GeoDict: An integrated tool for digital rock physics - Benchmark results for flow simulations -

Interpore 2018
New Orleans

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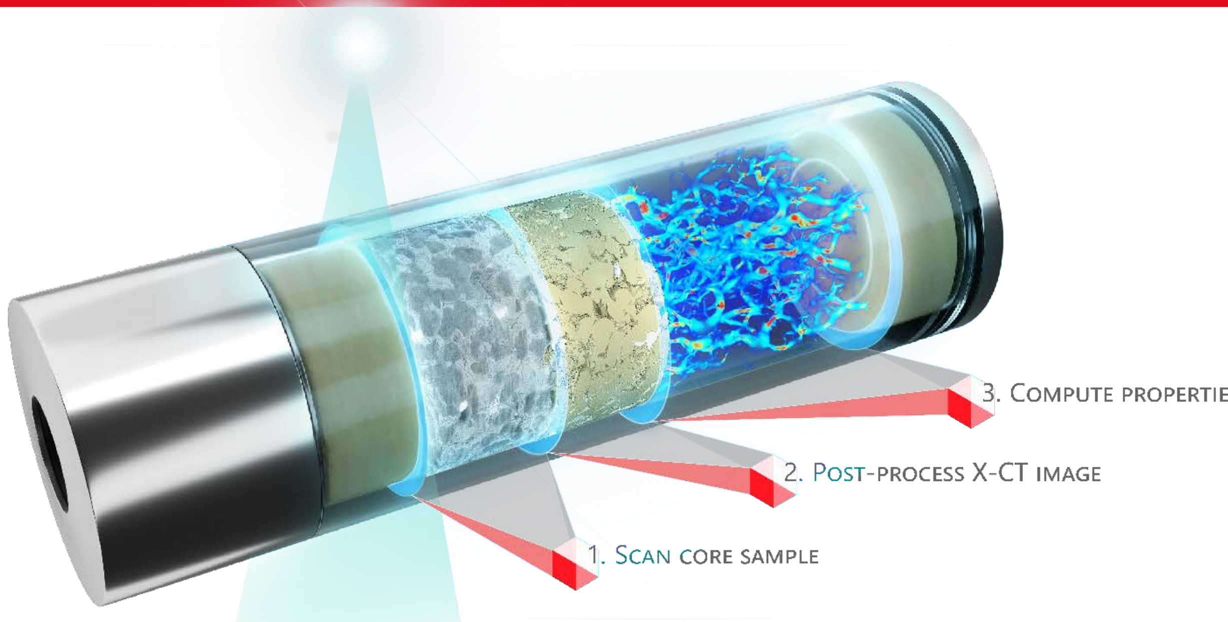

Location and Contact

MATH 2 MARKET

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WWW.GEODICT.COM

Math2Market Overview

GeoDict
The Digital Material Laboratory

Product

2011

Spun Off

2001
Fraunhofer

Started

GER

Location

38

Employees

150+

Customers

Digital Rock Physics

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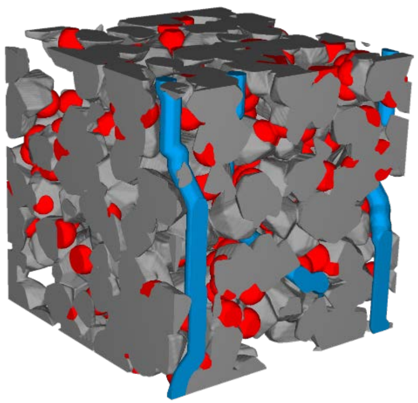
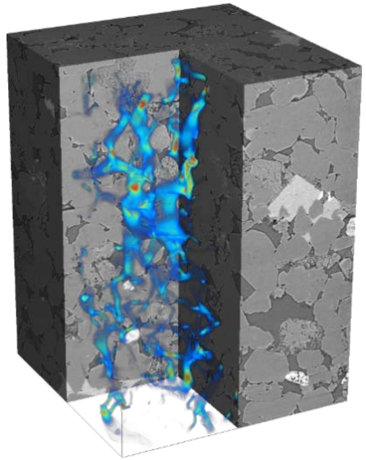
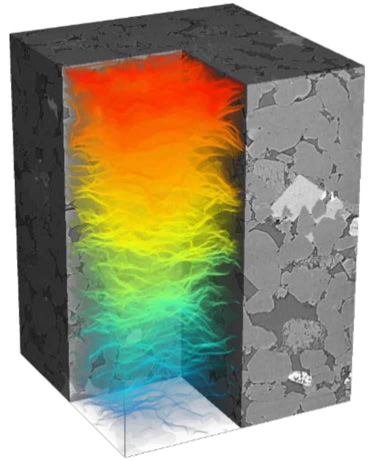
- Digital Rock Physics (DRP) is a tool for computing physical rock properties (e.g. permeability, porosity, tortuosity, …). DRP is a revolutionary rock properties analysis technology.
- DRP complements or replaces expensive and time-consuming or impractical laboratory measurements
- DRP improves and predicts oil recovery processes
- GeoDict® DRP offers simulations for complete workflows, from image processing to rock property determination.

