Ensemble Simulations With MRST
With Examples from CO_2 Foam Simulation

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Uncertainty quantification in reservoir simulation

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  Water production rate, saturation at time t', total amount of CO_2 stored etc.

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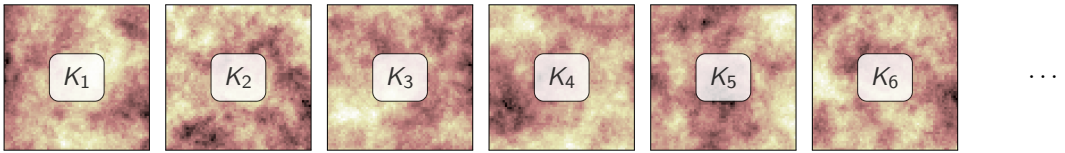
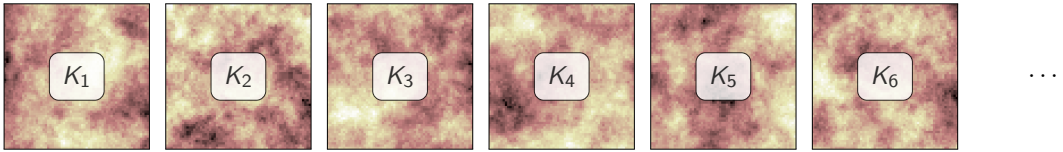


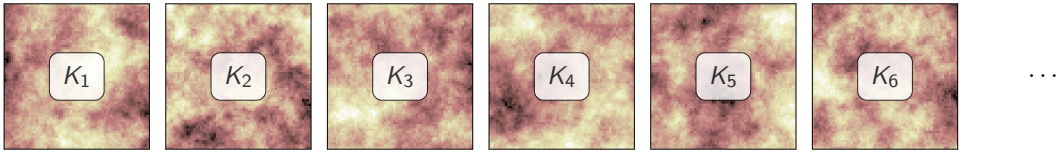
Uncertainty quantification in reservoir simulation

- Quantity of interest u typically derived from simulation results
  Water production rate, saturation at time t', total amount of CO_2 stored etc.
  ... which are all random variables due to uncertain subsurface properties
- Common to quantify this uncertainty by running **ensemble simulations**



Introduction

Ensemble simulations: Instead of running a single simulation, we use a number of equiprobable realizations of the same model in order to account for **uncertainties in the geomodel** and **uncertainties in the mathematical formulation**.



Introduction

In this webinar

Show how to use the MATLAB Reservoir Simulation Toolbox (MRST) to do ensemble simulations, and how it can be applied to uncertainty quantification in CO_2 storage

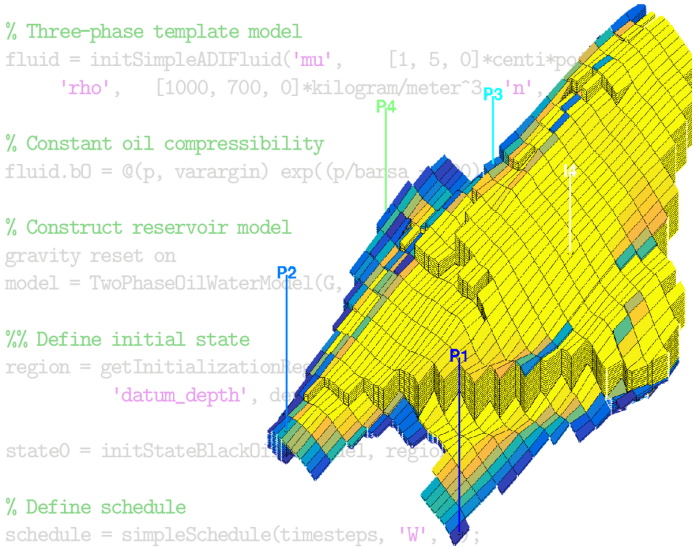
1. Short description of MRST
2. Introduction to the ensemble module
   - Define a simulation problem, a quantity of interest, and stochastic samples
3. Example: uncertainty quantification CO_2 storage with mobility control
4. Extensions of the module
   - Monte-Carlo/multilevel Monte Carlo, Ensemble-based History Matching

