Reservoir Simulation of Million-Cell Models on Desktop Computers

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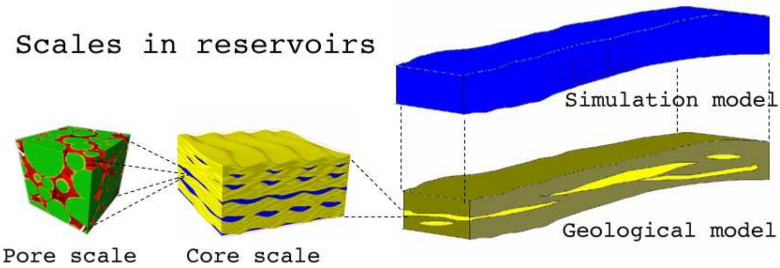
The 22nd Kongsberg Seminar, May 2009

Physical Scales in Porous Media Flow

... one cannot resolve them all at once

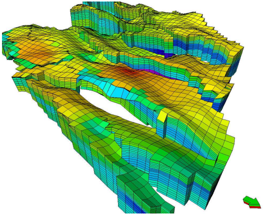
The scales that impact fluid flow in oil reservoirs range from

- the micrometer scale of pores and pore channels
- via dm–m scale of well bores and laminae sediments
- to sedimentary structures that stretch across entire reservoirs.



Geological models:

- here: geo-cellular models
- describe the reservoir geometry (horizons, faults, etc)
- typically generated using geostatistics
- give rock parameters (permeability and porosity)



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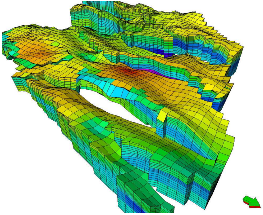
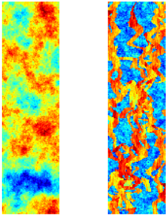


Rock parameters:

- have a multiscale structure
- details on all scales impact flow
- permeability spans many orders of magnitude

Ex: Brent sequence



Gap in resolution:

- Geomodels: $10^7 - 10^9$ cells
- Simulators: $10^5 - 10^6$ cells

Flow Simulation
Gap in resolution and model sizes

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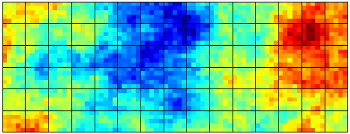
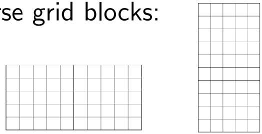
$\longrightarrow$ sector models and/or
upscaling of parameters



$\Downarrow$

Coarse grid blocks:



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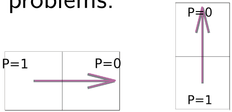

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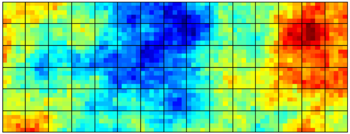

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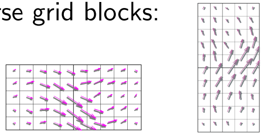

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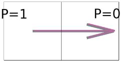

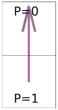

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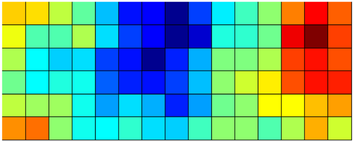

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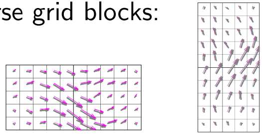

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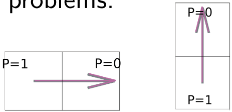

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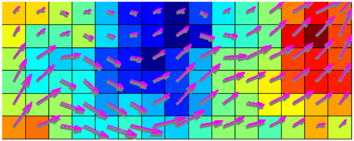

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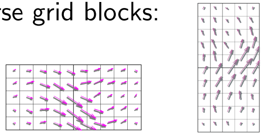

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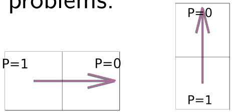

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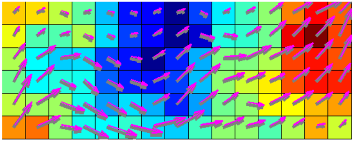
Many alternatives:

- Harmonic, arithmetic, geometric, ...
- Local methods (K or T)
- Global methods
- Local-global methods
- Pseudo methods
- Ensemble methods



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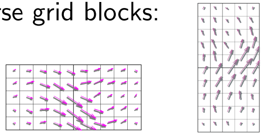

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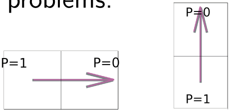

Upscaling:

- bottleneck in workflow
- loss of information/accuracy
- not sufficiently robust
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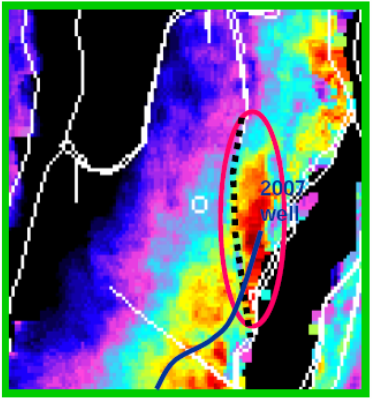
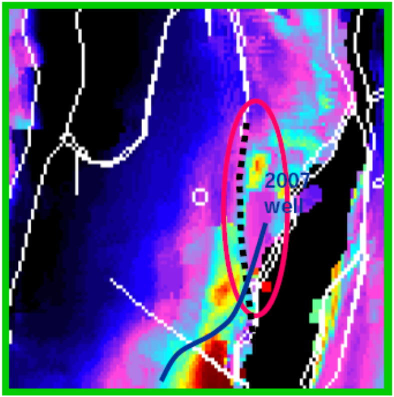
Simulation on seismic/geologic grid:

- best possible resolution of the physical processes
- faster mode building and history matching
- makes inversion a better instrument to find remaining oil
- better estimation of uncertainty by running alternative models

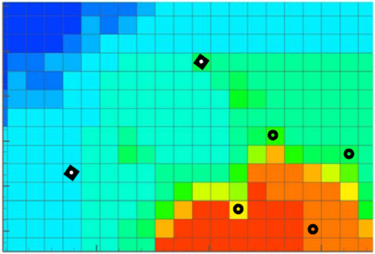
Bypassed oil (4D inversion vs simulation)

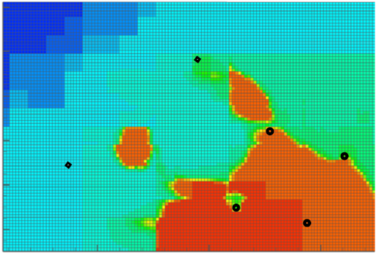




Arnesen, WPC, Madrid, 2008

Difference in resolution (10 million vs 1 billion cells)





From Dogru et al., SPE 119272

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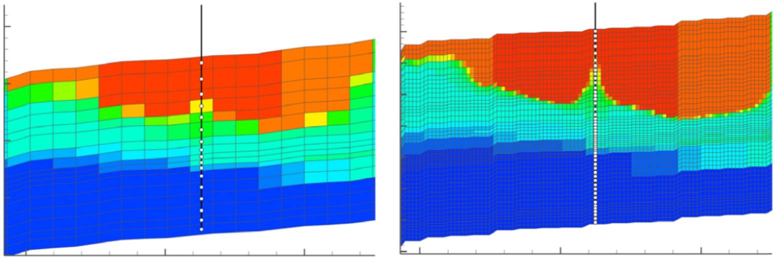