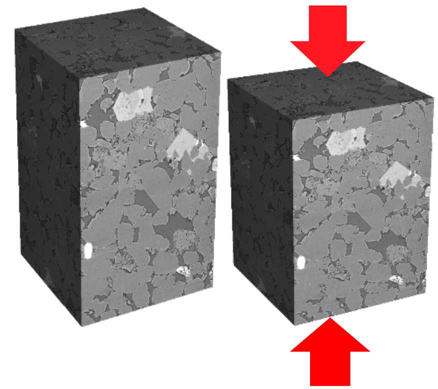
Math2Market GmbH, GeoDict for Oil and Gas: Digital Rock Physics Portfolio

Visit us at: www.geodict.com









Geometric parameters	Flow parameters	Electrical parameters	Mechanical parameters
Porosity	Absolute permeability	Formation factor	Elastic moduli
Pore size distribution	Upscaling of Flow	Resistivity index	Stiffness
Percolation	Multi-phase flow	Saturation exponent	In-Situ conditions
Surface area	Relative permeability	Cementation exponent	Poroelasticity
Tortuosity	Cap. pressure curve		

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- DRP complements or replaces expensive and time-consuming or impractical laboratory measurements
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- GeoDict® DRP offers simulations for complete workflows, from image processing to rock property determination.
- Similar to laboratory measurements, different DRP solvers yield different results for the same property
  - Which answer is the "correct" one?
  - How big is the uncertainty?
  - How fast can a "correct" answer be computed?
  - What resources (e.g. hardware) are required?

BENCHMARKING

- Benchmarking is used to measure performance using specific indicators resulting in a metric of performance that is then compared to others
- We focus on flow solver benchmarks computing absolute permeability in porous microstructures and compare delivered results, runtime, and memory
- Solver benchmark: **Quality** is fixed, **Runtime** is measured

$$Performance = \frac{Quality}{Runtime}$$

- How to fix quality?
  - Solvers compute different permeabilities due to different choices of equations, discretizations, boundary conditions, or stopping criterions
- When can we compare runtime?
  - CPUs/GPUs, different machines, parallelization, ...

Published DRP Benchmark

GeoDict

Saxena et. al., "Standards and Benchmarks for Image Computed Permeability for Digital Rocks and Geologic Materials," *Advances in Water Resources*, vol. 109, pp. 211-245, 2017

- Measured uncertainty associated with DRP computations of permeability
- Generated a benchmark dataset with 36 microstructures with 1024^3 voxels that can be used to test and improve novel numerical algorithms
- 9 stokes flow solvers (3 Lattice-Boltzmann, 3 voxel based, 3 CFD, and 2 semi-analytical) are compared with respect to permeability and runtime
  - GeoDict 2015 voxel based flow solvers (EJ, SimpleFFT, and LIR) are part of this benchmark study
- Coefficient of variation (100 x standard deviation / mean) for permeability ranges from 5% for pipes to 30% for rocks

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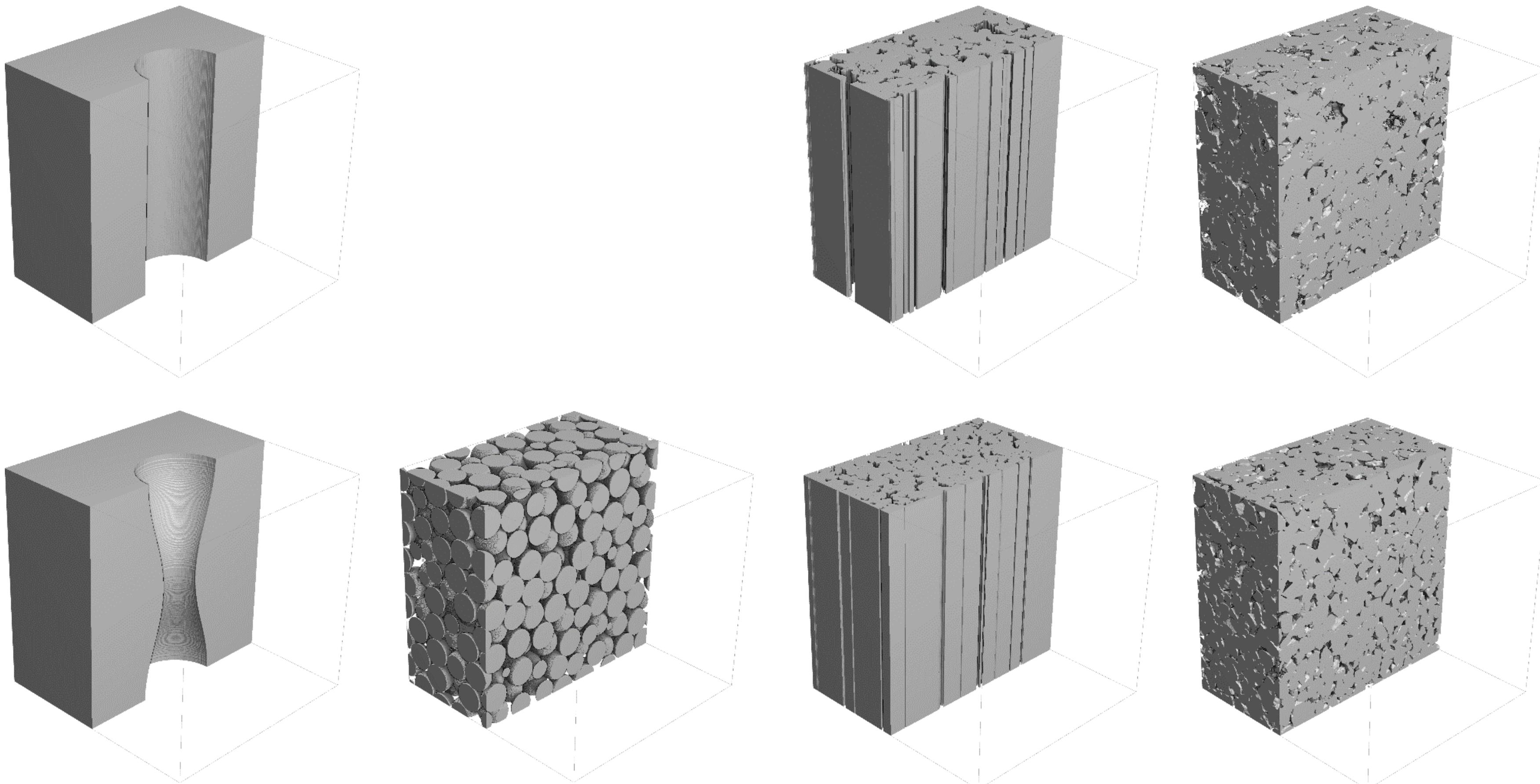
OUTLINE