MATLAB Reservoir Simulation Toolbox (MRST)

Transforming research on reservoir modelling

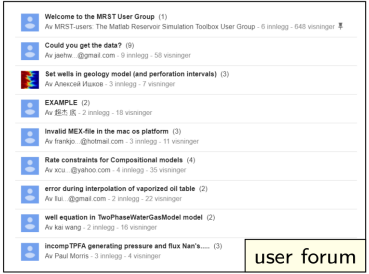
Unique prototyping platform:

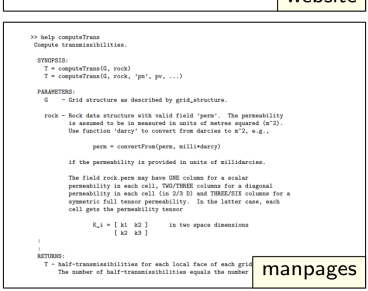
- Standard data formats
- Data structures/library routines
- Fully unstructured grids
- Rapid prototyping:
  - Differentiation operators
  - Automatic differentiation
  - Object-oriented framework
  - State functions
- Industry-standard simulation

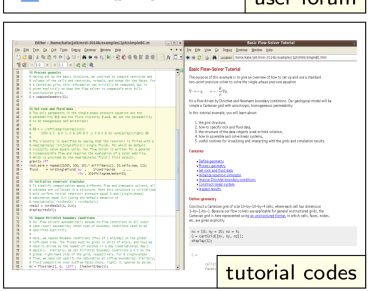


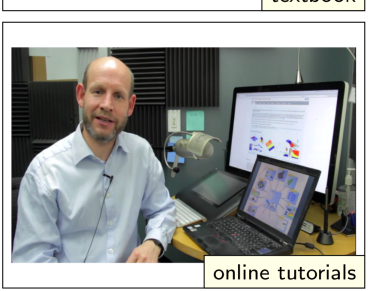
http://www.mrst.no

MATLAB Reservoir Simulation Toolbox – useful resources

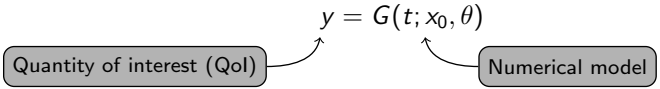






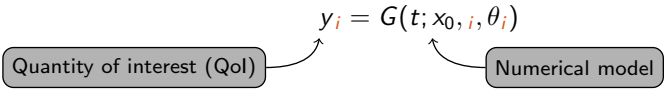


The Ensemble Module



- **We have** numerical representation of reservoir θ, initial state x_0, numerical model G
- **We want** quantity of interest (QoI) y at given time t
- Reservoir parameters θ and initial state x_0 known exactly $\rightarrow$ compute QoI directly

The Ensemble Module



- **We have** numerical representation of reservoir θ, initial state x_0, numerical model G
- **We want** quantity of interest (QoI) y at given time t
- Reservoir parameters θ and/or initial state x_0 given by **probability distributions** $p(\theta)$, $p(x_0)$
  - Generate ensemble with N members by sampling $\theta_i \sim p(\theta)$, $x_{0,i} \sim p(x_0)$
  - Compute QoI for each ensemble member
  - Estimate QoI (ensemble mean) and associated uncertainty (ensemble variance)

The Ensemble Module

$$y = G(t; x_0, \theta)$$

BaseProblem

All elements of a simulation model that is common across ensemble members

Examples: grid, injection strategy, well position

Samples

Stochastic realization of uncertain parameters

Examples: permeability, porosity, initial saturation

QoI

Quantity of interest (QoI) that we want to estimate with ensemble

Examples: stored CO_2 volume, breakthrough time

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- Worked example: quarter five-spot problem with water injection into oil
  - Common elements: fluid model, injection rates, well placement
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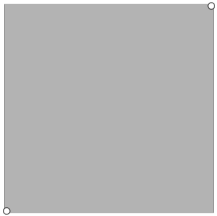
```
example = MRSTExample('qfs_wo'); % Setup up example
example.plot();                  % Plot setup
```