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Simplified flow physics

"Full physics" is typically only required towards the end of a workflow

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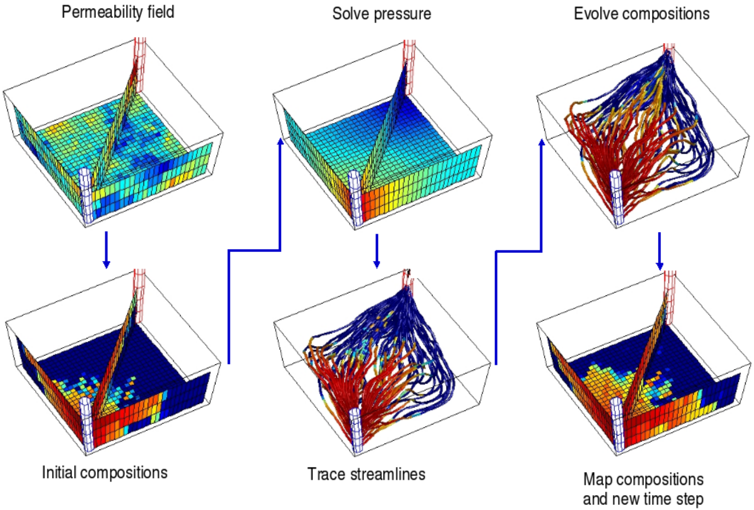
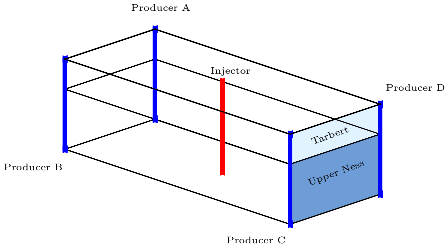
Operator splitting

- fully coupled solution is slow..
- subequations often have different time scales
- splitting opens up for tailor-made methods

Streamline Simulation
Operator splitting + Euler-Lagrangian formulation

(Figures by Yann Gautier)

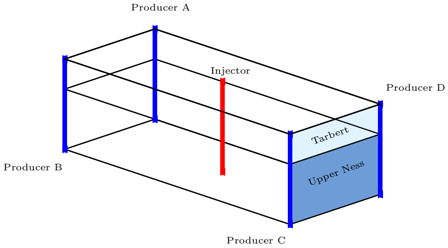


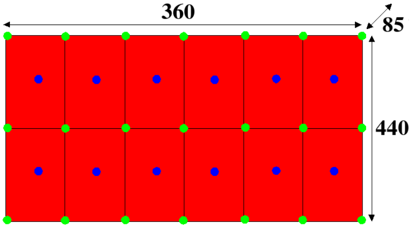


Inhouse code:

- $60 \times 220 \times 85 = 1.1$ million cells
- 2000 days of production from five-spot, 25 time steps
- Intel 2.4 GHz with 2 GB RAM:

multigrid:	8 min 36 sec
multiscale:	2 min 22 sec





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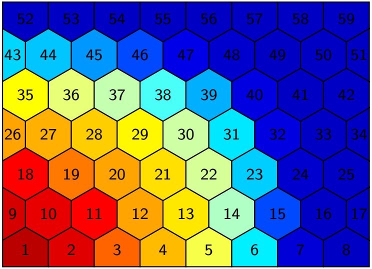
FrontSim:

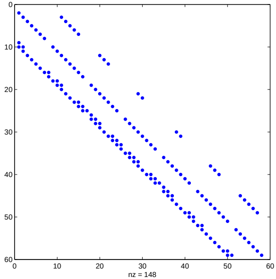
- $360 \times 440 \times 85 = 13.5$ million cells
- Intel Xeon 5482, 64 Gb, 3.2 GHz
- Single thread, 13.5 Gb RAM
- Computing time: 1 h 55 min

Fast Solution of Fluid Transport

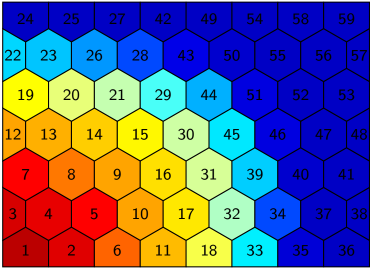
Optimal ordering: finite volumes (almost) as fast as streamline simulation?