1. Reproduce published results with GeoDict 2015
2. Compared with results from GeoDict 2017 and 2018

3. Runtime improvements: Relaxation and Multigrid methods
4. Quality control improvements: Error Bound stopping criterion

Benchmark Structures

GeoDict



13 Straight Pipes
12 Sinusoidal Pipes

1 Sphere Pack

5 2D Rocks

5 3D Rocks
(one has no percolating path)

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Benchmark Structures: 3D Rocks

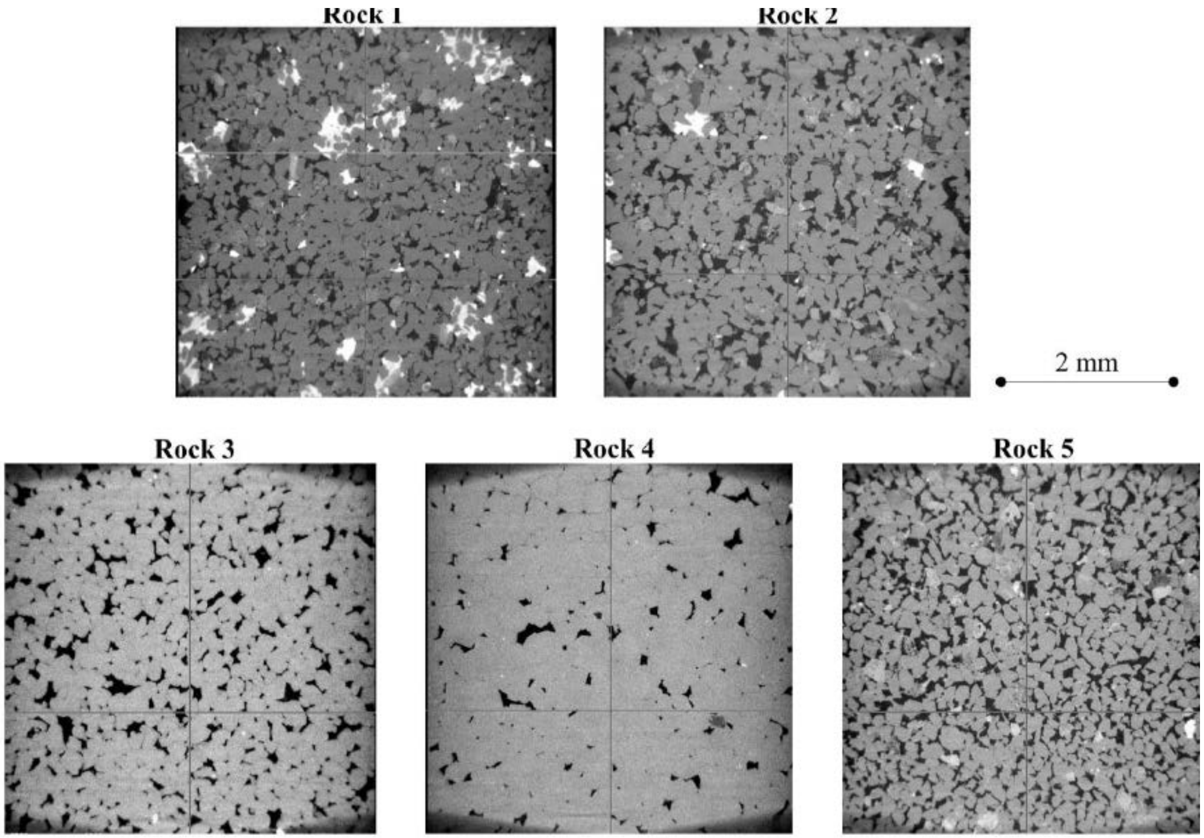


Figure 14. Micro-CT images from which digital rock microstructures in Fig. 13 were generated.

Simulation Set-up

- Shared memory computer with two AMD Opteron CPUs, 512 GB RAM and Linux OS
- Parallelization with 32 threads / processes
- Periodic boundary conditions with 10 voxels inlet/outlet in flow direction and periodic tangential boundary conditions
- Stokes flow in z-direction is computed
- Tolerance stopping criterion with $tol = 10^{-3}$