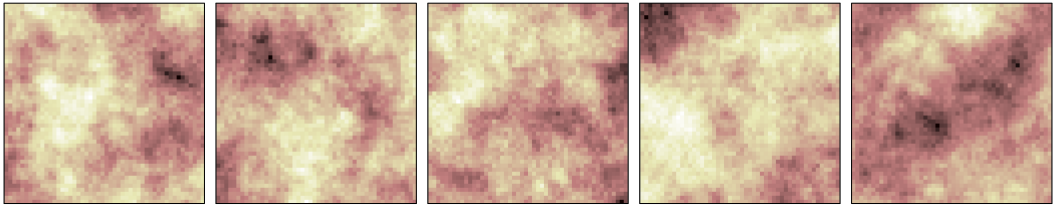


Stochastic Samples

- Stochastic samples can be defined in three ways:
  1. By a function that generates a sample when called
  2. By precomputed samples in a cell array
  3. By precomputed samples stored on disk (e.g., as `DECK` files)
- Here: use `RockSamples` to define stochastic permeability/porosity

```
% Set up samples using a generator function
generatorFn = @(problem, seed)                    ...
    generateRockSample(example.model.G.cartDims, ... % Gaussian field dimensions
                       'seed'     , seed         , ... % Random number seed
                       'toVector', true         );    % Stretch out to vector
samples = RockSamples('generatorFn', generatorFn);   % Set up rock samples
```

Stochastic Samples



```
for i = 1:5
    data    = samples.getSample(i, problem);    % Get sample number i
    problem = samples.setSample(data, problem); % Set sample to problem
    % Inspect rock sample
    example.plot(problem.SimulatorSetup.model.rock, 'log10', true); colormap(pink)
end
```

Quantity of Interest (QoI)

- QoI is what we are actually interested in obtaining from the simulations
- Can be any user-defined quantity – implement based on one of the `QoI` classes
- In this example: oil production rate as a function of time

```
% Oil production rate as a function of time
qoi = WellQoI('fldname', 'qOs', 'wells', 2);
% Water saturation after 20, 300 and 700 days
qoi = ReservoirStateQoI('name', 'sW', 'time', [20, 300, 700]*day);
% User-defined QoI based on a suitable parent class
qoi = CO2StorageQoI('type', 'mass');
```

The MRSTEnsemble Class – Putting it All Together

- Class MRSTEnsemble collects base problem, samples and QoI
  - Functionality for simulating ensemble members (all or a subset)
  - Functionality for writing/reading data to/from disk

```
ensemble = MRSTEnsemble(example, samples, qoi,                ... % Gather components
                        'directory'         , dataDir     ,   ... % Data directory
                        'simulationStrategy', 'background'); ... % Simulate in background
```

The `MRSTEnsemble` Class – Putting it All Together

- Class `MRSTEnsemble` collects base problem, samples and QoI
  - Functionality for simulating ensemble members (all or a subset)
  - Functionality for writing/reading data to/from disk
- Three ways to simulate multiple ensemble members
  1. In serial (only for small ensembles and debugging)
  2. In parallel using background MATLAB sessions
  3. In parallel using the MATLAB parallel computing toolbox

```
ensemble = MRSTEnsemble(example, samples, qoi,                ... % Gather components
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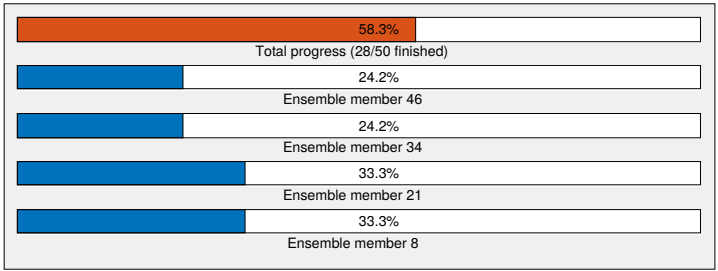
```