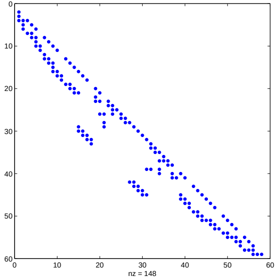
Natural order



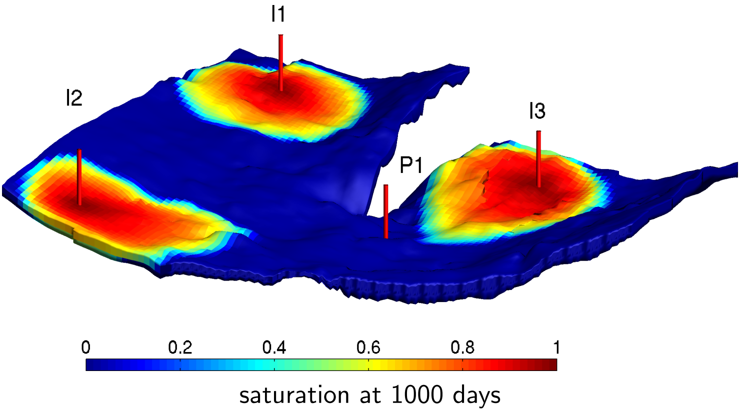


Topological order





Model: $50 \times 50 \times 1$ km, rescaled by a factor 0.1
Grid: 27 437 active cells.



Example

Johansen formation: runtime/step and iterations/cell

Δt	NR–UMFPACK		NR–PFS		NPFS	
days	time (sec)	iterations	time (sec)	iterations	time (sec)	iterations
125	2.26e+00	12.69	3.28e-01	12.69	4.44e-02	0.93
250	2.35e+00	12.62	3.32e-01	12.62	4.73e-02	1.10
500	2.38e+00	13.25	3.46e-01	13.25	4.16e-02	1.41
1000	2.50e+00	13.50	3.49e-01	13.50	4.21e-02	1.99
125	2.19e+00	12.69	3.91e-01	12.69	5.82e-02	1.33
250	2.02e+00	12.75	3.86e-01	12.75	6.07e-02	1.48
500	2.09e+00	13.25	3.90e-01	13.25	6.16e-02	1.79
1000	2.20e+00	14.00	4.11e-01	14.00	6.39e-02	2.38

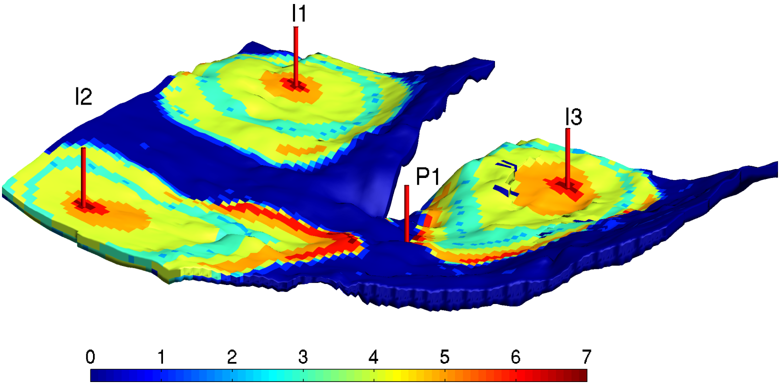
incompressible oil   compressible oil

Time to compute reordering: $3.6 \cdot 10^{-3}$ sec

cycles: 77.4 on average, involving 780 cells, 380 cells in largest cycle

Example

Johansen formation: localization of nonlinear iterations



Use of sparsity / (multiscale) structure

- effects resolved on different scales
- small changes from one step to next
- small changes from one simulation to next

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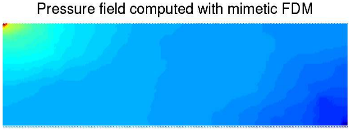
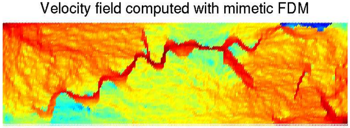
Example: SPE10, Layer 36



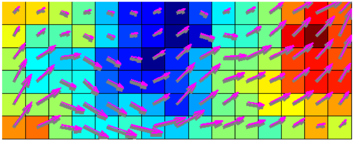


Observations:

- Pressure on coarse grid
- Velocity on fine grid

$\longrightarrow$ multiscale method

Standard upscaling:



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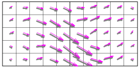
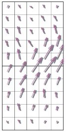
Coarse grid blocks:





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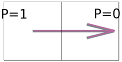

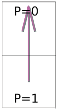

Multiscale Pressure Solvers

From upscaling to multiscale methods

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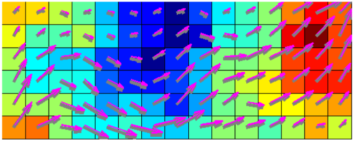

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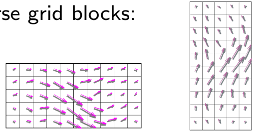

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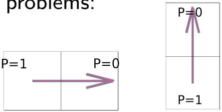

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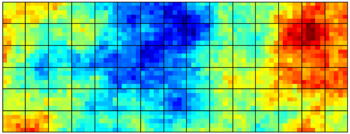

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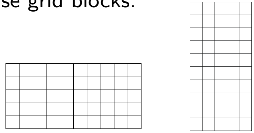

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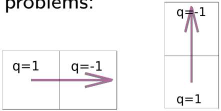

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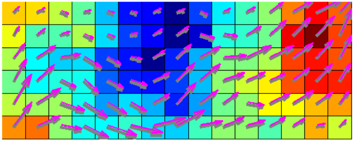

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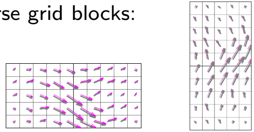

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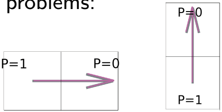

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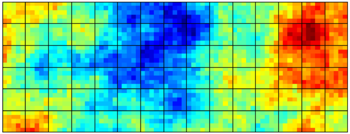

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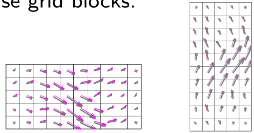

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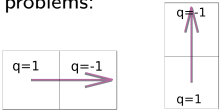

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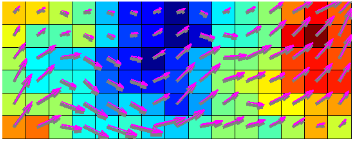

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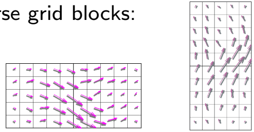

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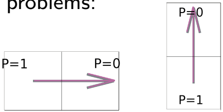
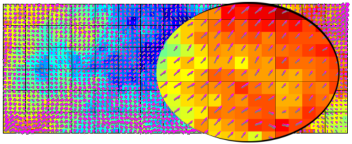
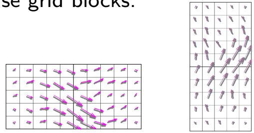


Multiscale method:



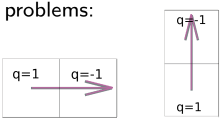
$\Downarrow \quad \Uparrow$

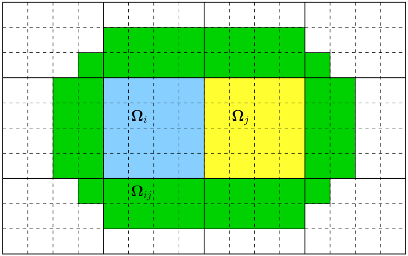
Coarse grid blocks:



$\Downarrow \quad \Uparrow$

Flow problems:

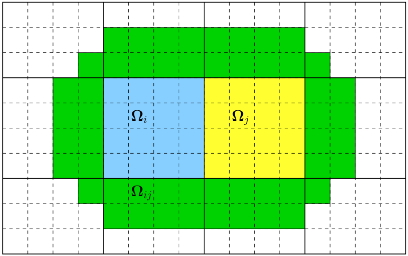




Each cell Ω_i: pressure basis ϕ_i
Each face Γ_{ij}: velocity basis ψ_{ij}

$$\vec{\psi}_{ij} = -\lambda \mathbf{K} \nabla \phi_{ij}$$

$$\nabla \cdot \vec{\psi}_{ij} = \begin{cases} w_i(x), & x \in \Omega_i \\ -w_j(x), & x \in \Omega_j \\ 0, & \text{otherwise} \end{cases}$$



