.

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MS36

Challenges and Status of GPS Enhanced Operational Near-field Tsunami Forecasting and Warning

In this talk we will discuss the challenging problem of forecasting expected tsunami intensities in the near-field of large earthquakes in the first 1-5 minutes after the start of rupture. Substantial progress has been made in developing algorithms that rely on on-shore geophysical data to quickly characterize an unfolding earthquake. Particularly, real-time high-rate GPS has been proven to provide critical information about the size and complexities of these large events. Here we will discuss how to couple such rapid earthquake source models to tsunami propagation codes to forecast the expected amplitudes at the coast. We will focus in particular on strategies based on efficient simulation of thousands of scenario events to characterize the uncertainties expected from these GPS-driven forecasts. We focus on the Cascadia subduction zone where there is a pressing need for this but the methodology can easily be applied elsewhere; GPS networks are becoming common place in all tectonically active regions.

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MS36

Fully Coupled Earthquake-tsunami Simulations and Real-time Tsunami Wavefield Reconstruction using the Ensemble Kalman Filter

Offshore sensor networks are revolutionizing local tsunami early warning by providing real-time estimates of wave height through measurements of pressure changes along the seafloor. Data assimilation techniques, in particular, optimal interpolation (OI), give real-time wavefield reconstructions and forecasts. Here we explore an alternative assimilation method, the ensemble Kalman filter (EnKF), and compare it to OI. The methods are tested on a scenario tsunami in the Cascadia subduction zone, obtained from a 2D dynamic earthquake-tsunami simulation, which couples an acoustic ocean in the presence of gravity to an elastodynamic earth. It takes into account seafloor and fault geometries, and complexities in geology. Tsunami waves are generated by time-dependent seafloor deformation in response to dynamic earthquake rupture. Data assimilation uses a 1D linear shallow water wave model. We find that EnKF achieves more accurate and stable forecasts than OI, especially for large station spacing and longer assimilation time intervals. Although EnKF is more computationally expensive, with development in high-performance computing, it is a promising candidate for real-time tsunami early warning.

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MS37

Convergence of a Numerical Method for 3D Inter-

facial Flow with Surface Tension

We present a non-stiff numerical method for 3D interfacial Darcy flow with surface tension. A fully explicit method would face a third-order stiffness constraint, making detailed calculations impractical. We instead develop a small-scale decomposition in the spirit of 2D work of Hou, Lowengrub, and Shelley, allowing for implementation of an implicit-explicit timestepping scheme. This timestepping scheme then only faces at most a first-order stiffness constraint. Turning to the question of convergence of the method, we develop a closely related version of the algorithm for which we can demonstrate consistency and stability. The estimates needed for stability are closely related to prior work on well-posedness of the system. This includes joint work with Yang Liu, Michael Siegel, and Svetlana Tlupova.

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MS37

Enforcing Discrete Maximum Principles in Discontinuous Galerkin Schemes: Application to Phase-field Methods

Many mathematical models derived from conservation laws are physically meaningful only if their unknown u stays within a certain range, i.e., if the maximum principle (MP) $u_{\min} \leq u(t,x) \leq u_{\max}$ holds. We propose a flux-limiting technique applicable to a large family of discontinuous Galerkin schemes that limits the mass fluxes across element boundaries such that this MP is enforced on the fully discrete level either for element-local mean values of the discrete solution or globally. A MP-preserving time step consists of solving the original problem (which may be time-explicit or time-implicit) while correcting mass fluxes as a local-iterative postprocessing step followed by a local slope limiting step if a global MP is desired. The proposed scheme is free of tuning parameters. If the original scheme is subjected to a CFL condition, application of the limiter brings further stabilization. Practical applicability is demonstrated by simulations of the advection equation and of the CahnHilliard equation. For the latter one, the discrete MP is also enforced when analytical solutions do not satisfy a MP. In this case, consistency with the analytical solution of the mathematical model is overridden by the requirement of physical consistency.

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MS37

Modeling and Numerical Methods for Two-phase Underground Water Flow

In this talk, we shall derive a degenerate Cahn-Hilliard-Stokes-Darcy model for general two-phase flows in underground water system. The model satisfies both an energy law and an entropy estimate. We then discuss numerical methods that preserve the properties of the continuous model.

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MS37

A Stable and Fast Linearization Scheme for Nonlinear Porous Media Problems

The nonlinear advection-diffusion equation models many problems rising in subsurface flows. The Richards equation is one of these equations that model unsaturated flow through porous media. In dimensionless form it reads

$$\partial_t S(p) = \nabla \cdot [k(S)\,(\nabla p - \hat{g})]\,. \tag{1}$$

Here $\hat{g}$ is the unit vector of gravitational acceleration and $k(S)$ is a nonlinear function that is determined based on experiments. Two unknowns are involved: S, the water saturation and p, the water pressure. Standard models assume that these are related by a nonlinear relationship determined, again, based on experiments:

$$-p = P_c(S). \tag{2}$$

(1) and (2) constitute a nonlinear parabolic system of equations which is difficult to solve numerically. In this work, we consider a linear scheme for these equations based on L-scheme [Pop, Radu & Knabner, 2004] and prove that it is globally convergent with convergence rate proportional to the timestep or square root of the timestep depending upon whether the Kirchoff transform is used or not. Finally, with three numerical examples, we show that it is more stable than standard schemes such as Newton and Picard scheme and is faster than Picard and L-scheme. This linearization scheme can be extended to the two-phase equation, domain decomposition methods and systems involving non-equilibrium effects like hysteresis.

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MS37

Coupling and Decoupling of Free Flow and Flow in Porous Media

Many physical, biological and engineering processes involve the coupling of free flows with flows in porous media. Well-known examples include filtration processes, flows in karstic geometry, hyporheic flow, and PEM fuel cell among many others. We focus on three interrelated important issues associated with the coupled system: (1) physically relevant interface boundary conditions that couple the free flow and the porous media flow; (2) accurate numerical schemes that are able to decouple the two sub-systems so that legacy codes can be utilized to efficiently simulate the long-time transport phenomena; and (3) physically important parameter regimes where the system can be reduced to decoupled effective systems. Analytically, numerical and experimental tools will be employed to demonstrate several recent results in these directions.

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MS38

Auxiliary Space Preconditioning for Mixed Finite Element Discretizations of Richards Equation

We seek to solve the steady state Richard's Equation in three dimensions using HAZMATH, a finite element discretization and solver package written by Ludmil Zikatanov, Xiaoze Hu, and James Adler. We first discretize using $RT0 - P0$ finite elements. We then use several different linearizations of the resulting nonlinear system and consider an auxiliary space method using Edge Averaged Finite Elements to precondition the resulting linear system. Physically realistic simulations are computed and analyzed and nonlinear time dependence is also considered.

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MS38

Multigrid and Multilevel HDG Approaches for Nonlinear Single-phase Flows

In this talk we present geometric multigrid and multilevel approaches for high order hybridized discontinuous Galerkin (HDG) methods applied to linear/nonlinear single-phase flows. For HDG methods, the linear system involves only the unknowns residing on the mesh skeleton, and constructing intergrid transfer operators is therefore not trivial. The key to our multigrid and multilevel algorithms is the physics-based energy-preserving intergrid transfer operators which depend only on the fine scale Dirichlet-to-Neumann (DtN) maps. Thanks to these operators, we completely avoid upscaling of parameters and no information regarding subgrid physics is explicitly required on coarse meshes. This gives robustness to the algorithm and capability to handle highly heterogeneous coefficients usually appearing in subsurface flows through porous media. With several numerical examples we demonstrate the effectiveness of the proposed approaches for linear and nonlinear single-phase flows.

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MS38

Quasi-static Crack Propagation in Nonlinear Elastic Solids

In this talk we describe a finite element approximation of anti-plane shear quasi-static crack propagation in nonlinear elastic solids. The class of constitutive models considered to model elastic solids gives rise to nonlinear relationship between classical linearized elastic strain and Cauchy stress. We formulate an energy minimization under constraint to describe quasi-static crack propagation. An iterative algorithm will be described for the solution of quasi-linear PDE. Numerical results will be presented to show the efficacy of the model.

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MS38

Uniqueness of Discrete Solutions of Quasilinear PDE on 2D and 3D Nonuniform Meshes

We will discuss an *a posteriori* condition which guarantees uniqueness of P1 finite element solutions of a class of nonmonotone quasilinear elliptic PDE in 2D and 3D without the assumption of a globally small meshsize. This generalizes recent results which show uniqueness of discrete solutions on acute meshes in 2D. Here, the angle conditions are less restrictive allowing for sequences of meshes generated by standard adaptive refinement algorithms in 2D and 3D. Extensions include infinity-norm estimates for the difference between discrete solutions under a Hölder condition on the nonlinear diffusion coefficient, allowing the theory to encompass more realistic modeling situations.

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MS38

Efficient and Accurate Solvers for Nonhydrostatic Simulations of the Atmosphere: The Interaction of High-order ImEx Methods and Customized Algebraic Solvers

Increasingly, modern computational science requires large-scale simulations that consistently and accurately couple distinct physical processes. While the mathematical models for individual processes often have well-known type (hyperbolic, parabolic, etc.), may be either linear or nonlinear, and are suitable for classical time integration methods, the same cannot be said for the coupled models. These multiphysics models are often of mixed type, involve both linear and nonlinear components, and involve processes that evolve at dissimilar rates. As such, many multiphysics simulations require novel, flexible time integrators that may be tuned for complex problems. In this talk we discuss our work toward next-generation algorithms for non-hydrostatic simulations in global climate modeling. We focus on both modern, high-order methods for mixed implicit-explicit time discretizations, and customized nonlinear and linear solvers for solution of the resulting implicit algebraic systems. These efforts are facilitated through use of our ARKode library, that provides flexible and accurate solvers for stiff, nonstiff, mixed implicit-explicit, and multirate systems of differential equations, and supports user-defined, problem-speific algebraic solvers. We conclude with a discussion of our recent work in development of next-generation time integration methods for such problems, including high-order exponential Rosenbrock and multirate methods.

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MS39

Simulation of Capillary Trapping in Three-phase Displacement using a Level Set Approach with Local Volume Preservation

Evaluating the potential for oil recovery and carbon dioxide storage in mature oil fields requires knowledge of the mechanisms for CO2 trapping and oil mobilization during three-phase flow in porous media and capabilities to predict relationships between initial and trapped fluid saturations. We have previously developed a multiphase level set (MLS) method to investigate three-phase capillary-controlled displacements on 3-D porous rock geometries accounting for uniform and non-uniform wetting states. Here, we present a method for local volume preservation within the MLS approach to investigate trapping and mobilization of isolated fluid ganglia during three-phase displacement, accounting for ganglia merging and splitting. The method is implemented in a patch-based software framework for parallelism and adaptive mesh refinement. First, we use the method to calculate capillary pressure curves and residual saturations for two-phase displacement in sandstone. Then we simulate three-phase capillary pressure curves for subsequent gas and water invasion cycles to compare residual oil and gas saturations between two- and three-phase displacement. We analyze evolution of isolated fluid ganglia during the displacements in terms of local capillary pressures, and shape and size distributions (e.g., power-law behavior). These simulations provide relations between initial and residual saturations that reservoir simulation models use to describe trapping behavior in three-phase flow.

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MS39

Mathematical Modelling of the Bio-plug Technology: Laboratory Experiments, Upscaling, and Numerical Simulations

In microbial enhanced oil recovery (MEOR), one of the strategies is selective plugging, where bacteria are used to form biofilm in the high permeable zones to diverge the water flow and extract the oil located in the low permeable zones. Therefore, it is necessary to build mathematical models that better describe the biofilm mechanisms. In the laboratory, biofilm is growth in a T-shape micro-channel. We built a mathematical model including water flux inside the biofilm and different biofilm components (extracellular polymeric substances, water, active bacteria, and dead bacteria). Using the best estimate of physical parameters from the existing experiments, we perform numerical simulations. The stress coefficient is selected to match the experimental results. A sensitivity analysis is performed to identify the critical model parameters. A reduction of the biofilm coverage area as the water flux velocity increases is observed. Homogenization techniques are applied in a strip and a tube geometry. Numerical simulations are performed to compare both upscaled mathematical models. In the macro-scale laboratory experiments, biofilm is growth in cylindrical cores. Permeability and porosity changes over time at different flow rates and nutrient concentrations are studied. Numerical simulations are performed to compare with the experimental results.

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MS39

Discontinuous Galerkin Methods for Solving Non-Newtonian Two-phase Pore Scale Flows

Over the last few decades, digital rock physics has undergone rapid development. The modern X-ray microtomography creates cross-sections of small rock samples on micrometer to millimeter scale, which subsequently can be used to construct high-resolution domains by 3D imaging software. This technique provides a geometry pattern of rock structure and enables further insight on flow phenomena through porous media by the use of accurate numerical methods such as the interior penalty discontinuous Galerkin (IPDG) methods. In this talk, a time-dependent Cahn–Hilliard–Navier–Stokes model for non-Newtonian flows is presented. We utilize an efficient pressure-correction projection algorithm, in conjunction with IPDG schemes for time and space discretization developed within the framework of a distributed parallel pore-scale flow simulation system. We employ an effective Helmholtz free-energy based approach for modeling wettability and the interaction of fluids and solid surfaces at the pore scale, which is straightforward for implementation within the DG framework. Results of extensive numerical experiments validate the proposed numerical algorithm. We demonstrate that the algorithm is numerically robust and lends itself naturally to large-scale 3D numerical simulations.