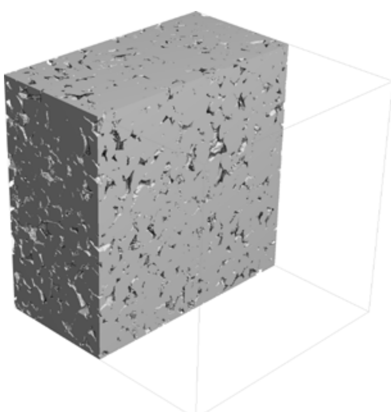
FLOW THROUGH ROCK STRUCTURE 1

GEODICT

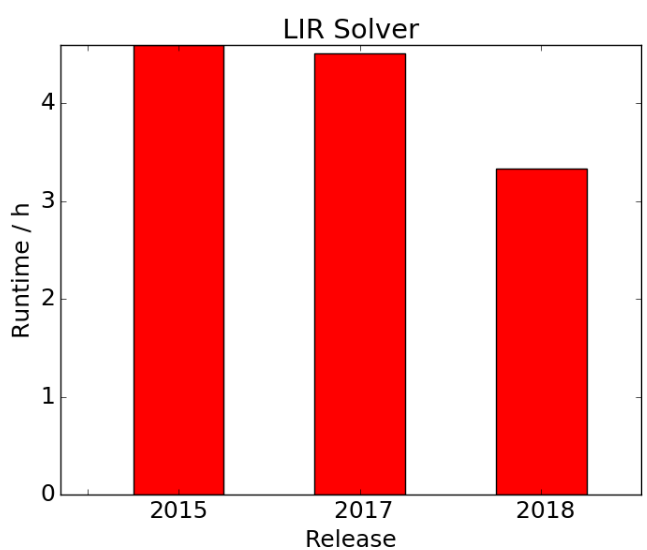
Top View on Rock 1

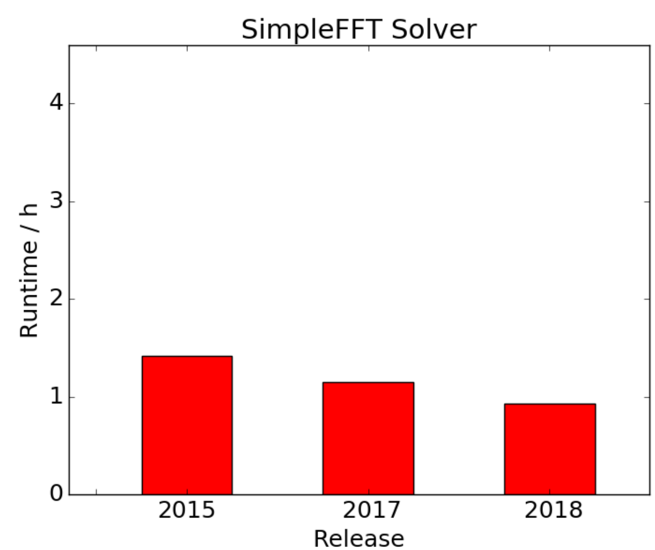
	LIR 2015	LIR 2017	LIR 2018	SFFT 2015	SFFT 2017	SFFT 2018
Permeability / (mD)	753	749	733	697	697	697
Runtime / (h)	4.59	4.51	3.33	1.42	1.15	0.93
Memory / (GB)	12.45	12.42	12.44	89.90	87.79	87.79

Porosity: 18.36%; Converged Averaged Permeability: 695.3 mD, Standard Deviation 3.65 mD



3D View of Rock 1





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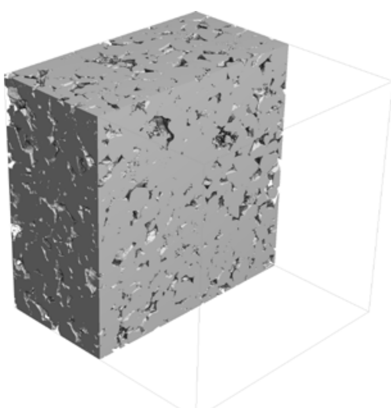
Flow through Rock Structure 2

GeoDict

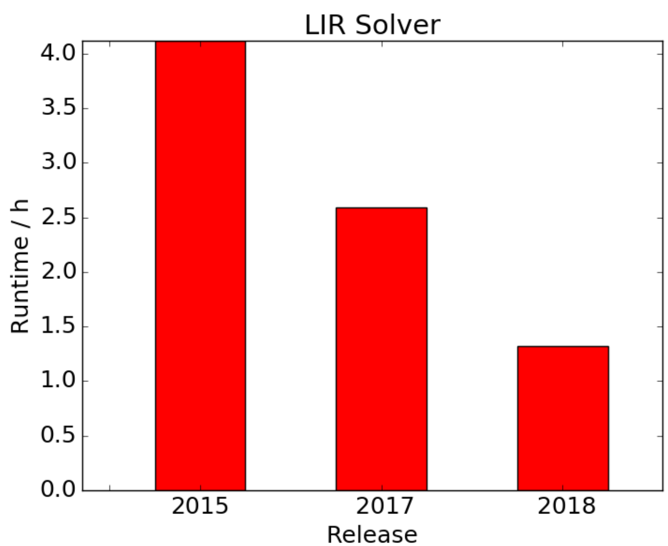
Top View on Rock 2

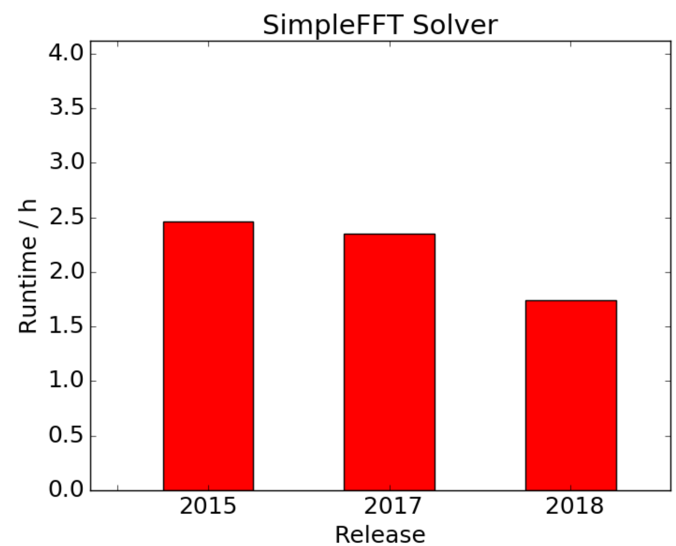
	LIR 2015	LIR 2017	LIR 2018	SFFT 2015	SFFT 2017	SFFT 2018
Permeability / (mD)	1392	1385	1358	1294	1294	1294
Runtime / (h)	4.12	2.59	1.32	2.47	2.35	1.74
Memory / (GB)	12.30	12.27	12.28	89.90	87.79	87.79

Porosity: 20.85%; Converged Averaged Permeability: 1298 mD, Standard Deviation 4.9 mD