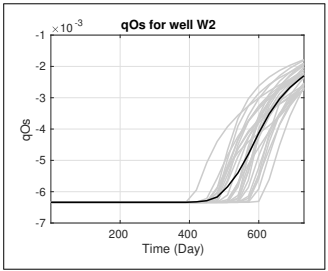
The `MRSTEnsemble` Class – Simulating Ensemble Members

- Simulate ensemble members in three different ways
  1. Specific ensemble members, referenced by number
  2. Batch of *n* ensemble members, starting from the last simulated member
  3. The entire ensemble
- Plot progress while the simulations are running

```
ensemble.simulateEnsembleMembers('range', 3:5);          % Simulate samples 3 to 5
ensemble.simulateEnsembleMembers('batchSize', 20);       % 20 more samples
ensemble.simulateEnsembleMembers('plotProgress', true); % Simulate entire ensemble
```

The MRSTEnsemble Class – Simulating Ensemble Members



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Example: Efficiency of CO_2 Foam Mobility Control

Efficiency of CO_2 foam mobility control with heterogeneous reservoir properties (Grimstad and Klemetsdal, TCCS-11)

- Storage of 250 kt CO_2 per year into brine-filled, 1400×1400×100 m reservoir
- Quadratic, Corey-type relative permeabilities, capillary entry pressure of 0.15 bar
- Three injection strategies (all simulations are run until breakthrough in production well)
  1. Inject CO_2 only
  2. Inject surfactant (1% wt) during first four years
  3. Inject surfactant (1% wt) during first four years, perm-dependent surfactant strength (surfactant model from Vassenden and Holt, 2000)

```
% Base case is defined in the function qfs_foam
example = MRSTExample('qfs_foam', 'cartDims', [30, 30, 20]);
```

Example: Efficiency of CO_2 Foam Mobility Control

Setting up stochastic rock samples

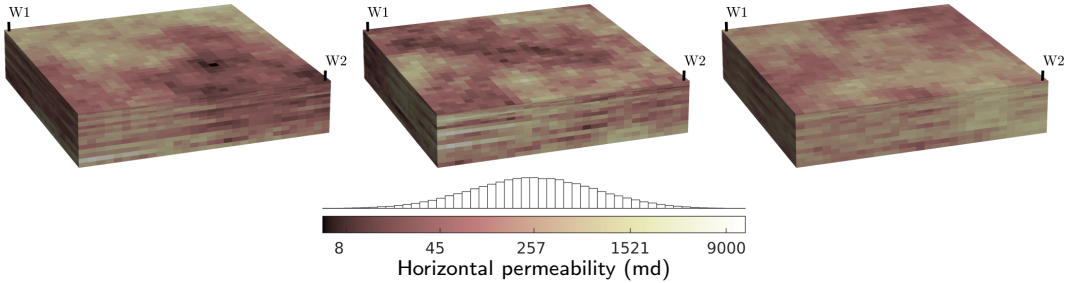
- Layered structure with log-normal permeablity (mean 260 md) and normal porosity

$$\log(K) = \mathcal{N}(-12.5, 0.5), \quad \phi = \mathcal{N}(0.25, 0.1)$$

- Vertical to horizontal permeability ratio $= 1/10$, 100 realizations

```
% Set up function for generating rock samples
generatorFn = @(problem, seed) generateLayeredRockSample(cartDims, seed,              ...
                                                         'avg_poro', 0.25           , ...
                                                         'min_poro', 1e-3           , ...
                                                         'avg_perm', 260*milli*darcy);
% Generate realizations, set kv/kh = 1/10, store to disk using ResultHandler rh (truncated)
samples = RockSamples('data', rh); % Set up rock samples
```