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MS39

Applications for Neural Networks in Digital Rock Physics

Deep learning refers to a flexible class of methods constructed using neural networks. Neural networks are computational graphs that can be trained based on observed data and optimization methods to perform a wide variety of functions. We review general capabilities of the method and consider applications for deep learning on digital rock data. Within this context, image processing operations on volumetric data sets represent a natural application area for existing neural network structures. Based on synchrotron micro-tomography data, we train V-net to segment raw micro-tomography images and consider the computational resources and data needed to train effective models for semantic segmentation. We consider how this approach might be used to augment traditional segmentation workflows, and consider opportunities to use neural networks for artifact removal and image enhancement. In addition to these more classical image processing applications, we evaluate the use of neural networks as general data fitting tools applied to constitutive models for two-fluid flow in porous media. We demonstrate how flexible neural networks can be constructed to infer relationships between physical variables, and compare the accuracy of these methods to more traditional regression techniques.

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MS39

Phase Field Model for Partially Miscible Fluids at Porescale

Phase field models have been successfully applied at porescale to model evolution of two immiscible fluid phases such as gas and liquid, or liquid and solid phases of a single component. The evolution relies on the energy functional whose gradient determines the evolution; the functional typically includes many terms responsible for the interactions between the two phases and with the walls of the pores. In principle, one could take a rigorous limit with respect to some small parameters to obtain a sharp interface model, or over an REV, to obtain an effective multiphase Darcy scale model. In this talk we discuss the multicomponent partially miscible case where one of the components can be dissolved in the liquid phase as long as its concentration does not exceed a maximum. The challenge is an appropriate connection to the sharp interface model, as well as to one at the Darcy scale. Further difficulty is to ensure that the (lack of) numerical accuracy does not interfere with the modeling precision. The model application is that of methane or CO2 in brine which can form hydrate or gas in favorable conditions. This is joint work with students and collaborators to be named in the talk.

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MS40

Verification Benchmarks for Single-phase Flow in Three-dimensional Fractured Porous Media

In this introductory presentation, we explain and discuss motivations, strategies, and expected outcomes of the benchmark study proposed to the scientific community and presented in [Berre at al. “Call for participation: Verification benchmarks for single-phase flow in three-dimensional fractured porous media’ arXiv:1809.06926]. Its aim is to compare mathematical models and numerical schemes for the solution of flow and transport in three-dimensional fractured porous media. We introduce the mathematical model and present the test cases. The latter are designed to challenge aspects of the different numerical schemes based on geometrical complexities of the fracture networks and heterogeneous and strong contrasts in problem parameters. This benchmark study is in line with a previous one carried out by the same organizers in a two-dimensional setting, [Flemisch at al. “Benchmarks for single-phase flow in fractured porous media’. Adv Water Resour 2018], which is now open for a broader participation and debate.

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MS40

Finite Volume-based Discrete Fracture Modeling of Flow, Transport and Deformation in Fractured Porous Media

In this contribution, we present four different discrete fracture-matrix models which are based on both cell-centered as well as vertex-centered finite volume schemes. The models are applied to the scenarios of the benchmark study presented in [Berre at al., Call for participation: Verification benchmarks for single-phase flow in three-dimensional fractured porous media, arXiv:1809.06926] and are compared to the various methods discussed therein. Furthermore, we present a model that additionally accounts for the mechanical deformation of the rock matrix, being able to capture the effect of fracture dilation. This model is then used to study the influence of fracture dilation on the effective permeability of fractured porous media with respect to fracture network characteristics.

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MS40

Algebraic Dynamic Multilevel Method for Projection-based Embedded Discrete Fracture Model

We present an algebraic dynamic multilevel method for efficient (scalable) and accurate simulation of multiphase flow and heat transfer in heterogeneous fractured porous media (F-ADM). Explicit fractures are modelled using projection-embedded discrete fracture method (pEDFM, Tene et al., ADWR, 2017). F-ADM allows for independent computational grids for heterogeneous matrix and fracture networks at multilevel dynamic resolutions. It also provides a unified framework to dynamically treat discrete fracture elements effectively (homogenised) or explicitly (pEDFM) at multiple coarse resolutions (HosseiniMehr et al., JCP, 2018). This is done by dynamic selection of the coarse scale resolutions and offline multiscale local basis functions for both fractures and matrix domains. Several 2D and 3D test cases are presented to investigate the efficiency and accuracy of this new computational method for single and multiphase flow.

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MS40

A Novel Enriched Galerkin Method for Flow and Transport in Fractured Porous Media

Fluid flow and solute transport in fractured porous media is the backbone of many applications including groundwater flow, underground energy harvesting, earthquake prediction, and biomedical engineering. The traditional continuous Galerkin (CG) method is not suitable for the transport equation due to lack of mass conservation. The discontinuous Galerkin (DG) method mitigates this problem; however, its computational cost is considerably more than the CG method. In this study, a robust and efficient discretization method based on the interior penalty enriched Galerkin (EG) method is proposed. This method requires fewer degrees of freedom than those of the DG method, while it achieves the same accuracy. The flow and transport models of rock matrix and fractures domains are investigated in both equidimensional and mixed dimensional settings. The CG and EG methods are compared in four geometries to evaluate the accuracy and efficacy of the proposed method [Inga et al., Verification benchmarks for single-phase flow in three-dimensional fractured porous media, 2018]. The results illustrate the superiority of the EG method in solving the flow and transport equations in fractured porous media. Furthermore, the computational burden of the EG method is not significant.

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MS40

Multiscale Simulation of Reactive Transport in Shales

Major concerns in shale gas production include the use of fresh water and the disposal of waste water during hydraulic fracturing. Recycling the fracking fluid can curb such impacts, however the barium in the recycled fluid may precipitate and clog the natural fractures in shale, blocking pathways for gas production. Currently, operators do not fully agree on the quality of water that must be achieved to prevent connectivity impairment. Since the rock system contains a few hydraulic fractures and thousands of smaller natural fractures, fully resolved simulations are too expensive, while traditional upscaling methods cannot capture the pore-scale features and the possible geometry changes

due to precipitation or dissolution. We developed a fully coupled multiscale algorithm to address this issue: we solve reactive transport only in a few selected natural fractures, while evaluating the influences of other natural fractures by interpolation and ensuring top-down bottom-up coupling between the hydraulic and the natural fractures. Specifically, we consider a fracture system with 600 natural fractures connected to one hydraulic fracture. The multiscale code is validated against both analytical solutions, whenever available, and fully resolved pore-scale simulations. We find the reaction rate can have a great influence after breakthrough even if the difference before breakthrough is small. This means the reaction can be underestimated if only the early-stage data is considered.

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MS41

New Advances in History Matching and Uncertainty Quantification Formulated Within the Bayesian Inference Framework

It is extremely challenging to properly quantify uncertainty of reservoir properties and production forecasts by conditioning to production data. In this work, we first summarize recent advances in history-matching (or model calibration) and then discuss an efficient method to generate an ensemble of reservoir models conditioned to production data through the integration of distributed Gauss-Newton optimization, Gaussian mixture model fitting, and parallelized acceptance-rejection techniques. We validate the method with a synthetic history-matching problem. The proposed method generates conditional samples that are comparable to MCMC samples, while reducing the computational cost by a factor of 100 compared to the MCMC method.

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MS41

Strategies for Ensemble-based Conditioning of Multiple-point Statistical Facies Simulation on Nonlinear Subsurface Flow Data

Multiple-point statistical (MPS) facies simulation has been developed to generate subsurface models with complex geological connectivity. Conditioning MPS facies simulation on nonlinear flow data is challenging due to the complex relation between flow responses and facies distribution. We have developed two ensemble-based approaches to condition MPS facies simulation on the flow data. In both approaches, Ensemble Smoother (ES) is used to integrate dynamic flow data to update the ensemble of model parameters (e.g., hydraulic conductivity, etc.) which then is used to constrain the MPS facies simulation and make the outputs geologically consistent. One way to incorporate the information from dynamic flow data into MPS facies simulation is to introduce pilot points and consider them as hard data to condition the simulation: first, a number of pilot points are strategically placed in a subsurface model and their facies types are inferred from the updated ensemble of model parameters; then these pilot points are treated as hard data to condition MPS facies simulation. Another way to integrate the information from flow data into MPS facies simulation is to construct and update facies probability maps which are then used to constrain the simulation outputs through the t-model. Numerical experiments are presented to show that these two approaches can reproduce geologically consistent connectivity patterns during while generating flow responses that match dynamic flow data.

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MS41

Tempered Ensemble Transform Particle Filter for Non-Gaussian Elliptic Problems

Sequential Monte Carlo methods (SMC) are typically stochastic. Ensemble Transform Particle Filter (ETPF) is a deterministic SMC method. It, however, still fails for strongly nonlinear problems, since the prior measure does not approximate well the posterior measure leading to the method degeneracy. Moreover, ETPF has a mutation that does not sample an invariant measure. In this paper we propose to mutate ETPF based on a Markov kernel with an invariant measure and to introduce intermediate densities to ETPF to avoid the filter collapse. We show that the adjusted ETPF outperforms a tempering SMC method and a regularized ensemble Kalman filter for non-Gaussian high-dimensional problems of parameter estimation.

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MS41

Use of the Particle Filter for Fault-slip Estimation

Assimilation of near-surface and indirect geophysical observations into seismic cycle models has the potential to improve probabilistic forecasts of seismicity. A recent application of the Ensemble Kalman Filter (EnKF) in a Seismo-Thermo-Mechanical (STM) model has shown the potential of state estimation of fault behavior in subduction zones with surprisingly few observations. Considering the strong non-linearity of the dynamics and non-gaussianity of the prior, methods based on the particle filter (PF) might form an attractive alternative to the EnKF. As a first step towards the implementation of the PF with the STM model, we propose a set-up in which the ensemble is generated using time-lagged evolutions of seismicity. Identical twin experiments demonstrate the effectiveness of the PF in this setup. With the aid of synthetic observations the PF updates five state variables: horizontal- and vertical velocity, normal- and shear stress, and pressure. With the current setup, the PF is less effective representing the state than the EnKF. Analysis indicates that the presence of trends in observed data is the main obstacle for assimilating the seismic cycle using time-lagged particles. The results furthermore suggest that the performance of the EnKF is related to the implicit variable correlations in the error covariance of this filter. Future work will investigate PF performance in less idealised experiments, and other sampling methods for ensemble generation.

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MS41

Ensemble Kalman Filtering with Iterative One-step-ahead Smoothing for History Matching

Recently, a filtering scheme with one-step-ahead smoothing (KF-OSA) was proposed with the aim to enhance the performance of classical Kalman filter under unideal conditions. The rationale behind the KF-OSA is to improve the sampling of the ensemble background with future observations, which is thus expected to enhance the filter's performance. Even though the same observation is exploited twice in the proposed filtering scheme, KF-OSA is a fully Bayesian-consistent framework, based on which ensemble Kalman filters with OSA-smoothing step (EnKF-OSA) were developed to deal with large-scale nonlinear data-assimilation problems. The performances of EnKF-OSA were demonstrated for hydrological and atmospheric problems. In this contribution, we further extend the EnKF-OSA to handle highly nonlinear problems by introducing an iterative process with a focus on the characterization of reservoir models. The history matching problem by nature is formally formulated as a parameter-estimation problem, therefore one way to apply the iterations to the EnKF-OSA is through the smoothing step of both parameters and state variables. In principle, any optimization method can be used, but here we focus on Levenberg-Marquard and multiple data assimilation methods. Numerical experiments are conducted to examine the performance of EnKF-IOSA as an alternative to other existing methods for history matching.

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MS42

The Role of Compressibility on the Blow-up of Solutions of Poro-visco-elastic Models

Modeling of fluid flows through porous deformable media is relevant for many applications in biology, medicine, bioengineering, and geophysics. These fluid-structure mixtures are described mathematically by poro-visco-elastic systems in bounded domains, with mixed boundary conditions, which are the drivers of the systems. We investigate the well-posedness of solutions in the case of externally applied boundary tractions that are discontinuous in time. We present an analytical study in the 1D case, corresponding to the experimental conditions of confined compression, and under the assumptions of negligible inertial effects in the balance of linear momentum for the mixture and constant hydraulic permeability. We highlight the contributions of viscoelasticity and compressibility and their role in the global existence vs. blow-up of solutions.