3D View of Rock 2





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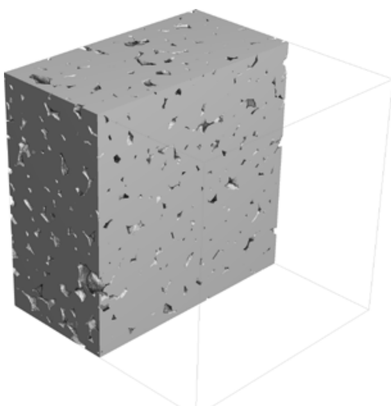
Flow through Rock Structure 3

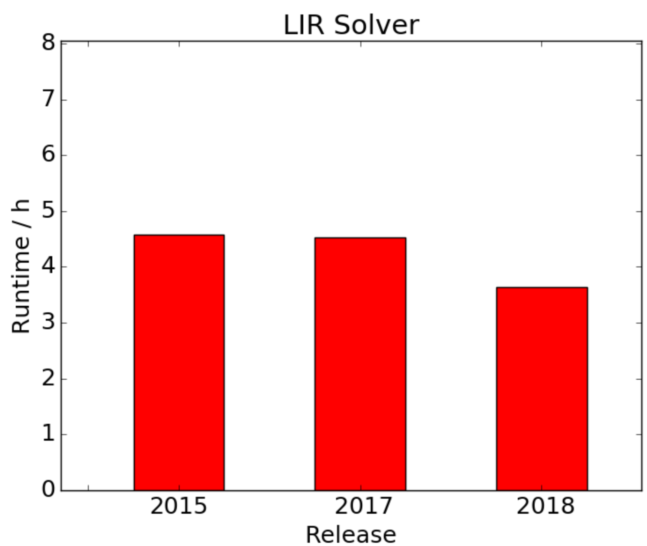
Top View on Rock 3

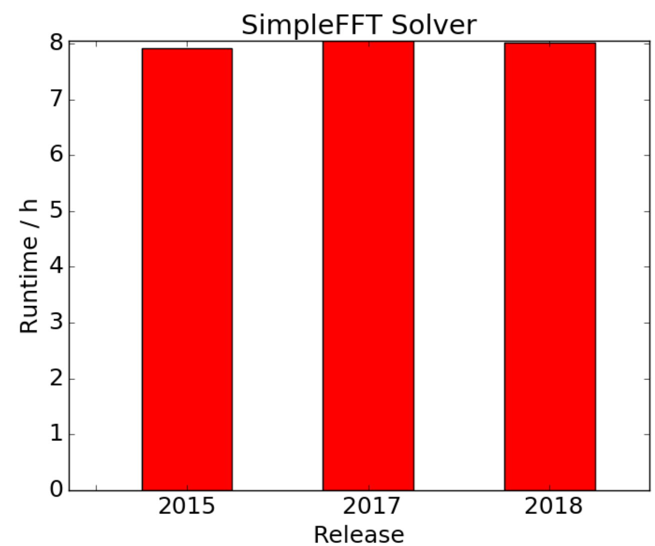
	LIR 2015	LIR 2017	LIR 2018	SFFT 2015	SFFT 2017	SFFT 2018
Permeability / (mD)	148	146	137	113	113	113
Runtime / (h)	4.58	4.52	3.63	7.91	8.05	8.02
Memory / (GB)	5.21	5.17	5.18	89.90	87.79	87.79

Porosity: 9.53%; Converged Averaged Permeability: 113 mD, Standard Deviation 0.2 mD