Example: Efficiency of CO_2 Foam Mobility Control

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```

Example: Efficiency of CO_2 Foam Mobility Control

Define quantity of interest (QoI)

- QoI is storage efficiency (fraction of pore volume occupied by CO_2) at breakthrough
- Implemented in user-defined QoI class with overloaded method `computeQoI`

```
classdef CO2StorageQoI < ReservoirStateQoI
    ...
    methods
        function u = computeQoI(qoi, problem)
            state    = problem.OutputHandlers.states{end};        % Get final state
            [pv, sG] = model.getProps(state, 'PoreVolume', 'sG'); % Get PV and CO2 sat
            u        = sum(pv.*sG)./sum(pv);                      % PV-weighted CO2 sat
        end
    end
end
```

Example: Efficiency of CO_2 Foam Mobility Control

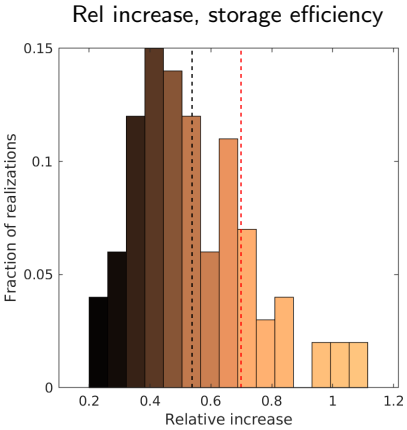
Set up and simulate ensemble

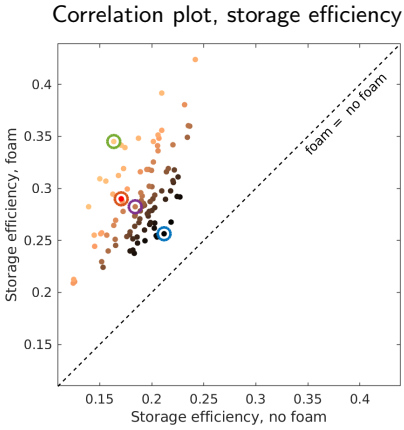
- One ensemble for each strategy (no foam, foam, and permeability-dependent foam)
- Simulate using background sessions and store all simulation data, not just the QoI

```
ensemble = MRSTEnsemble(example, samples, qoi,      ...
                'directory'         , dataDir     , ... % Directory for storing results
                'simulationStrategy', 'background', ... % Use background MATLAB sessions
                'maxWorkers'        , maxWorkers  , ... % Max # concurrent MATLAB sessions
                'storeOutput'       , true        );    % Save all output (not just QoI)
ensemble.simulateEnsembleMembers();                     % Simulate all 100 members
```