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MS42

Gradient Flow Perspective on Poromechanics

We present a framework for the analysis and numerical treatment for flow in deformable porous media driven by dissipation. In certain relevant situations (e.g. linear poroelasticity), flow in deformable porous media can be modeled as a generalized gradient flow: States, fully describing the system, change along the gradient of a driving energy subject to some dissipation. For such models, we exploit the specific gradient flow structure and derive with only very little effort (i) well-posedness results and (ii) robust numerical solvers (e.g. iterative splitting schemes), using tools from gradient flow and optimization theory, respectively. In particular, the results for linear poroelasticity are consistent with the literature, demonstrating the capability of the framework.

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MS42

Multiphysics Numerical Methods for a Nonlinear Poroelasticity Model

In this talk I shall present some multiphysics finite element methods for a nonlinear poroelasticity model which arises from soil mechanics and materials science (i.e., soft matters). This multiphysics approach is a generalization of our previous work for linear poroelasticity models (such as Biot's model and Doi's model) to nonlinear poroelasticity models. The main idea of our approach is to derive a multiphysics reformulation of the original poroelasticity model by introducing an "elastic pressure" and showing that such a pressure is governed by a linear diffusion process. Based on this new formulation we then propose a novel fully discrete finite element method for approximating the model. At each time step the proposed multiphysics finite element method consists of solving two sub-problems: one of which is a nonlinear Stokes-type problem for the displacement vector field (of the elastic body) and another is a diffusion problem for a "pseudo-pressure" field (of the solvent in the pores). Error estimate and numerical experiment results will be presented to demonstrate the accuracy and efficiency of the proposed method. This is a joint work with Zhihao Ge of Henan University, China.

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MS42

Microscale Analysis Demonstrating the Significance of Shear and Plasticity in Hydrostatic Compression of Porous Media

Experimental data for porous media exhibit nonlinear pressure-volumetric strain relations and a strong dependence on the Terzaghi effective pressure, defined as confining pressure minus pore pressure. In this talk we present results of a microscale analysis demonstrating a plausible reason for why the Terzaghi effective pressure plays such a dominant role. The results show that the stress field within a relatively small region around a pore contains shear stress proportional to the effective stress that produces a cascade of effects including the increased likelihood of the material entering into a plastic regime and pore sizes changing significantly.

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MS42

The Biot-Stokes System with Unilateral Constraints

A fully-saturated poroelastic medium is deformed by internal pressure-driven fluid flow and constrained on its boundary by the stress of the external fluid and bounding surfaces. The formulation leads to a well-posed unilateral initial-boundary-value problem for the Biot - fluid system and the unknown contact surface of the medium.

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MS43

Regularized Extended Finite Volume Method for Flow Induced Shear Failure

Abstract not available.

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MS43

Rate-and-State-Based Simulation of Induced Seismicity and Coupling to Reservoir Processes

Physics-based earthquake simulators, such as RSQSim, can be used to understand mechanisms that lead to fluid induced seismicity (IS). When coupled with geomechanical reservoir models, RSQSim, produces rich catalogs of synthetic seismicity induced by decreases in effective normal stress related to fluid overpressures and stress changes due to fault slip. Governed by rate- and state-dependent friction, RSQSim simulations show spatial and temporal clustering of observed IS. These computational efficient simulations can be used to systematically explore the parameters that control the mechanics. Statistical data can be drawn from simulations that may contribute to design of optimal injection operations that minimize risk of seismicity. We apply these methods to test the efficacy of an active pressure management technique (APM) (i.e. coincident CO2 injection and extraction of formation brine) to manage overpressures and IS. We conduct 25 experiments, where 5 extraction well locations are used to test the operational layout on the resulting seismicity. To determine the volume of brine to be extracted to reduce risk, 4 sets of simulations are conducted for every setup where the extracted volume is varied between 25% and 100% of the total CO2 injected. Simulation results are compared to the reference cases (injection-only at reduced volume) to evaluate the impact of APM on seismic risk. This work is funded by the DOE under NRAP and prepared by LLNL under Contract DE-AC52-07NA27344.

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MS43

Modeling Simultaneous Propagation of Multiple Pseudo-3D Hydraulic Fractures

This work presents a numerical algorithm for modeling the simultaneous propagation of multiple hydraulic fractures. We focus on the pseudo-3D fracture geometry, in which fractures propagate in elastically homogeneous solid, but the central reservoir layer is surrounded by two symmetric high-stress layers. The problem involves the solution of a coupled system of time-dependent non-linear and non-local equations for linear elasticity, viscous fluid flow, fluid leak-off into porous media, and fracture propagation. The elastic influence calculation is based on the hypersingular integral equations that relate fracture opening to the applied stress. Each fracture is discretized along its length using constant displacement discontinuity elements, where the fracture width solution for each element is constructed based on the plane strain assumption and the adopted stress profile. The elastic integrals, which describe the elastic interaction between the fractures and elements within each fracture, are evaluated using a combination of numerical and analytical integration. With regard to propagation condition, we utilize the multi-scale tip asymptotic solution as the boundary condition at the lateral fracture tip to include the effects of fluid viscosity and leak-off on the dynamics of fracture propagation. The accuracy of the developed numerical algorithm is tested by the comparison with analytical and numerical reference solutions.

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MS43

Fully Coupled Model for Chemically Induced Fault Slippage

In this study, we present a fully coupled numerical framework for modeling of chemically induced seismic events in faulted reservoirs. We use the Discrete Fracture Model (DFM) approach that allows combining the reactive flow and transport and contact-plane geomechanics for modeling the naturally fractured reservoirs. In our framework, the flow and transport governing equations are approximated by finite-volume method and the mechanics equations are discretized by means of continuous Galerkin finite-element approach. The mechanical behavior of the fault is modeled as a contact mechanics problem. The model captures both elastic interactions between fault and surrounding rock as well as flow, transport, and dissolution of rock minerals. In our study, we model the depletion process in natural gas reservoirs with the rising water-gas contact. Pressure evolution caused by the depletion changes a stress state on the fault which can potentially lead to the slippage of the fault and subsequent seismic events. In addition, the rising water induces chemical reactions between water and fault materials. This phenomenon can change the mechanical properties of the fault and accelerate the events. In our work, we present several case studies of practical interest.

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MS43

The Modeling of Fault Activation and Induced Seismicity by using Coupled Flow-geomechanics Simulation and its Field Application

A fault may exist in and/or near a site of fluid injection for subsurface CO2 storage or geothermal resource development. Fluid injection into the reservoir in such sites might reactivate the fault in response to the increase of pore pressure beyond a critical threshold. In the worst case, the fault reactivation might trigger earthquakes and increase its permeability resulting in fluid leakage to the aquifer located above the reservoir or the surface. It is, therefore, critical to evaluate the potential of fault reactivation prior to injection. In this study, we perform numerical investigation on geomechanical behavior during CO2 injection at the Janggi area located in the southeast area in South Korea. We focus on the reactivation potential of a fault detected in a pilot-scale CO2 storage site located in the Janggi sedimentary basin. The geophysical survey carried out in the stage of site characterization indicates that the fault is located about 180 m away from the injection well. We perform 3D numerical simulation of coupled multiphase fluid flow and geomechanics, taking the fixed-stress sequential method and the Mohr-Coulomb failure model. Considering various injection rates of CO2, we numerically simulate changes in the effective stress and failure status at the fault plane as well as calculate the moment magnitude of induced seismicity.

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MS44

Development and Verification of a Numerical Library for Solving Global Terrestrial Multi-physics Processes

Land Surface Models (LSMs) are multi-physics simulators that compute exchanges of water, momentum, energy, and nutrients at the Earth's surface. Current generation LSMs routinely omit several critical biophysical processes such as lateral subsurface transport of water, energy, and nutrients and transport of water through the soil-plant continuum. The global terrestrial model community actively participates in model intercomparison projects for model validation, but mostly ignores model verification. The goals of this study are to (1) develop a numerically robust standalone library for solving global terrestrial biophysical processes (TBP) with support for flexible coupling strategies; and (2) verify the multi-physics library for various problems, including coupled soil and plant hydraulics. To achieve the objectives of our study, we developed a sequential, open source Multi-Physics Problem (MPP) library for solving global TBP. The underlying numerical engine of the MPP library is PETSc, whose DMComposite subclass provides an interface for individual modules to assemble parts of a global matrix for solving a tightly coupled multi-component/process problem. We use the Method of Manufactured Solutions (MMS) to verify the MPP library for a range of problems comprising of single and multiple components/processes in one or multiple physical domains. We conclude by advocating for implementation of MMS approaches to verify all components of the next generation of ELM.

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MS44

Quasi-Newton Methods for Atmospheric Chemistry Simulations

Here we propose an approach for implicit DE solvers that improves their convergence speed and robustness. We achieve this by blending the existing Newton-Raphson (NR) method with Quasi-Newton (QN) methods. We test our approach with numerical experiments on the UK Chemistry and Aerosol (UKCA) model, part of the UK Met Office Unified Model suite, run in both an idealized box-model environment and under realistic 3D atmospheric conditions. A series of experiments over a range of chemical environments was conducted with the box-model showing a net 27% savings in the iterative solver routines. The 3D simulations show that our moderate modification speeds up the chemistry routines by around 13% resulting in a net improvement in overall run-time of the full model (i.e., with the other processes of transport, aerosol, photolysis etc.) by approximately 3% with negligible loss in the accuracy.

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MS44

Assessing and Improving the Numerical Solution of Atmospheric Physics in E3SM

The numerical errors arising from parameterized subgrid-scale atmospheric physics have been largely overlooked in Earth system models. As spatial resolution increases, the computational effort expended on atmospheric dynamics will only provide limited gains in overall accuracy due to numerical errors from parameterizations. In this talk, we discuss approaches for assessing the numerical convergence of the time integration methods utilized in the Energy Exascale Earth System Model (E3SM), identify causes of reduced order convergence, and explore approaches for improving the convergence and accuracy of the time integration scheme. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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MS44

Improving the Convergence Rate of Stochastic Approximations for Physics-dynamics Coupling

Stochastic approximations to physics-dynamics coupling aim at replacing the physics (subgrid) processes with appropriately chosen stochastic processes. The stochastic approximations need to be simulated numerically. Recent work has shown that when the stochastic process used is white noise then naive application of traditional numerical schemes can lead to convergence rate degradation and even complete loss of convergence. The addition of the Ito correction to the numerical scheme was shown to restore convergence. We have shown that the improvement in the convergence rate can be effected through the Ito correction also for colored noise which is more realistic. We will present the relevant constructions and provide numerical

results for illustrative purposes.

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MS44

Overview of Code and Calculation Verification Practices and their use in Scientific Computinguting

For scientific simulation codes, rigorous code verification is essential to provide confidence in code correctness and as a foundation for subsequent validation and uncertainty quantification activities. While a consensus theory of code verification has emerged, many issues remain in its practice. I will overview current methods for code verification and address considerations such as criteria of completeness, effective conveyance of results, and use of verification to improve code development. Lastly, I will overview some of the methods used in calculation verification and the role that such verification can play in a strong verification and validation program. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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MS45

Using Fast Forward Solvers to Enable Uncertainty Quantification in Seismic Imaging

Uncertainty quantification is an important aspect of seismic imaging. Bayesian interference supported by Monte Carlo methods is often used to solve inverse problems while also characterizing the uncertainty. As in any inverse problem, in this approach the main goal is to find the global minimum of the misfit function in a computationally efficient way. The way that these methods quantify uncertainty requires numerous models to be tested, and hence numerous forward modeling steps. Traditional finite-differences solutions of the wave equation in the entire domain are too computationally expensive to test more than a few hundred models. To reduce this computational cost, we are using two different solvers: an acoustic local domain solver and a field expansion method. We use these two methods to answer different uncertainty questions as well as to understand the issue of convergence. We find that both methods require closer to hundreds of thousands of iterations to converge than to the few hundred typically used explored. This has important implications for how we interpret uncertainties in seismic imaging.

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MS45

Uncertainty Quantification and Volcanic Hazards

The flow of hot ash, possibly mixed with water, is a major hazard threat consequent to volcanic eruptions. Using data from the Soufriere Hills Volcano on the island of Montserrat, we produce a hazard map indicating the probability of a catastrophic event occurring over the next T years. In order to construct this map we (i) define a system of equations that model pyroclastic flows, (ii) describe the TITAN2D simulation environment that solves these equations, (iii) build a Gaussian Process emulator that approximates TITAN2D outputs, (iv) locate the region in parameter space that defines those inputs which lead to catastrophic flows and those which do not. Along the way we construct a hierarchical model for the major dissipation parameter, and constrain uncertainties in other inputs.

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MS45

Trans-D Methods for Quantifying Uncertainty in Seismic Inversion

Limited illumination, insufficient offset, noisy data and poor starting models can pose challenges for seismic inversion. Solving this ill-posed problem in a trans-D Bayesian framework has various advantages. Firstly, Bayesian parsimony limits the velocity model dimension, making a sampling-based solution tractable. Secondly, the velocity model self-parametrizes non-linearly, depending largely on the data likelihood. Finally, geologically interpreted prior knowledge can be naturally incorporated into the solution. Together with parallel tempering to traverse rugged likelihood, trans-D Bayesian methods can feasibly estimate the inverse velocity model uncertainty.

