The GeoScale Project:

Multiscale Methods to Bypass Upscaling

Ingeborg S. Ligaarden

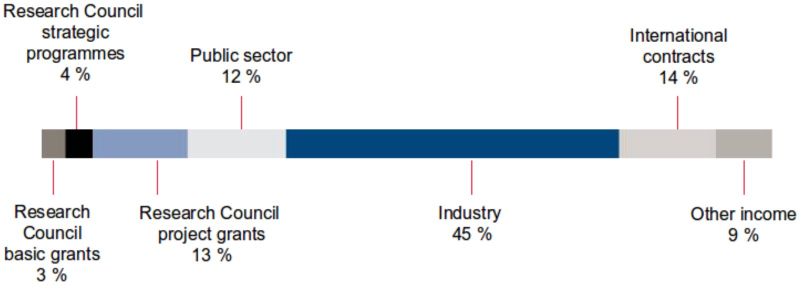
SINTEF ICT, Dept. Applied Mathematics

Shell Exploration & Production, Rijswijk

Outline of presentation

1. Introduction
   - About SINTEF
   - Research activity at SINTEF Dept. Applied Math.
2. The GeoScale Project Portfolio
   - Upscaling vs multiscale methods
   - MsMFE Method in a Nutshell
   - Recent news/advances..
     - Black-Oil
     - Modeling vugs and fractures
   - The Matlab Reservoir Simulation Toolbox (MRST)

- The largest research institution in Scandinavia, 2150 employees
- Broad-based, multidisciplinary research
  - technology, natural science, medicine and social science
- Turnover 2008: NOK 2.6 billion, ($\approx$ €290 million)
  - SINTEF, Dept. Applied Mathematics 2008, 38 employees: turnover of department 32.5 MNOK ($\approx$ 3.7 M€)

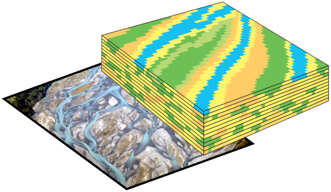


Simulation Group

SINTEF ICT Dept. of Applied Mathematics, Oslo

Research Group

- 7 research scientists (6 PhD)
- 1 postdoc
- 4 PhD students
- 1 programmer



Collaboration with national and international partners in industry and academia

Main Focus

numerical methods for flow and transport in porous media

Overview of Current Research Activity

Projects

- GeoScale - Direct Reservoir Simulation on Geocelluar Models
- Multiscale Simulation of Highly Heterogeneous and Fractured Reservoirs (Shell)
- Geological Storage of CO2 - Mathematical Modeling and Risk Analysis
- Partner in Center for Integrated Operations (NTNU)
- Various industry projects (Schlumberger, Statoil, . . .)
- $\Rightarrow$ Open Source Reservoir Simulators

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The GeoScale Project Portfolio

Research vision:

Direct simulation of complex grid models of highly heterogeneous and fractured porous media - a technology that bypasses the need for upscaling.

Key technologies

- the multiscale mixed finite element (MsMFE) method
- streamlines
- fast methods based on reordering
- accurate discretization on complex grids
- flow-based gridding of transport grids

The GeoScale Project Portfolio

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What is a Multiscale Method?
Introduction (I)

Multiscale Method

Designed to model phenomena that are governed by physical processes occurring on a wide range of time and length scales.

Porous media flow is multiscale

- Heterogeneities: from pore scale to the scale of the entire model
- Simulation: important to capture structures on different scales

What is a Multiscale Method?
Introduction (II)

Reservoir simulation today

- Gap between detailed geomodels and capabilities of reservoir simulators
- Solution: upscale information and simulate on coarse grid
- Result: costly upscaling and valuable information is lost

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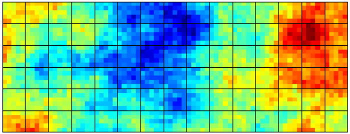
Alternative: Multiscale methods

- Based on two-scale approach
  - fine grid/geomodel
  - coarse/simulation grid
- Describe physical phenomena on coarse grid
- Incorporate fine-scale information into the coarse scale equations

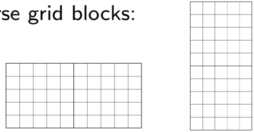
The MsMFE Method in a Nutshell
From upscaling to multiscale methods

Standard upscaling:



$\Downarrow$

Coarse grid blocks:



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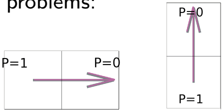
Flow problems:



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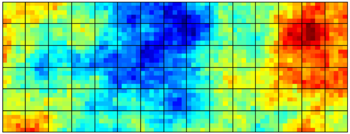

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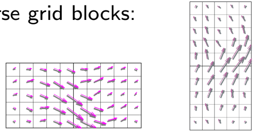

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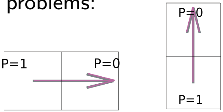

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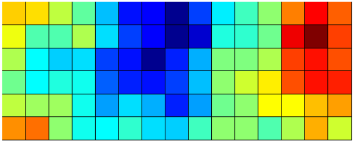

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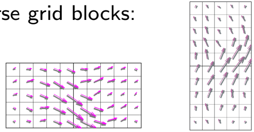

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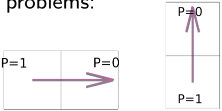

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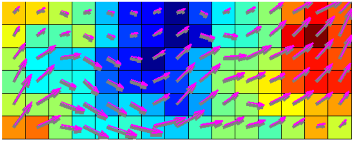

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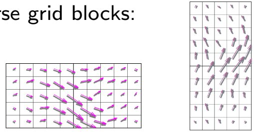
Coarse grid blocks:



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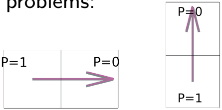

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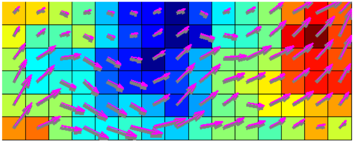

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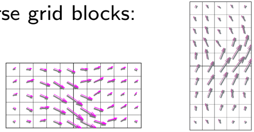

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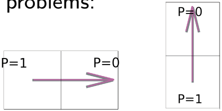
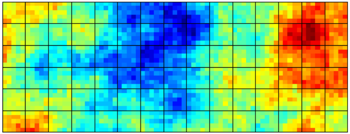


Multiscale method:



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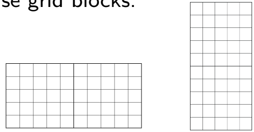

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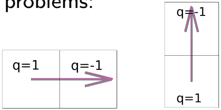

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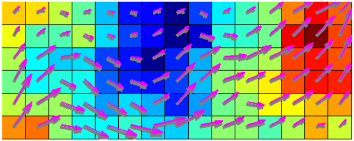

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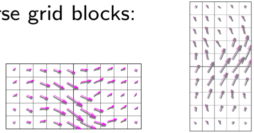

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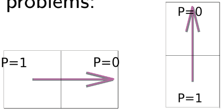

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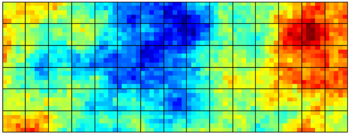

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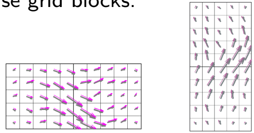

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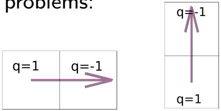

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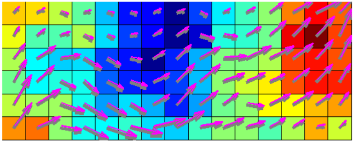

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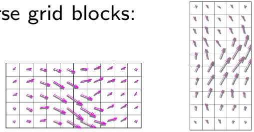

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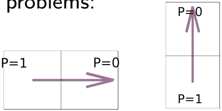

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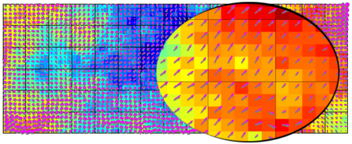

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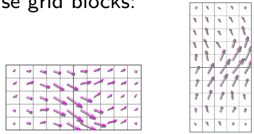

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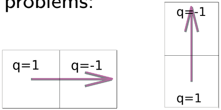
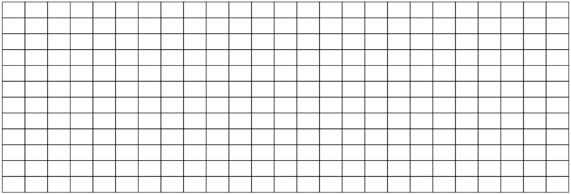


We assume we are given a *fine* grid with permeability and porosity attached to each fine-grid block.