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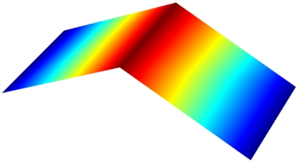
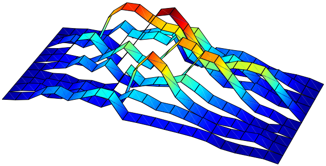
Homogeneous **K**:

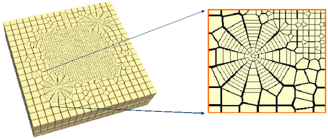


Heterogeneous **K**:

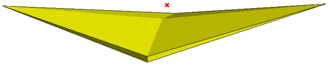


Multiscale Pressure Solvers
Challenges posed by grids from real-life models

Unstructured grids:

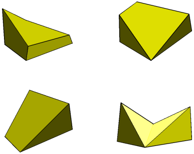


(Very) high aspect ratios:

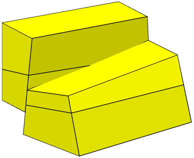


$800 \times 800 \times 0.25$ m

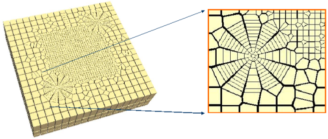
Skewed and degenerate cells:



Non-matching cells:



Unstructured grids:



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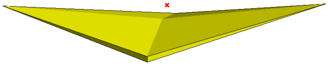
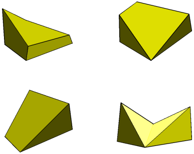
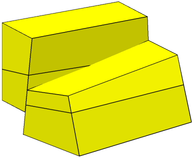


Skewed and degenerate cells:



Non-matching cells:

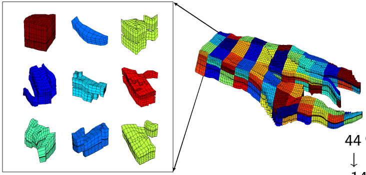


Meeting the challenges:

- Automated coarsening algorithms
- Multipoint/mimetic fine-grid discretization

Multiscale Pressure Solvers
Workflow with automated upgridding in 3D

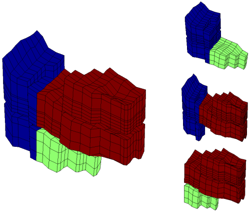
1) Automated coarsening: uniform partition in index space for corner-point grids



44 927 cells
↓
148 blocks

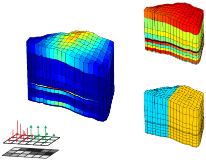
9 different coarse blocks

2) Detect all adjacent blocks



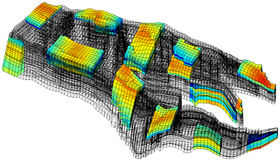
3) Compute basis functions

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



for all pairs of blocks

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

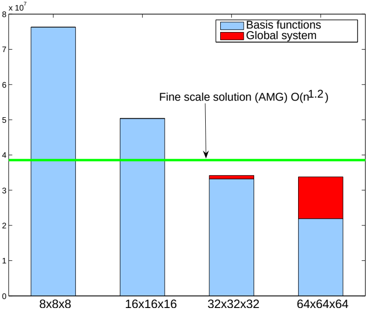


Computational cost consists of:

- **basis functions** (fine grid)
- **global problem** (coarse grid)

Example: 128^3 grid

\# operations versus upscaling factor



Computational cost consists of:

- **basis functions** (fine grid)
- **global problem** (coarse grid)

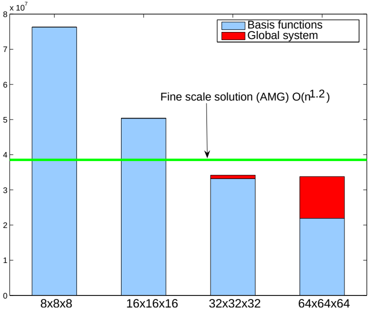
Full simulation: $\mathcal{O}(10^2)$ time steps

High efficiency for multiphase flows:

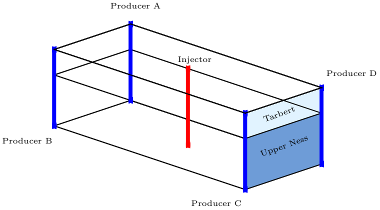
- Elliptic decomposition
- Reuse basis functions
- Easy to parallelize

Example: 128^3 grid

operations versus upscaling factor



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



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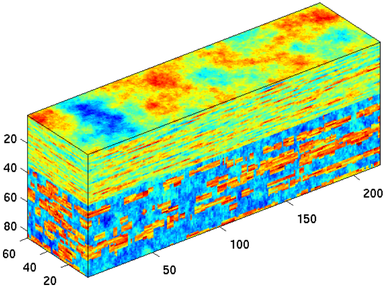
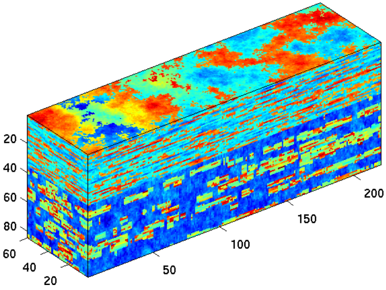
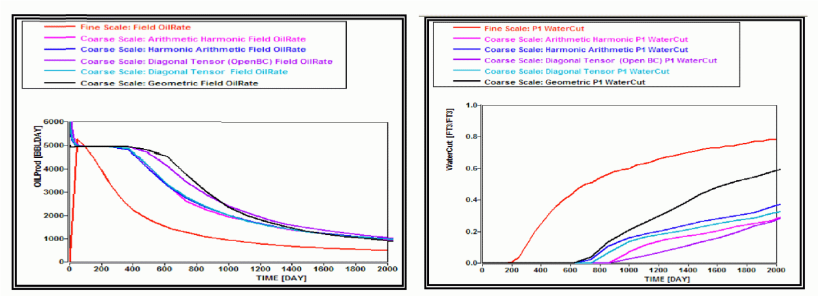
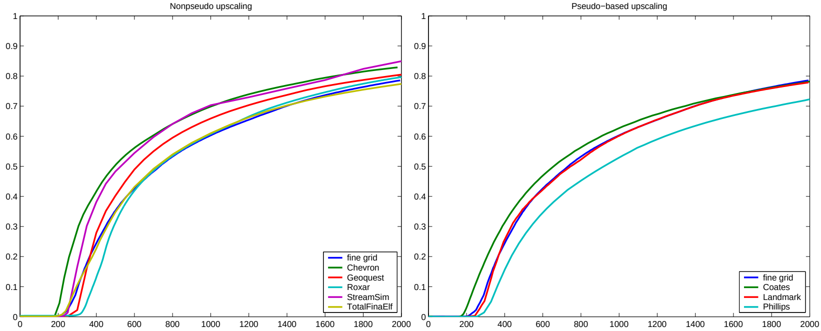