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MS45

Reducing the Computational Cost of Uncertainty Quantification for Seismic Inversion

The uncertainty information gained from Bayesian approaches to inverse problems using Markov chain Monte Carlo is desirable, but comes at a steep computational cost. In seismic velocity inversion, the acoustic wave equation must be solved tens of thousands of times in order to obtain enough samples to construct the posterior distribution. This talk will discuss techniques for reducing the computational cost of MCMC for seismic inversion, including using Operator Upscaling for the acoustic wave equation as an inexpensive filter to quickly reject unacceptable samples. This two-stage process results in faster exploration of the posterior distribution.

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MS45

An Ensemble Kalman Filter Method for Uncertainty Quantification in Full Waveform Inversion

Full Waveform Inversion (FWI) seek to estimate subsurface properties, based on ill-posed and computationally challenging inverse problem-solving. This methodology involves minimizing a data-misfit between synthetic wavefield computed from a prior subsurface estimate, and sparse indirect recorded waveform data, generally located at the surface. Although it is possible to come down to a reasonable data-fit, obtaining high-resolution subsurface models, the intrinsic properties of FWI make the process complicated: based on quasi-Newton local optimization schemes, making any claims on the validity of a unique solution is an unsound exercise. Therefore, it is crucial that FWI depart from the deterministic-mono solution frame, and move toward a more statistical approach, integrating uncertainty quantification at the heart of its processes. To that extent, we propose a new methodological development to recast our problem in the Bayesian inference framework, by borrowing and applying ensemble methods coming from the Data Assimilation (DA) community. We investigated uses of such methodologies on synthetic and real data tests, by applying a combination of quasi-newton FWI optimization scheme, and well known, Ensemble Transform Kalman Filter from the DA community. On top of proposing an ETKF-FWI scheme to estimate uncertainty, we also study the importance of prior knowledge and the challenges of ensemble representativity for high-dimensional state estimate problem such as FWI.

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MS46

Adaptive Fixed-stress Iterative Coupling Schemes based on a Posteriori Error Estimates for Biot's Consolidation Model

We develop in this paper adaptive iterative coupling schemes for the Biot system modeling coupled flow and geomechanics in a poro-elastic medium. We particularly consider the space-time formulation of the fixed-stress iterative scheme, where two common discretizations of this algorithm is introduced based on two coupled mixed finite elements methods in-space and a backward Euler scheme in-time. Therefrom, adaptive fixed-stress algorithms are build on conforming reconstructions of the pressure and displacement together with equilibrated flux and stresses reconstructions delivering a posteriori error estimate distinguishing the different error components, namely the spatial discretization, the temporal discretization, and the fixed-stress iteration components. Precisely, at the iteration $k \geq 1$ of the adaptive algorithm, we prove that our estimate gives a guaranteed and fully computable upper bound on the energy-type error measuring the differences between the exact and the approximate pressure and displacement. These error components are efficiently used to design adaptive and multiscale time-stepping strategy and adaptive stopping criteria for the fixed-stress algorithms. Numerical experiments illustrate the efficiency of our estimates and the performance of the adaptive iterative coupling algorithms.

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MS46

Augmented Lagrangian Methods for Coupling Flow and Deformation in Poroelastic Media with Non-linear Elastic Fractures

In this talk, we present a sequential iterative method for coupling flow and geomechanics in fractured poroelastic media. By considering fractures as joints, which are generated by traction, we explore the Barton-Bandis nonlinear elastic model for joints closure and construct an Augmented Lagrangian formulation seated on such a constraint. Numerical simulations are presented showing the impact of fracture distribution and closure on the magnitude of equivalent properties at coarser scales.

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MS46

Simulations of Coupled Flow and Geomechanics in Porous Media with Embedded Discrete Fractures

In fractured natural formations the flow and the geomechanical problems are strongly coupled. In fact, the hydrodynamical properties of the fractures are highly dependent on the geomechanical configuration. Thus, accurate simulation requires solving the coupled system of equations describing flow and geomechanics. In this work, we employ a finite-volume discretization for the flow equation coupled with a finite-element scheme for the geomechanics. Fractures are embedded in the rock matrix grid and their effect is captured by employing the embedded discrete fracture model (EDFM) [1,2] and the Assumed Enhanced Strain (AES) method [3,4], to represent their contribution to the flow and the mechanics, respectively. This embedded discretization allows for different grids to be used for the fractures and the matrix. EDFM considers fractures as lower dimensional entities which exchange a flux with the rock matrix. The discrete representation of the flux between the two media is directly related to how the fractures cells intersect the matrix ones. The AES method assumes, instead, a local enrichment of the FEM solution space inside each matrix cell cut by a fracture element. Numerical experiments are presented to study the convergence and the accuracy of the proposed method. A friction model is also considered in the test cases. [1] Lee et al., WRR (2001) [2] Hajibeygi et al., JCP (2011) [3] Simo et al., IJNME (1990) [4] Borja, CMAME (2008)

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MS46

Coupling of Flow and Mechanics in Fractured Porous Media

The coupled flow and geomechanical effects in fractured porous media are important. Fractures have strong influence on the flow behaviour and at the same time are the vulnerable regions for mechanical failures. We consider fractures that are big enough that they cannot be considered as a part of REV and are explicitly described by lower dimensional objects (Discrete Fracture Networks). The resulting model is a single phase quasi-static Biot model in the porous matrix coupled to a Darcy flow model on the fractures. We report here some of the developments in suitable iterative schemes for such models and their extensions. Our work has two components: 1. Developing suitable iterative schemes and 2. Developing multirate schemes by exploiting the different time scales of mechanics and flow solve by taking coarser time step for mechanics and smaller time steps for flow. We analyse these iterative and explicit multirate schemes and rigorously analyse the convergence and stability properties of these schemes.

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MS46

A Nonlinear Stokes-Biot Model for the Interaction of a Non-Newtonian Fluid with Poroelastic Media

A nonlinear model is developed for fluid-poroelastic structure interaction with quasi-Newtonian fluids that exhibit a shear-thinning property. The flow in the fluid region is described by the Stokes equations and in the poroelastic medium by the quasi-static Biot model. Equilibrium and kinematic conditions are imposed on the interface. A mixed Darcy formulation is employed, resulting in continuity of flux condition of essential type, which is weakly enforced through a Lagrange multiplier. We establish existence and uniqueness of the solution of the weak formulation using non-Hilbert spaces. A stability and error analysis is performed for the semi-discrete continuous-in-time and the fully discrete formulations. Applications to hydraulic fracturing and arterial flows are presented.

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MS47

A Finite-volume Approach to Dynamically Fracturing Porous Media

The mutual interaction between the fluid flow in fractured porous media and propagating, possibly bifurcating fractures is important for the overall systems' behavior in many natural and technical applications. We consider porous media where dominant fractures are kept in the mathematical model as geometric structures up to the Darcy scale. Those will be understood as sharp interfaces and will be represented by dimension reduced manifolds. Incompressible two-phase flow formulated in the fractional flow formulation will be considered in the bulk as well as in the fracturing domain. We propose a fully conforming Finite-Volume approach where all fractures coincide with volume edges. For the fracture network we rely on a Finite-Volume scheme formulated on manifolds. Appropriate coupling conditions are used to fix numerical fluxes orthogonal to the lower-dimensional fracture network. To track the fracture propagation we will employ a moving-mesh concept that restricts the topological changes to locally marked regions.

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MS47

Mixed-dimensional Discrete Fracture Matrix Models with Heterogeneous Discretizations and Non-matching Grids

We present a computational framework for simulation of flow in fractured porous media. The framework represents fractures and their intersections as lower-dimensional subdomains, embedded in the hosting porous media. In the computational model, porous media, fractures and intersections are represented as subdomains, and communication between the subdomains is formulated in terms of mortar variables located on the interface between subdomains. The approach allows for non-matching grids over the subdomain interfaces and is agnostic to the discretization schemes applied on specific subdomains; these can change between the subdomains. We present stability results for the scheme and provide computational results for the proposed benchmark for 3D fractured porous media ([Berre et al., 2018. Call for participation: Verification benchmarks for single-phase flow in three-dimensional fractured porous media. arXiv:1809.06926]), applying a combination of finite volume, and mixed and virtual finite element methods.

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MS47

Numerical Methods for Flow in Fractured Porous Media in a Unified Implementation

We present the following discrete-fracture methods for flow in fractured porous media: finite volume methods based on a two-point and a multi-point flux approximation, a lowest order mixed virtual element method and a lowest order Raviart-Thomas mixed finite element method. Some central strengths and weaknesses of each method are summarised and briefly discussed leading up to a short comparison of the methods. All methods are implemented in the open source simulation toolbox PorePy, which is based on a hybrid-dimensional representation of the domain, wherein the porous medium and explicitly represented fractures and fracture intersections are represented by subdomains of different dimensions. Discretisations are applied on the individual subdomains, and subdomains one dimension apart are coupled by appropriate conditions. We demonstrate advantages of the unified implementation in the context of the proposed benchmark study [Berre et al., 2018. Call for participation: Verification benchmarks for single-phase flow in three-dimensional fractured porous media. arXiv:1809.06926].

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MS47

From Discrete to Continuum Concepts of Flow in Fractured Porous Media

Abstract not available.

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MS47

A Generalized Finite Element Method for Flows in Fractured Porous Media

We consider a Darcy flow problem in fractured porous media governed by the Poisson equation. The fractures typically have a much smaller width than the length scale of the entire domain, thus can be modeled by lower dimensional interfaces for an improved efficiency. The porosity and internal interfaces give rise to a multiscale behavior of the underlying problem. In this talk, we present a variational multiscale finite element method in the localized orthogonal decomposition (LOD) framework. A special type of Scott-Zhang edge-based interpolation operator is devised, which leads to exponential decay of the corrected basis functions in the presence of interfaces. We derive a priori error estimate to prove that the method converges to first order in energy norm, even when the mesh does not resolve the fine scale features. Numerical experiments are presented to verify the analysis.

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MS48

Modeling Roots Water Uptake by Discontinuous Forcing Terms in Richards' Equation

Richards' equation, generally used for modeling the water infiltration into unsaturated soils, is a competitive tool for modeling the root water uptake activity. First, a sink term is added to the standard Richards' equation, in the θ-based form:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z} - K(\theta)\right] - R(\theta). \tag{3}$$

The sink can depend just on θ and is represented by a logistic curve, or by a Hill function: accordingly, the sigmoid curve can be replaced by a step function; the dependence of the sink term on the depth is modeled by considering

Richards' equation in layered soils, in each of which a different sink term applies, depending now just on the state variable:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z} - K(\theta)\right] - R_1(\theta), \quad \text{when} \quad z < \overline{z}, \tag{4}$$

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z} - K(\theta)\right] - R_2(\theta), \quad \text{when} \quad z > \overline{z}. \tag{5}$$

The treatment of this problem by Filippov theory is discussed.

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MS48

Plant Root Modeling via Optimal Transport

Plants are the main contributors to the mass/energy exchange between the soil and the atmosphere and have a modulating role that must be accurately simulated in climatic models. While a lot is known about their functioning in the aerial portion, lack of accurate observation has limited the understanding of the dynamics of their root system. We suggest that plant systems respond to environmental stresses by optimally allocating the newly formed biomass synthesized by photosynthesis looking for maximal efficiency of nutrient transport and minimal biomass allocation within the root system. In this work we propose a mesoscale model of plant root dynamics based on Optimal Transport (OT) theory, an expanding area of mathematics, using its particular declination called Branched Transport (BT). This framework provides a unified formulation of the leading principles believed to shape the plant morphology. All these systems can be reinterpreted as arising from problems of least-cost resource reallocation, the core theme of BT. However the BT mathematical theory has not been applied in real-word application due to the lack of efficient numerical methods. In our model, we first compute the additional biomass according to a given plant model and then use BT transport to describe how to optimally reallocate this biomass into the root system according to BT principles. Simple three-dimensional simulations are used to show the applicability of the proposed approach.

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MS48

Multiscale Analysis of Non-linear Transport Problems in Porous Media

In this talk we will review the challenges in the derivation and parametrisation of macroscopic effective models of solute and particle transport in realistic three-dimensional porous media, and present some recent advances in the field. In particular, we will focus on deterministic and stochastic approaches to model pre-asymptotic non-Fickian dispersion, and homogenisation for fast and non-linear reaction terms, such as the ones arising in surface adsorption and in particle collision and aggregation processes. Relevance for environmental and geo-energy applications will be discussed and numerical experiments will be used to identify the behaviour and the scaling of the macroscopic dispersion and reaction coefficients, with respect to the material, geometry, and flow parameters.