3D View of Rock 3



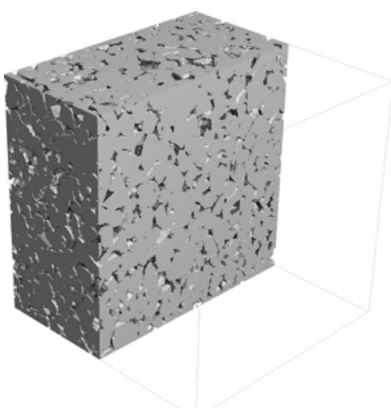


Flow through Rock Structure 5

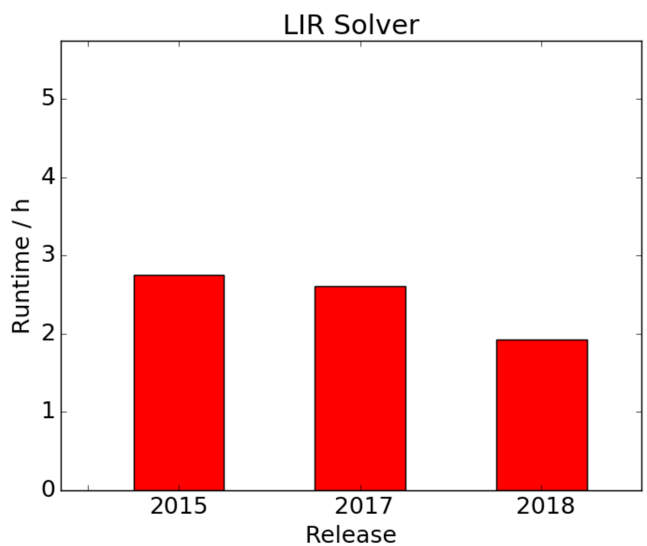
Top View on Rock 5

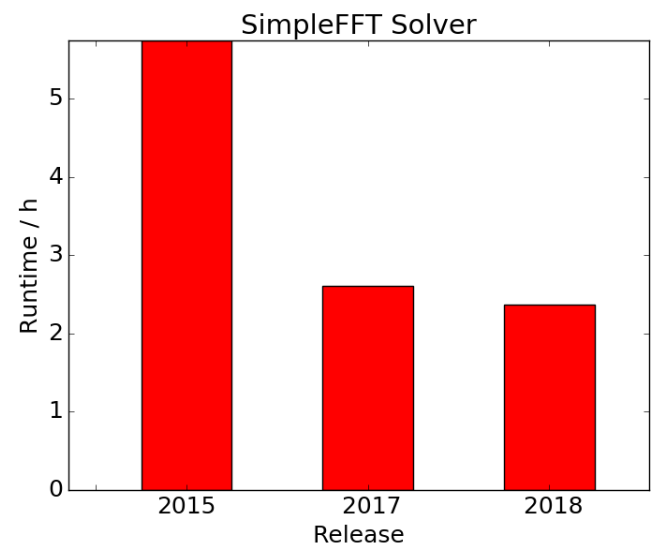
	LIR 2015	LIR 2017	LIR 2018	SFFT 2015	SFFT 2017	SFFT 2018
Permeability / (mD)	1666	1661	1639	1587	1587	1587
Runtime / (h)	2.75	2.60	1.93	5.75	2.61	2.37
Memory / (GB)	11.64	11.60	11.59	89.90	87.79	87.79

Porosity: 21.69%; Converged Averaged Permeability: 1593 mD, Standard Deviation 21.69 mD



3D View of Rock 5

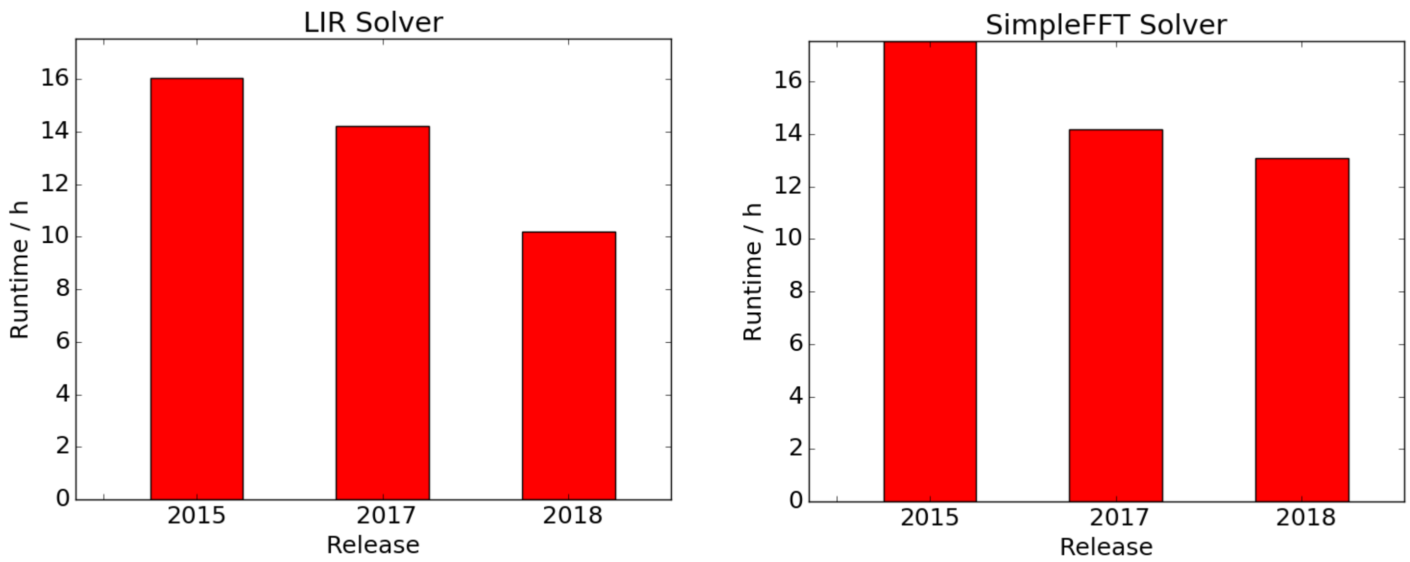




Benchmark Results – 3D Rocks

GeoDict

- We could reproduce published permeability results with GeoDict 2015
- We could reduce the total runtime in GeoDict 2017/2018 by up to
  - 25% for SimpleFFT while maintaining same result quality and
  - 40% for LIR with increased result quality



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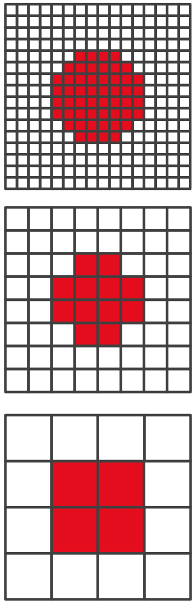
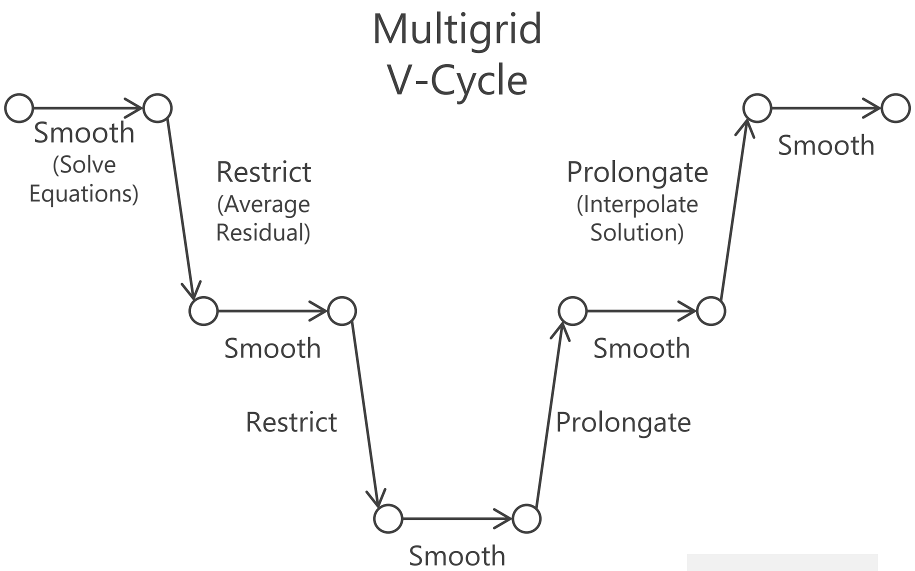
Further Improvements for 3D Rocks