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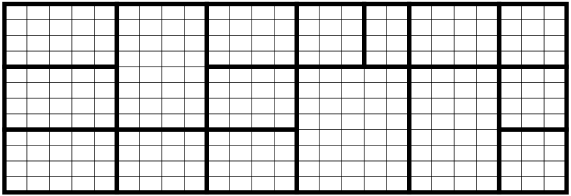

We construct a *coarse* grid, and solve local flow problems such that:

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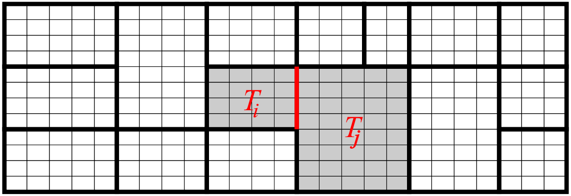


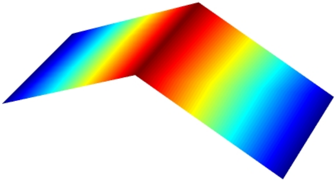
We construct a *coarse* grid, and solve local flow problems such that:

- For each coarse edge Γ_{ij}, there is a basis function ψ_{ij} for velocity and ϕ_{ij} for pressure.

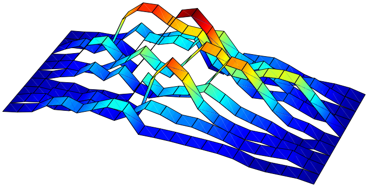
The MsMFE Method in a Nutshell
What are these multiscale basis functions?

Modified finite element basis functions capture the subscale variations

Original Raviart–Thomas:



Multiscale basis function:



Automatic reconstruction of fine scale velocity from the coarse solution

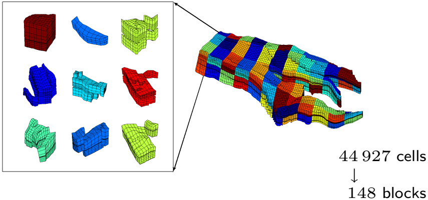
Global velocity:

$v = \sum_{ij} v_{ij}\psi_{ij}$, where v_{ij} are (coarse-scale) coefficients.

The MsMFE Method in a Nutshell

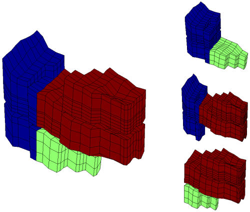
Workflow with automated upgridding in 3D

1) Coarsen grid by uniform partitioning in index space for corner-point grids



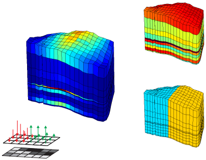
9 different coarse blocks

2) Detect all adjacent blocks



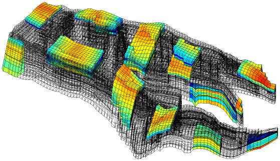
3) Compute basis functions

$$\nabla\cdot\psi_{ij} = \begin{cases} w_i(x), \\ -w_j(x), \end{cases}$$

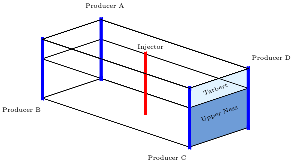


for all pairs of blocks

4) Block in coarse grid: component for building global solution



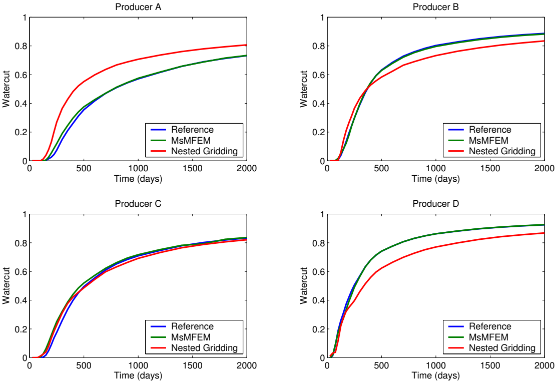
SPE 10, Model 2:



Fine grid: $60 \times 220 \times 85$
Coarse grid: $5 \times 11 \times 17$
2000 days production