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MS49

Automated Verification of Earth System Models with EVV

Climate change has become an ever-pressing, complex scientific and moral challenge in today's world. In order to meet the needs of the scientific community, Earth system models (ESM) are continuously and rapidly being developed. Model changes can impact models results in one of thee ways: 1. Changes continue produce "bit-for-bit' identical solutions 2. Changes that cause numerical difference, yet produce a statistically identical climate 3. Changes that cause numerical differences and produce a different climate Only in the third case must changes undergo an extensive review before being accepted into the model. This results in a large development burden as all non-bit-for-bit changes must be treated as climate changing and undergo a time-intensive validation process. However, Earth system models don't traditionally have a robust way to distinguish between type 2 and 3 changes. EVV, a verification and validation package for ESM, has been developed to quickly distinguish between type 2 and 3 changes by including a series of solution reproducibility tests which can be easily incorporated into developer workflows and automated testing suites. These test use ensemble simulations to look at many aspects of the atmosphere to determine the impact of model changes, such as time-step convergence, state divergence, and quality of distributions. We will demonstrate EVV, explain out current testing methods, and describe how new tests can easily be incorporated into EVV.

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MS49

Evaluation of the Convergence at High Resolution in Time of an Ostensibly First-order Microphysics Model

Abstract not available.

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MS49

Addressing Convergence Issues in a Simplified Condensation Model with a Rigorous Modelling of Subgrid Processes

Modern Earth System Models (ESMs) seek to capture an ever-growing number of global processes. In the atmosphere, physical processes are coupled to a dynamical core (dycore) that solves for the atmospheric flow. Numerical techniques for this flow have been thoroughly studied in the literature. As a result, dycore development has included rigorous numerical convergence analyses. This contrasts with the physics components of the atmosphere, where a focus on incorporating more processes at refined length scales has made numerical rigor less tractable. These components are not likely to attain expected convergence order or, in some cases, attain convergence at all. One such issue has been identified in the CLUBB package. When coupled to the CAM-SE dycore, the results do not attain the first-order convergence expected. To address this, a simplified condensation model (SCM) was derived that exhibits similar convergence issues. Both alternatives to the numerical techniques used and to the mathematical derivation have been explored to regain convergence. This work focuses on the latter: constructing a well-posed model at the sub-grid scale and then connecting grid-cell averaged values expected from the ESM. This approach has identified assumptions made in the model derivation that cause convergence issues when violated. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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MS49

Loss and Restoration of Time-step Convergence in an Atmosphere Model with Simplified Physics

Earlier work revealed that the atmosphere component of the Energy Exascale Earth System Model (E3SM) and its recent predecessors showed time-convergence rates substantially lower than first-order. In this work, a simplified model is configured, which consists of the dynamical core of the E3SM atmosphere model and a parameterization describing the condensation of water vapor (or reversely, the evaporation of cloud liquid). Like E3SM, this simplified model also shows poor convergence, and the time-stepping errors are larger than those in the dynamical-core-only configuration. We show that the original choice of splitting between the resolved dynamics and the parameterized physics is inconsistent with the physical concepts behind the parameterization, which leads to the occurrence of unphysical atmospheric states that occur as singularities in the numerical solution. A revised splitting removes such inconsistency and helps to restore convergence. This work demonstrates that poor convergence in atmospheric simulations can be understood; Improving convergence not only reduces the solution sensitivity to time step size but also helps to obtain a discrete model that is more consistent with the intended representation of the physical phenomena.

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MS49

Verification of Aerosol Microphysics Parameterizations in the E3sm Atmosphere Model

Aerosols are tiny liquid or solid particles that suspend in the Earths atmosphere which have significant impacts on air quality as well as the atmospheres water and energy budget. The Modal Aerosol Module (MAM) is a comprehensive suite of parameterizations that describes various physical and chemical processes in the aerosol lifecycle. During the original development of MAM, verification was performed but with very limited code coverage, and those efforts were not well documented. This talk will describe our new effort to systematically verify the MAM code. A bottom-up approach is used where we verify one physical or chemical process at a time. Different types of numerical calculations are verified and a selection of examples will be shown.

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MS50

Discontinuous Galerkin Method for Solving the Black-oil Problem in Porous Media

We introduce a new algorithm for solving the three-component three-phase flow problem in two dimensional and three-dimensional heterogeneous media. The oil and gas components can be found in the liquid and vapor phases whereas the aqueous phase is only composed of water component. The numerical scheme employs a sequential implicit formulation discretized with discontinuous Galerkin finite elements. The scheme operates the same independently of effect of phases appearance and disappearance. It also includes the action of capillary pressures and gravity effects. The convergence properties of the algorithm are tested with manufactured solutions. The method is also shown to be accurate and robust when phases appear or disappear with various tests involving mass transfer between the liquid and vapor phases, gravity effect and heterogeneous media with a random-generated absolute permeability of large ratio. Applications to the generation of viscous finger is also discussed.

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MS50

Numerical Study of Coupled Free Flow with a Poroelastic Medium

In this talk I will discuss a continuous finite element scheme for the coupled system of time dependent Stokes and fully dynamic Biot equations. The scheme is based on standard inf-sup stable elements in space and a Backward Euler scheme in time. I will present numerical results on manufactured solutions to verify theoretical convergence rates as well as realistic test cases to demonstrate the effectiveness of a heuristic pressure stabilization technique in the pore pressure solution.

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MS50

Modeling and Numerical Methods for Coupling Dual-porosity Flows and Free Flows

We consider a new model for confined flow in dual-porosity media coupled with free flow in embedded macro-fractures and conduits. The flow in dual-porosity media, which consists of both matrix and micro-fractures, is described by a dual-porosity model. And the flow in the macro-fractures and conduits is governed by the Stokes equation. Then the two models are coupled through four physically valid interface conditions on the interface between dual-porosity media and macro-fractures/conduits, which play a key role in a physically faithful simulation with high accuracy. The weak formulation is derived for the proposed model and the well-posedness of the model is analyzed. A finite element method is developed and analyzed to solve this model. Numerical experiments are presented to illustrate the proposed model and method.

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MS50

A Posteriori Error Estimates and Stopping Criteria for Space-time Domain Decomposition for Two-phase Flow with Discontinuous Capillary Pressure

We consider two-phase flow in a porous medium composed of different rock types, so that the capillary pressure field is discontinuous at the interface between the rocks and creates a capillary trap for oil or gas. This is a nonlinear and degenerate parabolic problem with nonlinear and discontinuous transmission conditions on the interface. We describe a space–time domain decomposition (DD) method based on the Optimized Schwarz Waveform Relaxation algorithm (OSWR) with Robin or Ventcell transmission conditions. Space-time subdomain problems across the time interval are solved at each OSWR iteration, and the exchange between the subdomains uses time-dependent and higher order transmission operators. Numerical approximation is achieved by a finite volume scheme, using the Matlab Reservoir Simulation Toolbox. We then show how a posteriori error estimators, based on reconstruction techniques for pressures and fluxes, lead to efficient stopping criteria for the DD iterations. The estimators are split into different components corresponding to the space and time discretization errors, and to the errors due to the Newton linearization and the DD iterations. The DD iterations can be stopped as soon as the DD estimator becomes smaller than the discretization estimators.

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MS51

Seismic Tensor Completion

Abstract not available.

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MS51

How Much Information is there in Dense, Continuous Seismic Data?

New technologies (e.g. wireless nodes, MEMS accelerometers, fiber optic sensors) have made continuous seismic data acquisition with dense sensor arrays increasingly affordable. Already, academic seismic data repositories are unable to accommodate these large datasets, and manual interpretation or denoising of raw data has become infeasible for many groups. Since September 2016 we have continuously recorded seismic data on 620 sensors along a 2.5 km fiber in underground telecom conduits under Stanford with two goals: ambient noise interferometry for near-surface imaging, and earthquake detection. The data have a clear heartbeat, with trends from day to night, weekdays to weekends, and seasonally. Even with temporal redundancies, analysis of all data shows there is added certainty in estimates of surface wave dispersion (important for earthquake hazard analysis) from longer recordings with certain types of repeated loud noises removed. To reduce the human effort needed to explore these data, we tested several clustering and neural network methods, which show high accuracy in removing car recordings from data. This automatic noise removal method greatly reduces manual labor and improves convergence rates of surface wave dispersion estimates. We also show results of data compression via wavelet transforms and low-rank decompositions, treating these data as first a matrix, then a tensor. We compare surface wave dispersion estimates from compressed and full fidelity data.

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MS51

Comparison of Tensor and Matrix Completion

Many methods currently exist for recovery of missing data in 2D datasets. Tensor based methods generalize these approaches to apply to higher dimensional datasets. However, high dimensional datasets can be deconstructed and interpreted as multiple 2D datasets. I will present my analysis of the tradeoffs in accuracy and computation time from applying tensor based methods with their corresponding matrix based method on high dimensional datasets. Additionally, I will compare different recovery methods and their effectiveness on a diverse range of datasets.

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MS51

A Robust Tensor Completion Method and its Application to 5D Seismic Data Reconstruction

Seismic data are represented by a 5D volume that depends on x,y source and receiver positions and time. Reflection seismology uses these data to image Earth's interior. Field data is often unevenly sampled and contaminated by random and coherent noise. We discuss a robust tensor completion method to reconstruct 5D seismic volumes. The seismic data reconstruction problem is posed as a low-rank tensor completion problem. Our algorithm also adopts a robust error measure to avoid contaminating the final reconstruction by large amplitude erratic noise that is often encountered on onshore seismic surveys.

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MS52

Frequency-dependent Seismic Reflectivity of Randomly Fractured Fluid-saturated Media

Fractures exist on a wide range of scales from microns to hundreds of meters, having a significant influence on fluid flow and physical properties of rocks. The average elastic properties of a randomly fractured fluid-filled rock are discussed for fracture distribution laws in association with the extremely slow and dispersive guided wave propagation within individual fractures. Krauklis wave is used as an asymptotic solution of the fluid interface wave (FIW) equations. Different fracture distribution laws within rocks in the seismic range of frequencies ($10-100$Hz) initiated high-velocity dispersion and attenuation of the P-wave. Different cases of acoustic impedance (AI) distributions vs. depth for assessing reflection properties from fractured and non-fractured layers are considered. Results demonstrate the remarkable difference for the P-wave reflection coefficient (RC) in the fractured and non-fractured layers. The biggest difference in the behavior of RC versus incident angle is observed at seismic low-frequencies (<15Hz). The thickness related tuning effect has the different impact on the seismic signal in the fractured and homogeneous. The results allow an interpretation of abnormal velocity dispersion, high attenuation, and special behavior of RC vs. frequency as the indicators of fractures. The numerical modeling explains a low-frequency seismic anomaly in fractured zones within source rock in the East-Surgut Basin, Western Siberia.

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MS52

A Global Sensitivity Approach for Optimizing Hydraulic Fracture Propagation and Recovery in Horizontal Wells

In this talk, we employ a global sensitivity analysis on a fully-coupled poroelastic geomechanical model, primarily, to understand the reorientation of the principal stresses in a depleted zone of the reservoir over time. Identifying this reorientation is crucial to the propagation direction of any new hydraulic fracture in the depleted zone. The developed model has applications in the stimulation of offset wells that may negatively affect the production and recovery of legacy and infill wells. We account for the fully-coupled relationship between pore pressure and stresses in the rock. Also, we use the Sobol sensitivity analysis a popular variant of global sensitivity methods that can systematically account for the variation of the outputs due to change of the whole range of inputs to identify the parameters that control the behavior of the infill wells hydraulic fracture. The input parameters include injection pressure, spacing of the parent wells fractures, geomechanical properties of the reservoir, hydrodynamic properties of the reservoir, and drainage from legacy well. Using representative results, we provide useful insights for selecting parameters that affect the performance of a child fracture propagating near a depleted zone. Finally, using the global sensitivity analysis, we suggest a reduced order model to calculate pressure as stresses at different locations around hydraulic fractures, which can be employed in numerical simulator to speed up calculations.

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MS52

Acoustic Waves Propagation in Fractured Porous Materials: High and Low Frequency Approximation

An asymptotic homogenization procedure is developed for acoustic waves propagation in multi-scale periodic heterogeneous medium. We suppose the existence of several length scales. The smallest spatial scale is the size of a miscrocrack or a micropore. The mezoscale is the characteristic size of representative elementary volume (REV) consisting of regularly distributed heterogeneities, and then we have a global macroscopic characteristic size of the material. The low-frequency approximation assumes the situation where the wavelength exceeds the mesoscales characteristic size. The high frequency approximation implies the same order of magnitude for these two characteristic lengths. For low-frequency and high-frequency cases we propose asymptotic expansions which allow us to replace a real heterogeneous materials with effective media. Resulting homogenized equations are deduced explicitly dependent on the macroscale with micro- and mesoscale represented by effective coefficients in low-frequency case and by integral quantities in the case of high frequency approximation. We study the effect of heterogenieties on the dispersion and attenuation of propagating waves. In high frequency case, solution of the dispersion equation reveals the fact that some waves frequencies can be forbidden from propagating through the material due to the peculiarities of structure on micro and mezo levels.

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MS52

CFD-DEM Modeling of Fracture Initiation Induced by Fluid Injection

Abstract not available.