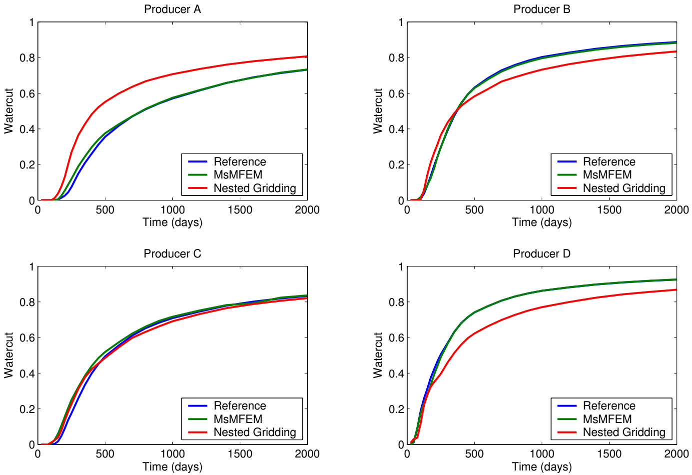


Fine Scale: Field OilRate
Coarse Scale: Arithmetic Harmonic Field OilRate
Coarse Scale: Harmonic Arithmetic Field OilRate
Coarse Scale: Diagonal Tensor (OpenBC) Field OilRate
Coarse Scale: Diagonal Tensor Field OilRate
Coarse Scale: Geometric Field OilRate
OILProd [BBL/DAY]
TIME [DAY]
Fine Scale: P1 WaterCut
Coarse Scale: Arithmetic Harmonic P1 WaterCut
Coarse Scale: Harmonic Arithmetic P1 WaterCut
Coarse Scale: Diagonal Tensor (Open BC) P1 WaterCut
Coarse Scale: Diagonal Tensor P1 WaterCut
Coarse Scale: Geometric P1 WaterCut
WaterCut [FT3/FT3]
TIME [DAY]



Nonpseudo upscaling
fine grid
Chevron
Geoquest
Roxar
StreamSim
TotalFinaElf
Pseudo−based upscaling
fine grid
Coates
Landmark
Phillips

Water-cut curves at the four producers

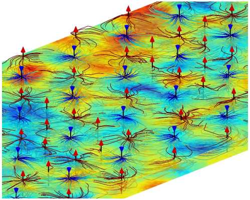


upscaling/downscaling, multiscale, fine grid

Assimilation of production data to calibrate model

- 1 million cells, 32 injectors, and 69 producers
- 2475 days $\approx$ 7 years of water-cut data

Generalized travel-time inversion (quasi-linearization of misfit functional) with analytical sensitivities along streamlines



Solver	CPU-time (wall clock) Total	Pres.	Transp.
Multigrid	39 min	30 min	5 min
Multiscale	17 min	7 min	6 min

Computer: 2.4 GHz Core 2 Duo, with 2 GB RAM
History match: 7 forward simulations, 6 inversions

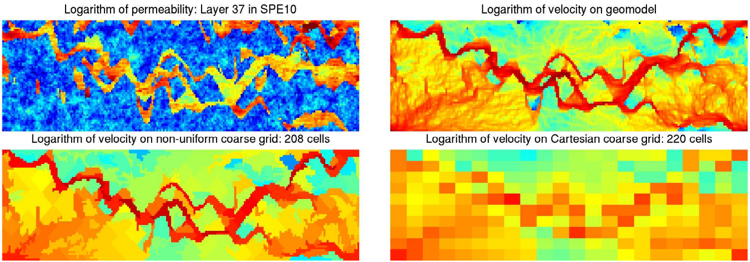
Notice: obvious potential for parallelization of basis functions, streamline tracing and 1D transport solves not utilized

Adaptive Model Reduction of Transport Grids

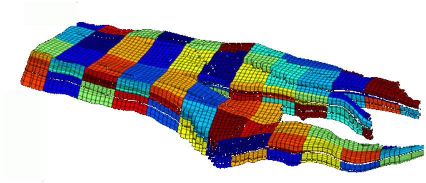
Flow-based nonuniform coarsening

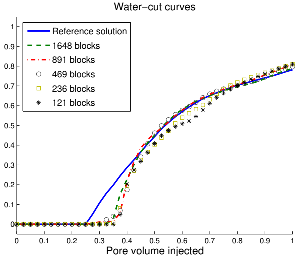
1. Segment the domain according to ln $|\vec{v}|$
2. Combine small blocks
3. Split blocks with too large flow
4. Combine small blocks

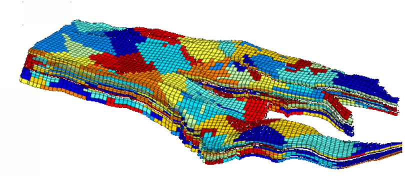
SPE 10, Layer 37

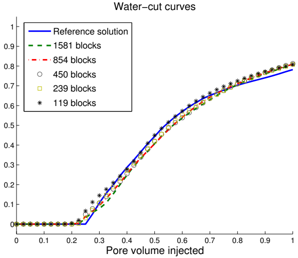


Example
Production data for a real-field model









Summary

Keys to enable fast simulation on seismic/geological grids:

- Simplified physics
- Operator splitting
- Sparsity / (multiscale) structure

In the future: fit-for-purpose rather than one-simulator-solves-all..?

Current and Future Research