4M + streamlines:
2 min 22 sec on 2.4 GHz desktop PC

Water-cut curves at the four producers



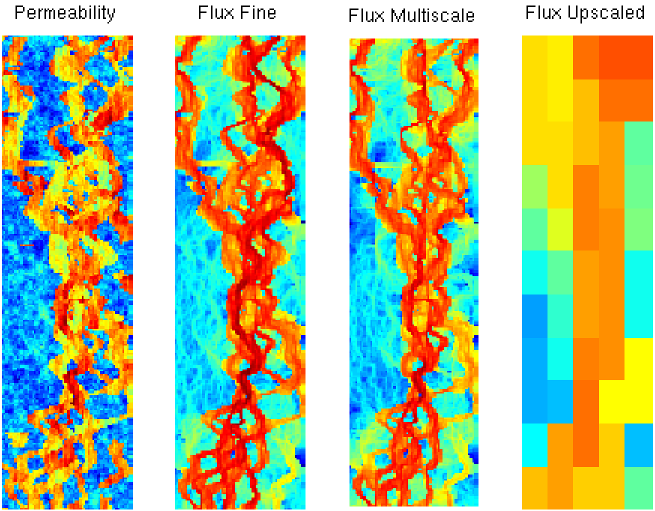
upscaling/downscaling, 4M/streamlines, fine grid

The MsMFE Method in a Nutshell
Example: Layer 63 from SPE10

Single-phase flow with pressure boundary on top/bottom

Fine grid:
60×220

Coarse grid:
5×11

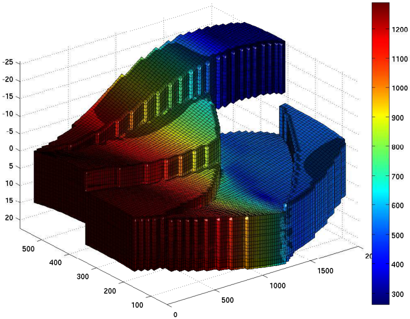


Four new developments in the last year:

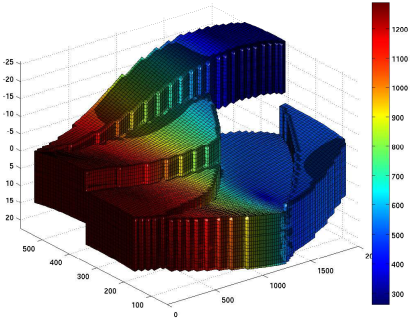
- Extension of the MsMFE method to compressible three-phase flow
- A prototype implementation in FrontSim, applied to fractured media
- Extension of the MsMFE method to the Stokes-Brinkman equations to model flow in vuggy and naturally-fractured porous media
- Combination of the MsMFE method and flow-based gridding to give a very efficient solver

Recent Advances in MsMFEM #1:
Black-Oil Simulation Example

Multiscale:



Fine-scale:



Comparison of pressure results at end of simulation (1500 days) on semi-realistic reservoir model with five curved faults.

Standard approach:

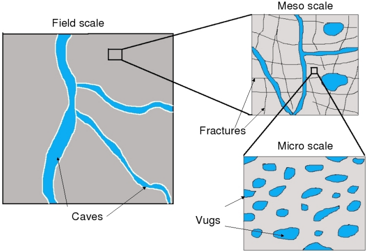
Porous region (Darcy):

$$\mu \mathbf{K}^{-1}\vec{u}_D + \nabla p_D = \vec{f}, \quad \nabla \cdot \vec{u}_D = q.$$

Free-flow region (Stokes):

$$-\mu\nabla\cdot(\nabla\vec{u}_S + \nabla\vec{u}_S^{\mathsf{T}}) + \nabla p_S = \vec{f}, \quad \nabla\cdot\vec{u}_S = q$$

Problem: requires interface conditions and explicit geometry



Stokes–Brinkman (following Popov et al.)

$$\mu \mathbf{K}^{-1}\vec{u} + \nabla p - \tilde{\mu}\Delta\vec{u} = \vec{f}, \qquad \nabla \cdot \vec{u} = q$$

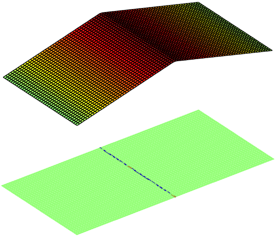
Here: seamless transition from Darcy to Stokes (with $\mu = \tilde{\mu}$)

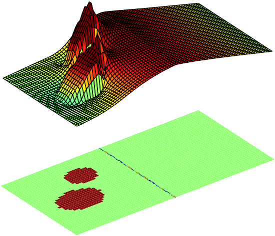
Fine scale system with Taylor–Hood elements:

100×100 cells $\Rightarrow 91,003$ degrees of freedom $\Rightarrow$ multiscale

Idea:

- use Stokes-Brinkman to calculate multiscale basis functions
- use Darcy on the coarse scale



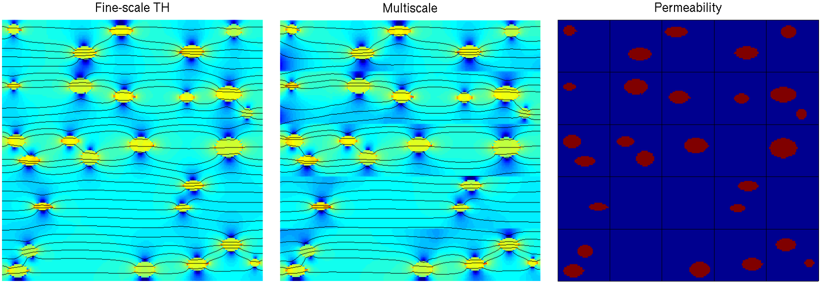


Test of the multiscale Darcy/Stokes-Brinkman method:

1. 2D vuggy reservoir (short correlation)
2. 2D fractured reservoir (long correlation)
3. 2D vuggy and fractured reservoir (short and long correlation)
4. 3D core sample

Modeling of Vuggy and Naturally Fractured Reservoirs

Example 1: Vuggy reservoir (short correlation)

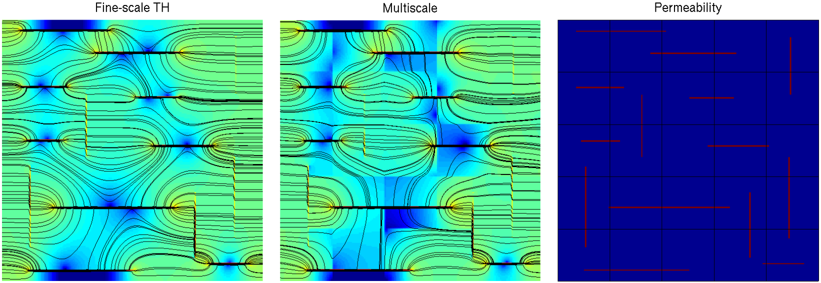


Fine-scale model:
200×200 cells

Multiscale model:
5×5 blocks

$K_{vugs} =$
$10^7 \times K_{matrix}$

26 random vugs (areas= 1.8–10.4 m^2)



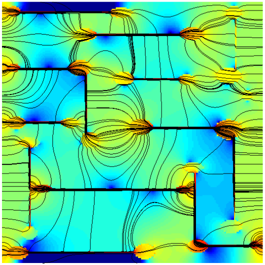
Fine-scale model:
200×200 cells

Multiscale model:
5×5 blocks

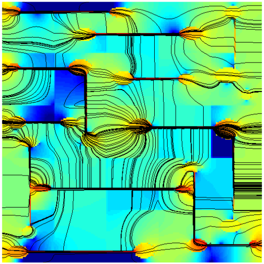
$K_{vugs} =$
$10^7 \times K_{matrix}$

14 random fractures of varying length

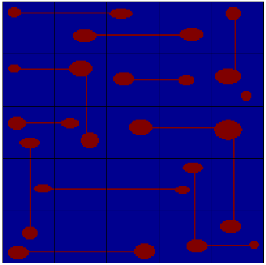
Fine-scale TH



Multiscale

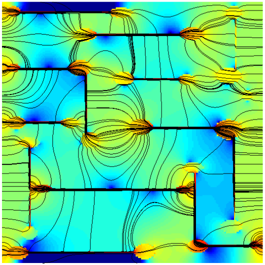


Permeability

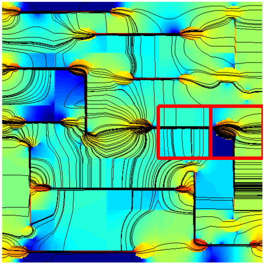


Example 3: Vuggy and fractured reservoir

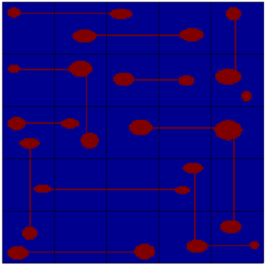
Fine-scale TH



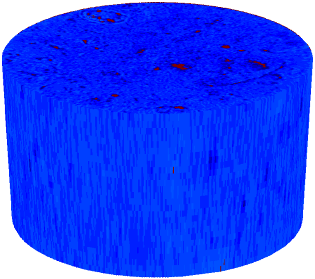
Multiscale



Permeability



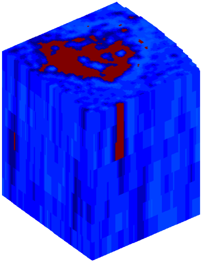
Full model:



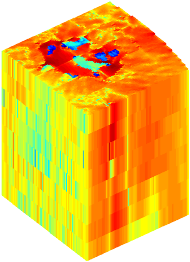
$512 \times 512 \times 26$ cells
3.449.654 active

Subsample:

Log10 permeability [Darcy]



Log10 MS flux [m/day]



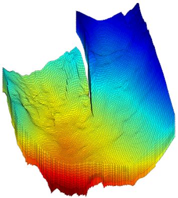
$85 \times 85 \times 8$ cells, 55.192 active, 75 blocks
pressure boundary conditions

Most of our research on multiscale methods have been done in Matlab.

- **Result:** substantial code base
- **Idea:** release code as an Open Source Reservoir Simulation Toolbox
- **First step:** single- and twophase flow

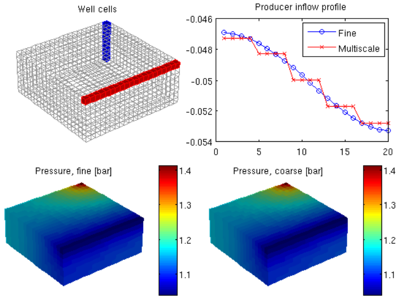
Toolbox functionality

- reading, representing, processing and visualizing *unstructured grids*
- *mimetic* and *multiscale* pressure solvers
- simple transport solvers
- support essential parts of *Eclipse-type input files*



MRST has a simple "interface" and can be used for both simple educational examples and real field models.

Simple Cartesian grid

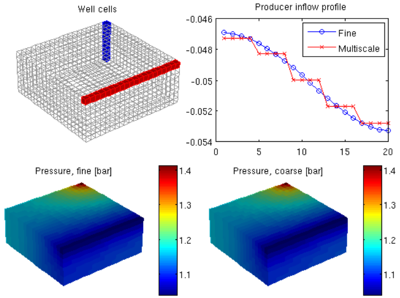


Matlab code

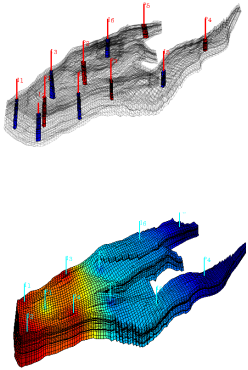
```
%% Define the model and set data
nx = 20; ny = 20; nz = 8;
Nx = 5; Ny = 5; Nz = 2;
G = cartGrid([nx ny nz]);
G = computeGeometry(G);
rock.perm = repmat(100*milli*darcy, [G.cells.num, 1]);
fluid = initSingleFluid();
%% Set two wells, one vertical and one horizontal
W = verticalWell(...);
W = addWell(...);
W = generateCoarseWellSystem(...);
%% Partition the grid
p = partitionUI(G, [Nx, Ny, Nz]);
%% Generate the coarse-grid structure
CG = generateCoarseGrid(G, p);
%% Generate system matrices
S = computeMimeticIP(G, rock);
CS = generateCoarseSystem(G, rock, CG, mob);
%% Solve the global flow problems
[xrRef, xwRef] = solveIncompFlow(...);
[xrMs, xwMs] = solveIncompFlowMS(...);
%% Plot solution
```

MRST has a simple "interface" and can be used for both simple educational examples and real field models.

Simple Cartesian grid

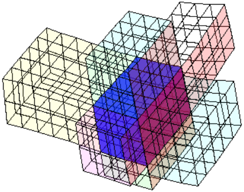


Real field example



So far no advertising.. but with a little help from Google:

- 100 unique downloads
- 54 institutions
- 32 countries



.. since release in late April 2009 ..

http://www.sintef.no/Projectweb/GeoScale/Simulators/

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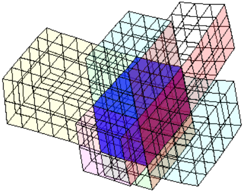

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Next: Open Source C++ Toolbox
for more computationally challenging cases