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MS52

Nonlinear Elasticity with Density Dependent Material Properties: Acoustic Behavior with Application to Modeling Damage Initiation in Porous

Media

Most materials exhibit some degree of density dependent constitutive properties. For porous materials, this dependence is often significant and can be correlated with damage initiation and progression. This talk presents recent results on a model of damage formation and progression for a fully nonlinear elastic body with density dependent material properties. In this setting, complete material failure is predicted through a strong instability occurring at a critical loading threshold. Of particular interest is wave propagation and its use in anticipating when the instability threshold occurs at points interior to the body.

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MS53

Mathematical and Computational Challenges for Multi-phase Porous Media Flows in Chemical EOR

In this talk, we will first give an overview of recent progress made by our team in the modeling, simulation and stability studies of multi-component multi-phase fluid flows arising in the context of chemical EOR. Then we will discuss some current ongoing work in this area motivated by a need to develop proper modeling and simulation techniques for displacement processes involving one or more non-Newtonian fluids. There are challenges at various levels including stability studies of such flows which we will discuss in this talk. This work has been possible due to the financial support from the U.S. National Science Foundation grant DMS-1522782.

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MS53

Results on the Stabilization of Fingering Instabilities in Porous Media Flows

The viscous fingering instability is an important limiting factor in oil recovery. In order to design efficient flooding schemes of chemical enhanced oil recovery, we have been investigating this instability for multiphase multi-component immiscible Newtonian fluid flows with more than two fluid regions in rectilinear and radial geometries [1,2,3]. In this talk, we present some recent results on the stability of multi-layer radial Hele-Shaw flows of Newtonian fluids. In particular, we consider time-dependent injection strategies and how they are affected by increasing the number fluid layers. We also look at the stability of flows that contain a fluid with variable viscosity. Results to be presented are based on current ongoing and as yet unpublished work of the authors. This work has been possible due to the financial support from National Science Foundation grant DMS-1522782. This is based on joint work with Prabir Daripa. [1] P. Daripa, *Hydrodynamic Stability of Multi-Layer Hele-Shaw Flows*, J. Stat. Mech. 2008 (2008) 32 pages, Article No. P12005. [2] P. Daripa, *Studies on Stability in Three-Layer Hele-Shaw Flows*, Phys. Fluids,**20**, Issue 11 (2008) Article No. 112101. [3] C. Gin and P. Daripa, *Stability Results for Multi-Layer Radial Hele-Shaw and Porous Media Flows*, Phys. of Fluids, **27**, 012101 2014.

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MS53

On the Immiscible Displacement of Viscoelastic Fluids in a Hele-Shaw Cell

Hele-Shaw flow has long been used as a prototype model for porous media flow due to the Darcy law used in both problems. However, the procedure used to derive the Darcy law from Hele-Shaw flow does not apply to the non-Newtonian case, except in certain asymptotic limits where the fluid effectively becomes a generalized Newtonian fluid. Since a dilute polymeric solution is often used in the driving fluid layer in chemical EOR, this motivates us to investigate the interface problem in Hele-Shaw cell where now the involved fluids are non-Newtonian. In particular, two immiscible and incompressible Oldroyd-B fluids are confined in a doubly infinite rectilinear Hele-Shaw cell. The linear stability of the fluid-fluid interface is studied using the classical normal mode approach on a set of simplified governing equations obtained within the thin gap approximation while the Debroah number is kept in the moderate range so that elastic features of the fluids are preserved in the equations. Through the use of a pre-averaged version of the interface conditions, the dispersion relation and some bounds on the unstable modes are derived. Numerical results may be presented if time permits. The talk is based on current ongoing work. This work has been possible due to the financial support from the U.S. National Science Foundation grant DMS-1522782. The talk is based on joint work with Prabir Daripa of Texas A&M University.

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MS53

Pore-Scale Analysis of Interfacial Instabilities in Porous Media

Fluid displacement in porous media is an important class of flow to understand enhanced oil recovery mechanisms in complex environments. Immiscible fluid interface instabilities during flow through porous media occur often and the prediction of water and oil flow pattern is essential to determine the efficiency of oil recovery processes. Although numerous experimental and numerical studies have been conducted in the past to reproduce and analyze the interfacial instabilities during immiscible fluid displacement in porous media, only a few of such studies show the flow details at complex 3-D pore-scale and relate the mechanisms to macroscale information. In order to better understand the interface instabilities phenomenon under different force balance conditions, Several pore-scale LBM simulations have been carrier out which will be presented in this talk. The talk is based on joint work with Zhipeng Zhu at LSU

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MS54

A Survey of Recent Advances in Storm Surge Simulations

In this talk we will review the methodological advances of storm surge and flood predictions over the years. This will comprise an overview over available measurement data, numerical algorithms as well as hazard quantification and risk management. Meteorological and hydrological data is crucial for accurate flood predictions. Historical hydrological records are still useful today although, nowadays, we mainly depend on sophisticated networks of a range of measurement devices. To a large extent, todays forecasts are based on computer simulations. Increasing computational resources allow us to simulate flood events with higher accuracy and the continuous improvement of numerical algorithms contributes to an efficient usage of high-performance computers as well as our understanding of the relevant underlying physical processes. Flood predictions play an important role in hazard assessment and the development of warning tools and mitigation strategies. They form the basis of the decision making process of whether to close barriers or evacuate certain areas with the aim to protect coasts and their population during storm events.

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MS54

Modeling Hurricane Waves and Storm Surge

We will discuss advances in modeling storm surge and waves through the use of high performance computational algorithms. We will point out recent successes in real-time storm surge forecasting and the accuracy of the forecasting models. We will also discuss research on advancing algorithms and high performance computing infrastructure for storm surge modeling on future computer architectures.

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MS54

A Green's Function Approach to Efficient Shallow Water Uncertainty Quantification

In order for communities to assess impending risks and prepare for flood events, they must rely on time-intensive nonlinear forecast models. It is important to characterize uncertainty of flood predictions in real-time to optimize resilience. Variance estimation of forecast models typically relies on ensemble forecasting, severely compounding the time required. We propose an efficient and flexible methodology for ensemble forecasting which circumvents the need for repeated random sampling of a nonlinear model. The method uses numerical Green's functions for a set of linearized perturbation dynamics to quickly compute ensembles of perturbed solutions to a given forecast. Kriging is then used to immediately interpolate statistical information (variance) within the domain of interest, providing timely results to communities and stakeholders. The method is demonstrated as a proof of concept for the shallow water equations, in particular for initial condition problems such as a tsunami, and discussed is the applicability to other problems such as storm surges as well as incorporating some other sources of uncertainty in these geophysical processes.

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MS54

Surge Dynamics Across a Complex Bay Coastline, Galveston Bay, Tx

Abstract not available.

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MS54

Application of Adjoint Methods to Storm Surge Sensitivity Analysis

An accurate surge forecast model relies on accurate model inputs, typically including atmospheric forecasts with large associated uncertainties. These uncertainties must therefore be propagated through the surge model to estimate the resulting uncertainty in the surge prediction. Adjoint techniques provide a computationally efficient method to compute the sensitivities of a numerical model with respect to its inputs, and can thus be used to complement ensemble methods in quantifying the effect of input uncertainty on a surge prediction. Here we use the Thetis coastal ocean model, which is based on the Firedrake finite element code generation framework, to establish an unstructured mesh shallow water tide-surge model. Using the North Sea surge of December 2013 as a case study, the model is validated/calibrated using tide gauge data, with the UK operational surge model a benchmark for model performance. The adjoint is readily available within Firedrake-based models, via the use of pyadjoint to automatically generate adjoint code. Here we apply the Thetis adjoint model to compute the sensitivities of tide and surge hindcast simulations with respect to their inputs, and discuss the implications for forecast modelling.

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MS55

Upscaling of Multi-phase Flow and Transport using Non-local Multi-continuum Approach

We discuss a novel multi-phase upscaling technique, which uses rigorous multiscale concepts based on Constraint Energy Minimization (CEM-GMsFEM). CEM-GMsFEM concepts use local spectral problems to design multiscale basis functions, which are supported in oversampled regions. The coarse-grid solution using these basis functions provides first-order accuracy with respect to the coarse-mesh size independent of high permeability contrast. The degrees of freedom in multiscale methods represent the coordinates of the solution in the multiscale space. To design an upscaled model, we modify these basis functions such that the degrees of freedom have physical meanings, in particular, the averages of the solution in each continua. This allows rigorous upscaled models and account both local and non-local effects. The transmissibilities in our upscaled models are non-local and account for non-neighboring connections. To extend to nonlinear two-phase flow problems, we develop non-linear upscaling, where the pressures and saturations are interpolated in an oversampled region based on averages of these quantities. Multicontinua concepts are used to localize the problem to the oversampled regions. Our upscaled model shares some similarities with pseudo-relative permeability approach with the following differences: (1) upscaled relative permeabilities are non local depend on pressures; (2) local problems, in oversampled regions, involve constraints and require multi-contiuum concepts.

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MS55

Multiscale Formulation for Pore-scale Compressible Darcy-Stokes Flow

Direct numerical simulation of fluid dynamics in digital images of porous materials is challenging due to the cut-off length issue where interstitial voids below the resolution of the imaging instrument (i.e., microporosity) cannot be resolved. A micro-continuum framework can be used to address this problem, which applies to the entire domain the Darcy-Brinkman-Stokes (DBS) equation that recovers Stokes equation in the resolved macropores and Darcy equation in the microporous regions. However, the DBS-based micro-continuum framework is computationally demanding. Here, we develop an efficient multiscale method for the compressible Darcy-Stokes flow arising from the micro-continuum approach. The method decomposes the domain into subdomains that either belong to the macropores or the microporous regions, on which Stokes or Darcy problems are solved locally, only once, to build basis functions. The nonlinearity from compressible flow is accounted for in local correction problems. A global interface problem is solved to couple the local bases and correction functions to obtain an approximate global multiscale solution, which is in excellent agreement with the reference single-scale solution. The multiscale solution can be improved through an iterative strategy that guarantees convergence to the single-scale solution. The method is computationally efficient and well-suited for parallelization to simulate fluid dynamics in large high-resolution digital images of porous materials.

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MS55

Nonlinear Multigrid Solvers for Finite Volume Problems using Spectral Coarsening

We present nonlinear multigrid solvers using full approximation scheme (FAS) for nonlinear partial differential equations discretized by finite volume method. The hierarchy in the multigrid is provided by a multilevel algebraic coarsening method for graph Laplacians, which is based on local spectral decomposition. This multilevel coarsening method is an extension of the two-level method introduced in [Barker, Lee, and Vassilevski, Spectral Upscaling for Graph Laplacian Problems with Application to Reservoir Simulation, SISC, 39(5), S323–S346]. In order for FAS to be effective, it is important that the coarse spaces have good approximation property. The latter can be improved by adding more local spectral basis functions, as observed in our numerical experiments.

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MS55

Multiscale Data-model Integration using an Event-driven Approach for Understanding Nutrient Cycles in Plant-microbe-soil Systems

The rhizosphere is a complex system in which many diverse and heterogeneous small-scale components (e.g, plant roots, fluids, microbes, and mineral surfaces) interact with one another, often in nonlinear ways, giving rise to emergent system behaviors. Ecosystem-scale perturbations, such as nitrogen limitation or drought, drive changes in micro-environments through a cascade of complex interacting processes, leading to a bidirectional feedback across scales between microbial and plant habitats at the microscale and ecosystem function at the macroscale. We are developing a modular and extensible simulation framework based on event-driven execution of integrated data processing and multiscale modeling scientific workflows. The framework is enabled by a recent development in information technology known as orchestration, a class of solutions to problems of deployment and execution of cloud-oriented software. Orchestration technology is well-suited to automating complex scientific workflows, both in model-coupling efforts and experimental analysis pipelines. It is being applied to integrate several community software packages spanning scales from molecules to ecosystems, linked to experimental data from the Environmental Molecular Sciences Laboratory (a national scientific user facility), to address critical scientific questions related to soil nutrient cycling.

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MS55

Multi-scale Modelling Based on Non-linear Finite-volume Schemes

Many important applications in porous media like CO2-Storage, EOR, remediation of groundwater, etc., require large scale simulation of complex physical processes. Due to limitations of computational resources huge model domains often have to be simulated on relatively coarse grids. However, porous media are in general heterogeneous on all spatial scales and the smallest length scale which is important determines the required discretization resolution. One solution strategy is provided by multi-scale methods which allow to decrease the global degrees of freedom while preserving important features. In previous work, we have combined adaptive grid methods based on multi-point flux approximation or mimetic schemes with different local up-scaling techniques. Up-scaling of multi-phase parameters is based on a capillary equilibrium assumption, where resulting effective parameters like relative permeabilitys can be full second order tensors. Especially, the correct treatment of these anisotropic coefficients is a challenge for the numerical scheme. In this talk, we present a combination of these approaches with recently developed nonlinear finite-volume schemes. It is demonstrated for different test cases that these nonlinear finite-volume schemes can accurately resolve multi-scale processes.