We further reduce the runtime of the LIR solver by using two acceleration methods

- Successive Over-Relaxation (SOR)
  - Algorithm to solve linear systems with relaxation parameter $\omega \in (0,2)$
  - The ideal value ω is very hard to estimate and depends on the linear system
  - High ω values reduce the runtime but too high values lead to divergence, here we use $\omega = 1.5$
- Multigrid Methods
  - Grids with coarser resolution are used to speed up convergence on the finest grid
  - Coarse grids allow faster information propagation

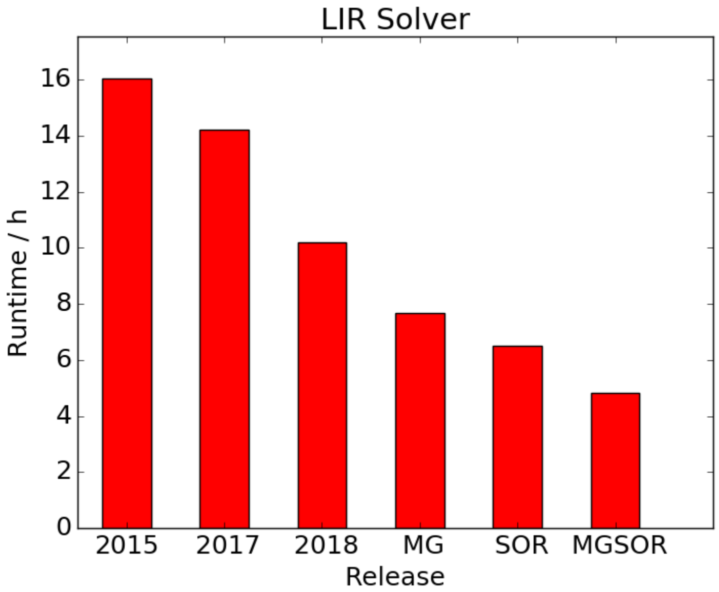




Benchmark Results with LIR Improvements

Computing **improved permeability compared to GeoDict 2018:**

- With Multigrid the runtime could be reduced by 52%.
- With Relaxation the runtime could be reduced by 59%.
- The combination of both methods reduces the runtime by 70%.

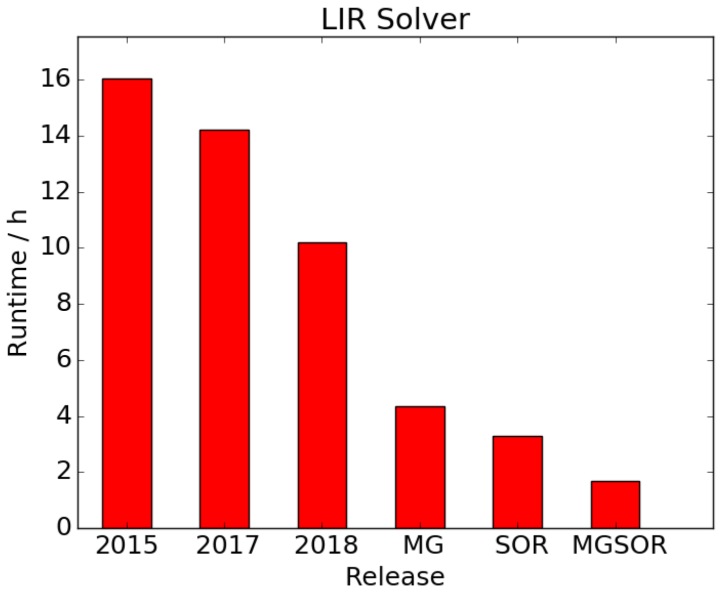


BENCHMARK RESULTS WITH LIR IMPROVEMENTS

GEODICT

Computing the **same permeability as LIR in GeoDict 2018:**

- With Multigrid the runtime could be reduced by 73%.
- With Relaxation the runtime could be reduced by 80%.
- The combination of both methods reduces the runtime by 90%.