Example: Efficiency of CO_2 Foam Mobility Control

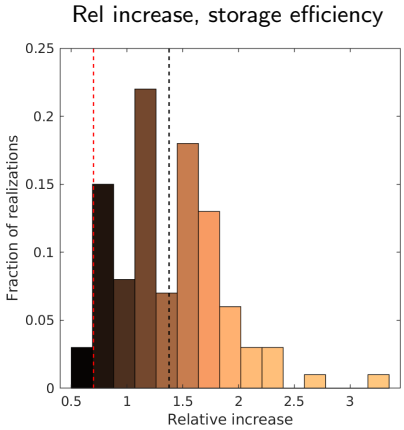
Results – foam vs. no foam

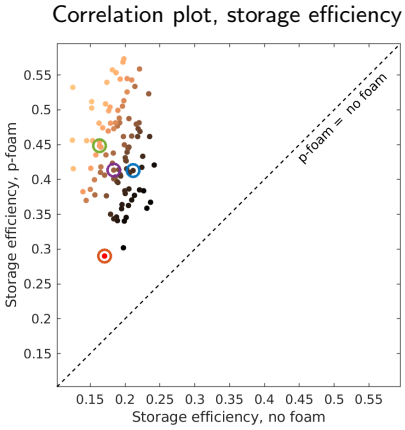




Example: Efficiency of CO_2 Foam Mobility Control

Results – perm-dependent foam vs. no foam





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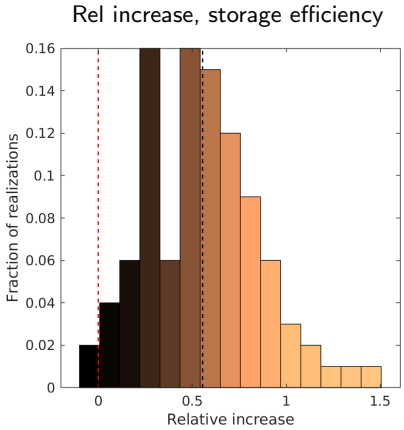
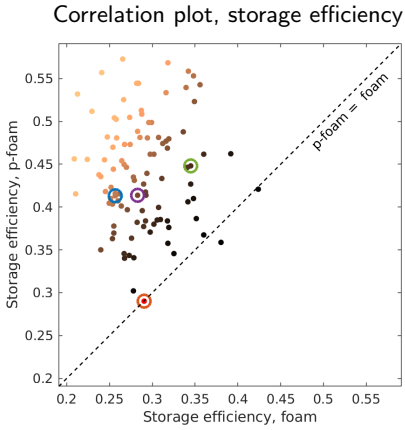
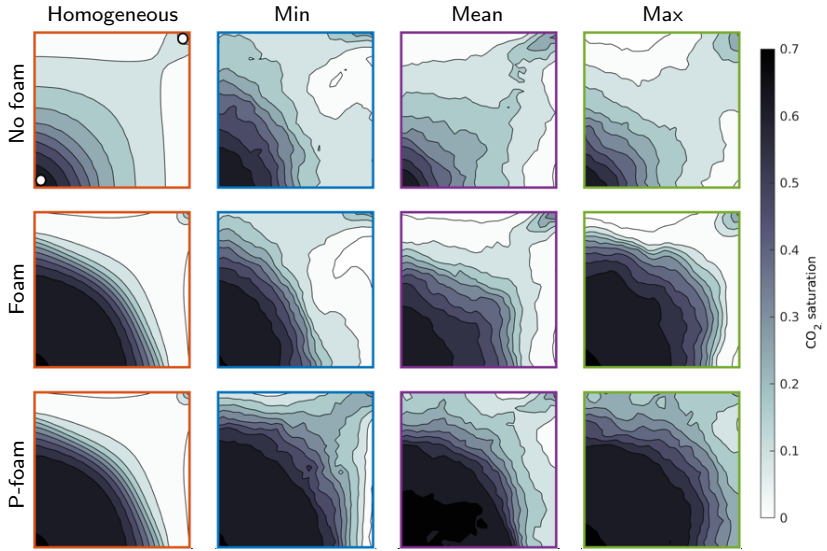




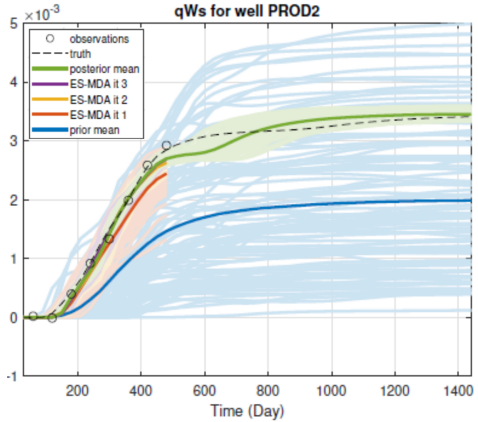
Example: Efficiency of CO_2 Foam Mobility Control

CO_2 plumes (horizontal)
Min/Mean/Max correspond to gain with foam vs. no foam



Extensions of the Ensemble Module

- Monte Carlo simulation (MC)
  - Simulate new realizations until QoI uncertainty (RMSE) is less than prescribed tolerance
- Multilevel Monte Carlo simulation (MLMC)
  - Highly generic level hierarchy (spatial/temporal upscaling, solver-based, etc.)
  - Potentially much faster alternative to MC
- Ensemble-based history matching
  - Ensemble smoother with multiple data assimilations (ES-MDA)