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MS56

Coupling Fem and Meshfree Peridynamics for Efficient Simulation of Hydraulic Fracturing

Abstract not available.

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MS56

Fully Coupled Multimesh Algorithms for Non-isothermal Multiphase Flow and Mechanics in Geological Formations

Abstract not available.

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MS56

Constrained Energy Minimization Based Upscaling for Coupled Flow and Mechanics in Fractured Porous Media

In this work, our aim is to present (1) an embedded fracture model (EFM) for coupled flow and mechanics problem based on the dual continuum approach on the fine grid and (2) an upscaled model for the resulting fine grid equations. The mathematical model is described by the coupled system of equation for displacement, fracture and matrix pressures. For a fine grid approximation, we use the finite volume method for flow problem and finite element method for mechanics. Due to the complexity of fractures, solutions have a variety of scales, and fine grid approximation results in a large discrete system. Our second focus in the construction of the upscaled coarse grid poroelasticity model for fractured media. Our upscaled approach is based on the nonlocal multicontinuum (NLMC) upscaling for coupled flow and mechanics problem, which involves computations of local basis functions via an energy minimization principle. This concept allows a systematic upscaling for processes in the fractured porous media, and provides an effective coarse scale model whose degrees of freedoms have physical meaning. We obtain a fast and accurate solver for the poroelasticity problem on a coarse grid and, at the same time, derive a novel upscaled model. We present numerical results for the two dimensional model problem.

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MS56

Phase-field Fracture Modeling of Fluid-filled Fractures in Porous Media

In this presentation, we consider modeling and numerical simulations of fracture propagation in porous media using a phase-field technique. A smoothed indicator function determines the crack location and is characterized through a model regularization parameter. In addition, modeling assumes that the fracture can never heal, which is imposed through a temporal constraint, leading to a variational inequality system. For reliable numerical simulations, key aspects are robust and efficient algorithms for imposing the previously mentioned crack irreversibility constraint, treatment of the indefinite Jacobian matrix, and local mesh adaptivity for a high mesh resolution of the fracture zone. As applications, we focus on multiphysics phase-field fracture such as pressurized fractures and fluid-filled fractures in porous media that include achievements as well as current limitations. Recent advancements include phase-field fracture models for proppant flow and two-phase flow inside the fracture. References:

- S. Lee, A. Mikelic, M. F. Wheeler, T. Wick; Phase-field modeling of two phase fluid filled fractures in a poroelastic medium, SIAM Multiscale Modeling and Simulation (MMS), accepted in July 2018
- S. Lee, M.F. Wheeler, T. Wick; Iterative coupling of flow, geomechanics and adaptive phase-field fracture including level-set crack width approaches, J. Comput. Appl. Math., Vol. 314 (2017), pp. 40-60

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PP1

Efficient Numerical Solution for 3D Partial Differential Equation

In this poster, we consider the solution of the steady flow in a three-dimensional lid-driven cavity using numerical methods. The three-dimensional velocity-vorticity formulation, used by Davies & Carpenter (2001), is considered. The cubical lid-driven cavity problem is solved. The problem is discretized using the Chebyshev discretization in the y and z directions, and fourth-order finite differences are used for the discretization in the x direction. Newton linearization is used to linearize the problem and a direct solver is devoted to solve the problem. The problem has been coded in both the MATLAB and FORTRAN environments. The lid-driven cavity problem is used typically to test new methods and codes. The lid-driven cavity can be introduced as a fluid contained in a cube domain with stationary rigid walls and a moving wall.

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PP1

Mathematical Modelling of the Removal of Micropollutants.I Linear Cometabolism Model

Prior to their discharge into rivers, municipal and industrial wastewaters are treated to reduce the pollutant concentration being discharged into the environment. There is growing concern as to whether wastewater treatment plants are able to effectively reduce the concentration of micropollutants that are contained in their in uent streams. We investigate a mathematical model for the removal of micropollutants by wastewater treat- ment plants taking into account the three main mechanisms of micropollutant removal: biodegradation, cometabolism, volatilisation and sorption. Biodegradation is modeled by a linear cometabolism model. Steady-state analysis is used to investigate the removal of the micropollutant and to identify the most effective mechanisms for their removal.

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PP1

Equilibrium Statistics and Entropy Computation for Vortex Filaments on a Cubic Lattice: A Modified Pivot Algorithm

We present an extension of the results obtained by Chorin and others in the early 90s on the equilibrium statistics of the vortex filaments constrained to the cubic lattice. We present the pivot algorithm for generation of self-avoiding walks and its modification that allows to extend the computational results to a much wider range of temperatures, both positive and negative. We also discuss a way to reliably estimate the entropy of such filaments using the hypothetical scanning method of Meirovitch and another, computationally efficient algorithm if average energies are known.

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PP1

Modeling Ice/Water Phase Transition at the Porescale

We consider phase field models for phase transitions in porous media at the porescale. Phase field theory describes a situation where multiple phases are present, and it pays particular attention to the evolution of phase interfaces. Each phase is modeled using a heat diffusion parabolic partial differential equation, but accounting for the interface evolution and, e.g, latent heat at phase transitions leads to a nonlinear free boundary problem. We consider phase field models and their numerical approximation using both smooth and non-smooth energy functionals, with different stabilizing and destabilizing parts. In particular, we consider convexity splitting, formulating the numerical algorithm based on the expansive and contractive term at each time step. We compare various approaches, and present applications to crystal formation at the porescale.

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PP1

Performance and Cost Analysis of Single and Double U-Tube Ground Heat Exchangers

Vertical U-tube ground (or borehole) heat exchangers (GHEs) are widely used as shallow geothermal energy systems to achieve sufficient heat exchange capacity under a confined surface area. This is possible because the temperature below a certain depth remains constant over the year. The presence of more than one U-tubes in the GHE in a single borehole may increase the efficiency of the system. It is hence of interest to study the performance of such systems in relation to their manufacturing/installation costs. The scope of this study is to compare the energy behavior of a single U-tube GHE with a double one. The performances of two such systems, installed under similar ground characteristics, are studied via a Building Management System for a certain time period. The energy dissipated in the ground is obtained by measuring/considering mass, specific heat capacity and temperature difference in the system. Then, a CFD model based on the convection-diffusion equation and transient time analysis is validated through the installed systems. The numerical model allows for parametric analyses and comparisons of the two systems, leading to a cost analysis.

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PP1

Re-stating the Four-Color Theorem, using Graph Theory

We claim that any planar map can be converted to a planar graph. Once converted, we have to determine the degree of the graph. The degree of a given planar graph may be defined as the number of vertices that connect to a given node, that has the greatest number of vertices. The number of colors necessary to color a given map is determined by the country that has the most neighbors, as specified by the degree of the corresponding graph. If the degree is 0, we have only one country, and need only one color. If the degree is 1, we have pairs of contiguous countries and we need only two colors. If the degree is 0 modullus 2 different from 0, we need two to three colors. If the degree is 1 modullus 2 different from 1, we need three to four colors. That exhausts all the possibilities, so we conclude that any given planar map may be colored with at most four colors. The number of colors necessary depends only on the degree of the graph. This is a re-statement of the Four-Color Theorem, using graph theory. However, how do we prove the theorem? We propose a challenge. This version of the theorem may be proved either by mathematical induction, or by contradiction. Alternatively, it may also be disproved by a counterexample, if the proof is mistaken.[1]

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PP1

Seismic Data Interpolation and Denoising based on Orthogonal Tensor Dictionary Learning

This talk will be on a novel method based on tensor-based dictionary learning which can avoids the vectorization step for sparse representation of seismic data during the reconstruction process. The choice of sparsity-promoting dictionary is a key step in sparsifying signals. When we deal with high dimensional seismic data, many existing dictionary learning methods would be computationally in feasible. Moreover, these methods deal with vectorization which likely to destroy the inherent ordering information of the data and reduce the discriminability and expressibility of the resulting representation. In this talk, we will focus on the orthogonal tensor dictionary which is a learning based method for both denoising and reconstruction of missing seismic traces. The orthogonal tensor dictionary learning that learns a dictionary from the input data by employing orthogonality and separability is proposed as sparse regularization to achieve seismic data interpolation and denoising to overcome these stated drawbacks. The separability of the dictionary makes the result by the proposed

[1] I would like to propose a minisymposium to be held in approximately one year, to discuss this re-statement; and its proof.

method to highly scalable and orthogonality among dictionary atoms leads to a very efficient sparse coding computation while solving the proposed optimization problem of the proposed method. The performance of the proposed method in seismic data interpolation and denoising individually as well as simultaneously will be presented.

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PP1

Simulating the Viscous Fingering Effect in Porous Media

When producing oil from a reservoir, a common strategy to optimize the amount of recoverable oil available is to inject water into the reservoir to displace the oil and push it towards the well. However, in certain reservoir scenarios, this process can lead to the physical phenomena known as the viscous fingering effect, which causes the injected water to branch out in a finger-like pattern throughout the reservoir. These branches of water greatly reduce the amount of recoverable oil available; thus, the ability to accurately and efficiently model this phenomena is critical in mitigating its effect in the oil recovery process. The objective of this project is to provide computational results simulating the viscous fingering effect for immiscible, 2 phase flow. Results are generated in 2D utilizing an iterative-sequential solver. A mesh and order (h and p) refinement study is performed to give validity to the location and shape of the fingers, as well as understand their convergence properties under each scenario. The PDE system is solved using a discontinuous Galerkin (DG) numerical scheme; utilizing the DG method to study the immiscible, 2 phase viscous fingering effect in such a way has never been done before to our knowledge. Analyzing the viscous fingering effect in such a way would provide significant understanding in the behavior of said fingers during computational simulations.

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PP1

Economics of a Sustainable Geothermal System for Air-conditioning a Typical House in Moderate Climates

Air-to-Air Heat Pumps (HPs), used for air-conditioning buildings are very efficient as they use the atmosphere as heat source/sink to absorb/reject heat. Yet, in a town in summertime for example, heat is collectively rejected to the surrounding environment, increasing its temperature in the absence of breeze. A sustainable way of utilizing HPs is the use of the deeper ground layers around a building to absorb/reject heat with ground heat exchangers (GHEs). Such systems, shallow geothermal energy systems (SGES), exhibit increased HP efficiency, minimizing electricity expenses, as in summer the ground has lower temperature than the air in the environment (vice-versa in winter). The evolution of SGES has led to competition with Air-to-Air HPs and the manufacturing of custom-designed inverter technology ducted series HPs. This paper studies the SGES case of a typical house thermal load in moderate climate, through an experimentally validated CFD model based on the convection-diffusion equation and transient time analysis. Water inlet temperatures are examined for summer/winter. The GHE length is optimized and the power rejected to the ground is discussed with regard to system efficiency, affected by the fluid temperature entering the HP. A lower entering fluid temperature increases the system cost as the GHE will need more boreholes for temperature reduction. A cost analysis and a comparison of total energy savings is also done.

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PP1

Fast Least-Squares Reverse Time Migration with Hessian Matrix Approximated by the Superposition of Kronecker Product

Least-squares reverse time migration (LSRTM) for complex fields imaging becomes an increasingly popular imaging method as it does not impose a limitation on the dips of reflectors. It also enjoys some other advantages. For example, it is capable of attenuating migration artifacts, compensating the image amplitude which is distorted by geometrical spreading, improving resolution via compressing the seismic source wavelet and it can also handle incomplete and noisy data. However, the massive computational overhead of LSRTM poses a big challenge for modern super-computers and its computation time can easily exceed hundreds of hours. To overcome the shortcoming above, we propose a fast alternative method for LSRTM. The new approach is formulated in model (image) domain. The Hessian matrix is approximated via the sum of Kronecker products which honour the block-banded characters of the Hessian matrix. Our numerical tests show the computation time is reduced significantly (50Hs to 3minutes on a 40 cores cluster) and the result of the proposed method is comparable to the output of conventional LSRTM. Also, approximating the Hessian matrix by a superposition of Kronecker products permits for an efficient exploration of trade-off parameters between data fitting term and a constraint.

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PP1

Advances in use of Meshless Computational Methods in Geosciences and Related Topics

Seldom does one encounter an investigation in a Geoscience topic that is not accompanied by a computer modeling application describing the situation. Research into improvements to computational methods continues with advances providing increased computational accuracy and reduced computational burden. One category of such research in computational methods includes the techniques generally classified as "meshless methods". Research continues in improving computational efficiency in the more classical mathematical approximations, such as the Fourier or Taylor Series. In the meshless methods, the procedures can be viewed as finite linear sums of selected basis functions, with coefficients determined based on a collocation procedure or other error-minimization technique such as minimization of a selected Lp-norm residual. For example, solving a steady state soil-water flow situation in an earthen slope susceptible to mass wasting may be investigated using basis functions that involve singularities. In this work, we will discuss the progress made in our ongoing research towards optimization of the nodal point locations and associated collocation points, minimizing computational error. It will be shown that the presented algorithm procedure will locate nodal points such as to maximize their effectiveness in modeling the governing PDE, and hence reduce the number of nodal points required as well as the computational error.