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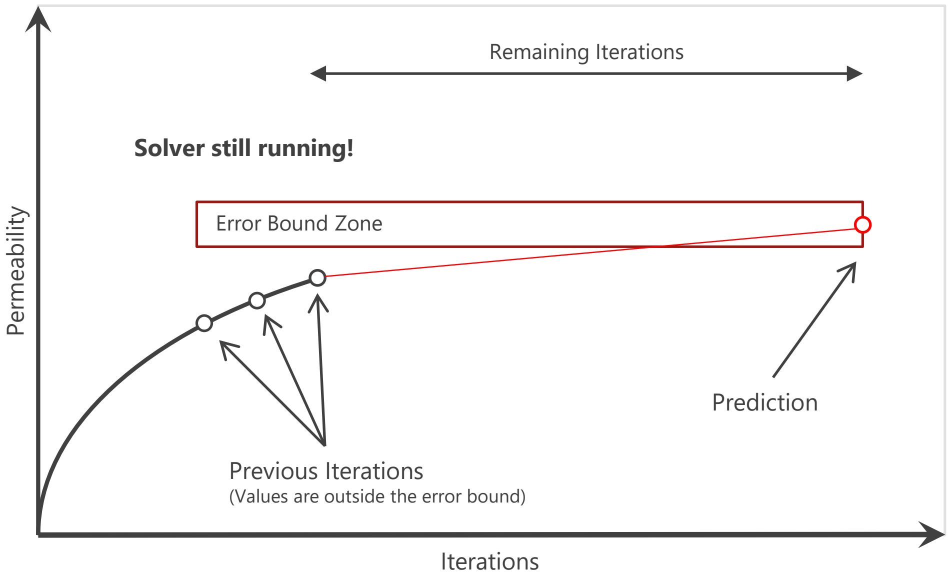
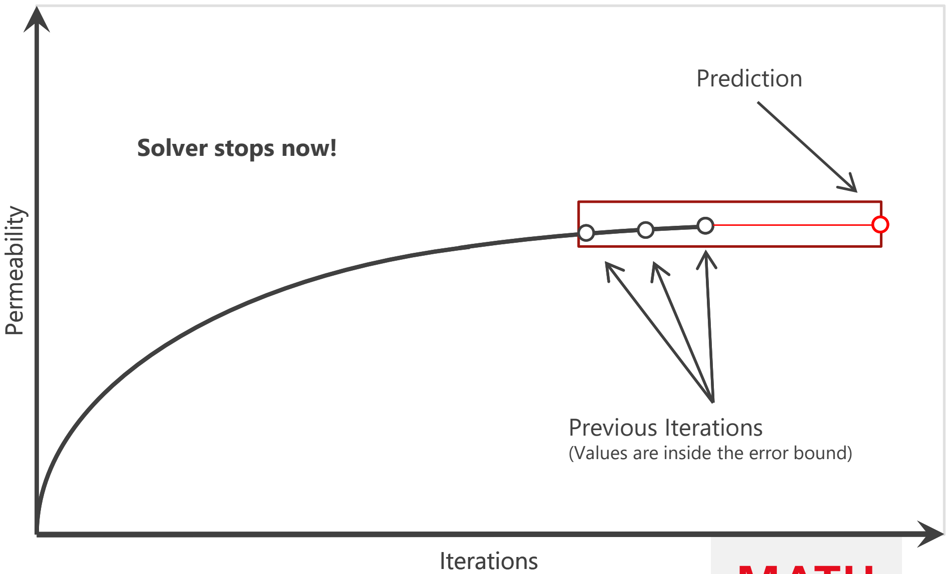
Tolerance Stopping Criterion

- Improvements of the LIR solver that increase the convergence speed lead to different results compared to published ones
  - Reason is the tolerance stopping criterion
- How to test delivered quality? For example:
  - Solve for two digits desired (x.x......)
  - Solve for four digits desired and assume first two digits are correct (x.xxx......)
  - Compare first two digits
- The tolerance stopping criterion in a commonly used stopping criterion that looks for stagnation of numerical methods
  - The solver is stopped if the relative change of current and past iterations is smaller than a given threshold tol
- A $tol = 10^{-2}$ does not mean 1% accuracy with respect to the fully converged permeability!
- That property makes it difficult to compare the quality delivered by different solvers!

Error Bound Stopping Criterion

- Use results from previous iterations and predict the final solution
  - Measure relative error to this prediction
  - Stop if the relative error of previous iteration is smaller than the given error bound
- Recognize oscillations in convergence behavior
  - Detect if the solver approaches a local minimum or maximum and prevent stopping
  - Fit damped curve through the oscillating curve and stop with respect to that

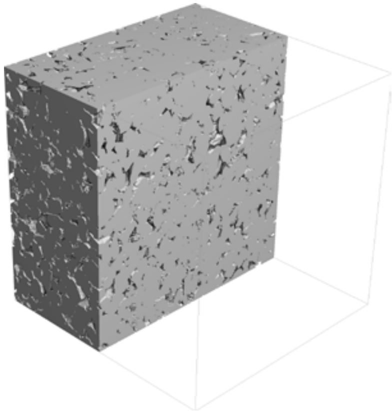




Benchmark Results with Error Bound Stopping criterion for Rock 1

GeoDict

Top View on Rock 1



3D View of Rock 1

Solver	Stopping Criterion	Permeability / mD	Reached Accuracy / % (Desired Accuracy)	Runtime / h
LIR 2018	Tolerance 1E-3 (0.1%)	733	**5.08 (0.1)**	3.33
S-FFT 2018		697	0.63 (0.1)	0.93
LIR 2018	ErrorBound 1E-2 (1.0%)	707	**1.37 (1.0)**	8.81
S-FFT 2018		698	**0.70 (1.0)**	0.74
LIR 2018	ErrorBound 1E-4 (0.01%)	698	Reference for LIR	
S-FFT 2018		693	Reference for S-FFT	

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Stopping Criterion Benchmark Results for all Rocks

GeoDict

- Desired accuracy could be reached with Error Bound but not with Tolerance
- Runtimes with Error Bound are now comparable
- LIR needs more runtime and SimpleFFT needs less runtime to compute desired accuracy compared to Tolerance

Solver	Stopping Criterion	Reached Accuracy / % (Desired Accuracy)	Runtime / h
LIR 2019 SOR+MG	Tolerance 1E-3 (0.1%)	**1.9 (0.1)**	5.35
LIR 2018		**8.26 (0.1)**	10.21
S-FFT 2018		0.2 (0.1)	13.07
LIR 2019 SOR+MG	ErrorBound 1E-2 (1.0%)	**1.5 (1.0)**	7.86
LIR 2018		**1.3 (1.0)**	51.75
S-FFT 2018		0.3 (1.0)	9.81

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Summary & Conclusions

- Published permeability results of LIR & SIMPLE-FFT could be reproduced and they differed by up to 20% in 2015
  - They were reproduced also with 2018 version with reduced runtime
- We improved the numerical methods in LIR with SOR and Multigrid
  - With same results the runtime could be reduced by 90%
  - With improved results the runtime could be reduced by 70%
- We improved the quality control of the methods
  - Now, results differ by at most 1% and are the same as original SIMPLE-FFT results

Thank you for your attention.

Meet us at HALL I-1 BOOTH #8

GeoDict