Acknowledgements

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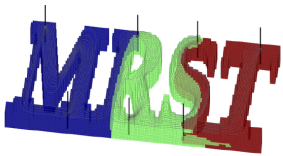


mrst.no

Full source code available in the open-source MATLAB Reservoir Simulation Toolbox

The MRSTEnsemble Class – Simulating Ensemble Members

simulateEnsembleMember does everything involved in simulating a single member

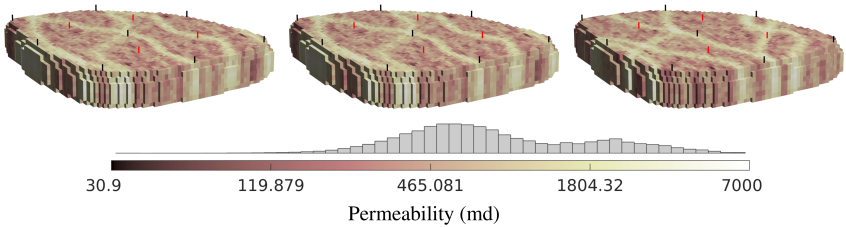
```
function simulateEnsembleMember(ensemble, seed, varargin)
    % Get base problem
    baseProblem = ensemble.getBaseProblem;
    % Set up sample problem from seed
    problem = ensemble.samples.getSampleProblem(baseProblem, seed);
    % Solve problem
    ensemble.solve(problem);
    % Compute QoI
    ensemble.qoi.getQoI(problem);
end
```

Example: samples from disk – the Egg model

- Geomodel realizations often given as a collection of files (e.g., DECK)
- The ensemble module provides a convenient way of reading samples from disk
- Here: The Egg ensemble (Jansen et. al, 2014)
  - Quantity of interest: oil rate in all production wells

```
example = MRSTExample('egg_wo'); % Set up example
% Function getDeckEGG reads an Egg deck file from disk and returns a model
% Realizations are numbered from 0 to 100 but seed must be > 0, hence seed-1.
generatorFn = @(problem, seed) getDeckEGG('realization', seed-1);
samples     = DeckSamples('generatorFn', generatorFn, ... % Generator function
                          'num'        , 101        );    % Number of samples
% For our QoI, we choose the total oil production rate
is_prod = vertcat(example.schedule.control(1).W.sign) < 0;
qoi     = WellQoI('wellIndices', is_prod, 'fldname', 'qOs');
```

Example: samples from disk – the Egg model

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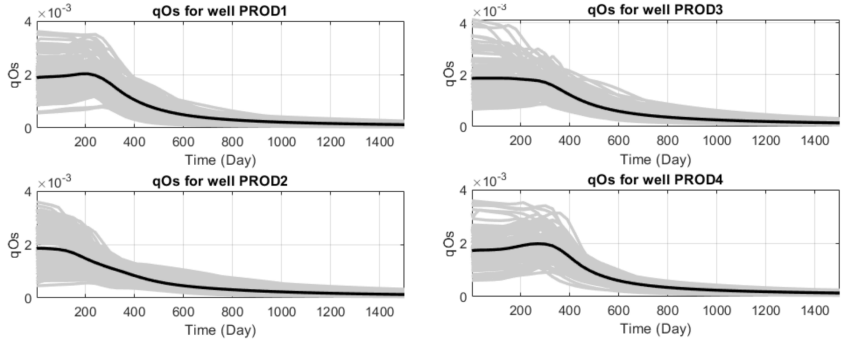


```
ensemble = MRSTEnsemble(example, samples, qoi, ...
                'simulationStrategy', 'background'); % Run in the background
% We simulate 8 samples. Each time the code in this block is called, 8 new samples will be
% simulated until all ensemble memebers have been run. To reset, call ensemble.reset();
ensemble.simulateEnsembleMembers('batchSize', 8, 'plotProgress', true);
```