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PP1

Impact of Time-dependent Wettability Alteration on Capillary Pressure

Wettability plays an important role in porous media applications such as enhanced oil recovery and CO_2 storage in terms of capillarity. In many applications, the wetting property of the rock surface is assumed to be static. However, the compositions of many fluids are capable of altering the wettability of rock surfaces continuously in time. Core-scale experiments have shown a time-dependent WA that significantly alters the Darcy-scale capillary pressure. Due to the dynamics in WA, the standard capillary pressure model that assumes static wettability may be insufficient to describe the flow physics. We simulate capillary pressure curves using a bundle-of-tubes approach, where a Langmuir type model for WA is introduced at the pore-scale. The simulated curves are used to understand the nature of WA induced capillary pressure. Based on the information acquired from the simulated data, we proposed a capillary pressure model that considers the impact of time-dependent WA mechanisms. Further, we showed that WA can lead to significant hysteresis in capillary pressure-saturation relations which is not seen in the standard bundle-of-tubes model. This study shows the importance of time-dependent WA for determining capillary pressure over time scales of weeks and months.

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PP1

Inelastic Wedge Failure and Along-Strike Variations of Tsunami Generation in the Shallow Subduction Zone

One important puzzle about the 2011 Tohoku tsunami is that the largest tsunami heights were observed along the Sanriku coast (between 39 and 40N), 100 km north of where the largest slip (¿50 m) occurred at the trench (38N). Tsunami inversions suggest that near-trench slip needs extend further north of 39N, however, bathymetry surveys north of 39N before and after the 2011 Tohoku earthquake indicate no large slip at the trench. Here we show that inelastic wedge failure can probably solve this puzzle. In the Japan subduction zone the amount of sediments in the overriding wedge increases from south to north. We construct a 3D shallow subduction earthquake model allowing wedge failure, with a closeness-to-failure (CF) parameter larger in the north motivated by the above observation. Our simulations show that large slip at the trench occurs in the south due to wedge far from failure (small CF), which causes large horizontal seafloor displacement and small uplift because of shallow fault dip. However, in the north, due to large presence of sediments (large CF) the inelastic deformation in the wedge diminishes the fault slip at the trench, but causes uplift efficiently landward from the trench, similar to our previous 2D results. The uplift in the north can be well more than twice larger than in the south. This along-strike seafloor uplift pattern is consistent with the tsunami height observations of Tohoku tsunami, suggesting possible biases in elastic dislocation models.

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PP1

A Model Reduction Method for Multiscale Elliptic PDEs with Random Coefficients using an Optimization Approach

In this paper, we propose a model reduction method for solving multiscale elliptic PDEs with random coefficients in the multiquery setting using an optimization approach. The optimization approach enables us to construct a set of localized multiscale data-driven stochastic basis functions that give optimal approximation property of the solution operator. Our method consists of the offline and online stages. In the offline stage, we construct the localized multiscale data-driven stochastic basis functions by solving an optimization problem. In the online stage, using our basis functions, we can efficiently solve multiscale elliptic PDEs with random coefficients with relatively small computational costs. Therefore, our method is very efficient in solving target problems with many different force functions. The convergence analysis of the proposed method is also presented and has been verified by the numerical simulation.

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PP1

Two-scale Finite Volume Method for Flows in Fractured Media

Porous media may contain fractures of different types and scales. Small fractures can be accounted in the permeability tensor during the upscaling procedure within a mesh cell, while large fractures intersect several mesh cells and can dramatically affect the subsurface flow. We propose a two-scale FV method for the single- and two-phase flows in fractured media. The method combines the embedded fracture approach with advanced nonlinear FV schemes for the porous media. For extremum-preserving FV schemes it can be shown that the two-scale method for the matrix-fracture system is extremum-preserving as well. Numerical experiments demonstrate good agreement of the two-scale method with the reference fine grid solution and with the discrete fracture method.

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PP1

Development of a Numerical Framework for the Study of Solid Earth Tides

Since the Wegener theory has been proposed many steps towards the understanding of the driving forces of plate tectonic have been made. The contributions of mantle convection and slub-pull forces to plate tectonics have been studied in many papers. On the other hand the importance of the Earth's rotation and of the Moon and Sun attraction on the Earth is strongly debated. The aim of this work is the development of some numerical tools for the investigation of such phenomena. The problem shows an intrinsic time dependency, given by both the dynamics in time of the astronomical bodies and by the Earth deformation model. Therefore the study has been focused on two topics In the first part a new code based on Galerkin variational integrators has been developed in order to simulate the mechanical system involving the Earth, the Sun and the Moon. In the second part a fully parallel code to simulate the Earth deformation has been developed on the top of deal.II library. The solver is based on a geometric multigrid method. The code allows to perform simulations on long time scale. These two tools will constitute the basis for the realization of a series of scenarios to evaluate the contributions of the Moon and the Sun attraction on the Earth deformation and hence on plate tectonics. In the present talk we will present some preliminary numerical results concerning both parts and some scenarios.

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PP1

Characterizing Volumetric Strain at Brady Hot Springs, Nevada, USA using InSAR, GPS, Numerical Models and Prior Information

The geothermal field at Brady Hot Springs, Nevada has subsided over the past decade. Between 2004 and 2014, the rate of downward-vertical displacement was on the order of 10 mm per year, as measured by two independent geodetic techniques: interferometric synthetic aperture radar (InSAR) and Global Positioning System. The observed deformation field forms an approximately elliptical bowl that is 4 km long and aligned with the trace of the NNE striking normal fault system. We use modeling to estimate the plausibility of pressure changes or thermal contraction as the cause of the observed subsidence. As a result, Bayesian inference favors with "very strong evidence" thermal contraction over other hypotheses as the dominant driving mechanism for the observed subsidence. Using InSAR data spanning from 2016 July 22 to 2017 August 22, we estimate the volume change rate in the significantly deforming volume to be (-29 +/- 3) thousand cubic meters per year and the total rate of change in thermal energy between -53 and -79 megawatt. We infer the total volume of cubes where the estimated volumetric strain rate is significantly different from zero with 95 percent confidence to be 119 million cubic meters. We find that the main region of significant cooling occurs between the injection and production well locations. This result supports the idea that highly permeable conduits along faults channel fluids from shallow aquifers to the deep reservoir tapped by the production wells.

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PP1

Effective Models for Two-phase Flow in Porous Media with Evolving Interfaces at the Pore Scale

When two fluids flow through a porous medium they dynamically interact with each other, affecting how the other fluid flows through the pores. On Darcy scale, this is usually modeled through relative permeabilities, but it is unclear how the relative permeability would behave. In this presentation we derive effective (Darcy scale) models for two-phase flow in porous media. We start with the model at the pore scale and account for the presence of an evolving sharp-interface separating two immiscible phases. A thin strip is considered as a simplified pore geometry. The movement of each fluid phase is described by the Navier-Stokes equation. For describing the movement of this interface we impose the continuity of the fluid velocities and of the tangential components of the normal stresses, whereas the jump in the normal components depend on the surface tension effects. In particular, Marangoni effects are considered. Assuming that the ratio between the pore width and length is small, we use asymptotic expansion methods to derive effective equations valid at the Darcy scale. These equations are derived for different capillary numbers and viscosity ratios. In particular, the surface tension effects are important for small capillary numbers whereas Marangoni effects appears for moderate capillary numbers.

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PP1

Novel Principles for Effective Earth Model Grid Management While Geosteering

Conventional 3D earth modelling methods are based on an inflexible, global corner-point grid to represent the geological structure and the petrophysical properties. The management of this model is time consuming; much work is required for manual modelling of the geological structure, the control with the grid resolution is poor, and uncertainty modelling of the geological structure requires a full reconstruction of the grid and the petrophysical properties for each realization. Geosteering is a real-time decision process where the aim is to place the well optimally in the reservoir, based on geological interpretation of the measurements that are received while drilling. But conventional methods are not made for real-time handling, preventing proper model-based decision support when drilling in complex formations. To pave the way for more effective earth model management, novel principles for i) local updates of the geological structure in an existing unstructured grid, ii) multi-resolution management allowing local control of the resolution of both the geological structure and the grid, and iii) local-scale uncertainty management including the geological structure are proposed. The aim is to enable an always updated multi-realization 3D model at optimal resolution while drilling, suitable for real-time decision support under uncertainty, as well as allowing effective generation of grids at fit-for-purpose resolution for potentially any subsurface application.

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PP1

Imaging of Densely Located Many Point-like Scatterers by the Application of the Pseudo Projection Method and Kirchhoff Migration

An imaging method is developed for densely located many point-like scatterers in an elastic half space. Imaging of scatters by means of multiple frequencies is also possible in this method. During the formulation, the pseudo projection approach (Touhei, IJSS, 136-137, 2018, pp. 112-124) and Kirchhoff migration (for example, Moscoso et al., SIAM J IMAGING Science, Vol. 10, No. 3, pp. 1005-1032) are incorporated into the method. It is known that imaging method such as the MUSIC algorithm (Cheney, Inverse Problems, 2001, pp. 591-595) requires the number of the point scatters are small compared to that of grid arrays for sending and receiving the signals. The point-like scatters also have to be located sparsely. In order to resolve the limitation, the proposed method defines the far-field operator with respect to each probing point, which improves the resolution of the imaging. This definition of the far-field operator becomes possible by the introduction of the pseudo projections. By the use of the defined far-field operator, the time reversed signals can be sent back to the wave field and received again by the grid arrays, which is the procedure of the Kirchhoff migration. As a result, analysis using the multiple frequencies becomes possible. Several numerical calculations are carried out to examine the resolution of the results.The effects of the use of the multiple frequencies on the accuracy of the results are also examined.

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PP1

Explicit Relaxation Technique for Solving the Green-Naghdi Equations for Dispersive Waves

We revisit a relaxation technique introduced in Favrie and Gavrilyuk (2017) for solving the Green-Naghdi equations. We propose a version of the method and a space/time approximation thereof that is scale invariant. The approximation in time is explicit and the approximation in space uses a length scale for the relaxation that is proportional to the mesh size. The method is compatible with dry states and is provably positivity preserving under the appropriate CFL condition. The method is numerically validated against manufactured solutions and is illustrated by comparison with experimental results.

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PP1

Joint Inversion of Surface Wave Dispersion and Bouguer Gravity Anomalies using Constrained Optimization

In order to characterize the location and condition of faults and ancient strains in the lower crust, it is vital to understand the tectonic evolution of the Earth through the inversion and analysis of both seismic and non-seismic datasets. Information obtained from these datasets helps to determine the structure models associated with a region of study; however, the reliability of such models varies based on the resolution and accuracy of each dataset. Combining the resolution of surface wave group velocities and Bouguer gravity anomalies has proven helpful to identify complex shallow structures in the subsurface. This work aims to improve 3-Dimensional Earth structure models through the optimization of the joint inversion of complementary seismic (surface wave group velocities) and non-seismic (Bouguer gravity anomalies) datasets. The proposed framework uses constrained optimization for the inversion by implementing Primal-Dual interior point methods providing further improvement to 3-D Earth models by limiting the solution space and focusing only on feasible velocity-density models satisfying the known a-priori structural conditions. The combined resolution of these datasets will allow us to identify key features in the subsurface that may be overlooked by one or both of the surveys by themselves. We test this approach using synthetic datasets so as to determine its advantages with respect to other inversion techniques based on regularized least squares algorithms.

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PP1

Generalized Approximate Static Condensation Method for a Heterogeneous Multi-material Diffusion Problem

We introduce an approximate static condensation algorithm for solving heterogeneous diffusion problem in the mixed form. The method locally relies on mimetic finite difference approach and efficiently handles discontinuous material interfaces as well as general polygonal cells. We prove that the underline system matrix is SPD, and demonstrate convergence results for several benchmarks, both stationary and time-dependent.

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Organizer and Speaker Index

SIAM Conference on

Mathematical

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in the Geosciences

March 11 – March 14, 2019

Houston Marriott Westchase

Houston, Texas, U.S.

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GS19 Conference Budget

Conference Budget
SIAM Conference on Mathematical & Computational Issues in the Geosciences

March 11-14, 2019
Houston, TX

Expected Paid Attendance	350	
Revenue		
Registration Income		$138,295
Total		$138,295
Expenses		
Printing		$4,700
Organizing Committee		5,000
Invited Speakers		8,100
Food and Beverage		25,000
AV Equipment and Telecommunication		22,300
Advertising		8,000
Conference Labor (including benefits)		43,563
Other (supplies, staff travel, freight, misc.)		9,700
Administrative		16,212
Accounting/Distribution & Shipping		9,210
Information Systems		15,897
Customer Service		5,586
Marketing		10,603
Office Space (Building)		6,396
Other SIAM Services		6,013
Total		$196,280
Net Conference Expense		($57,985)
Support Provided by SIAM		$57,985
		$0
Estimated Support for Travel Awards not included above:		
Early Career and Students	29	$24,500

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