SINTEF

OPM DEVELOPMENT STORIES

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About SINTEF

Vision: **technology for a better society**

- independent, not-for-profit organization
- largest for-contract research in Scandinavia, fourth largest in Europe
- 2100 employees
- NOK 3.1 billion turnover, 90% 'won' in open competition
- more than 7000 research projects for some 2300 clients
- offices in Trondheim, Oslo, Bergen, Brussels, Houston, . . .

Computational Geosciences group

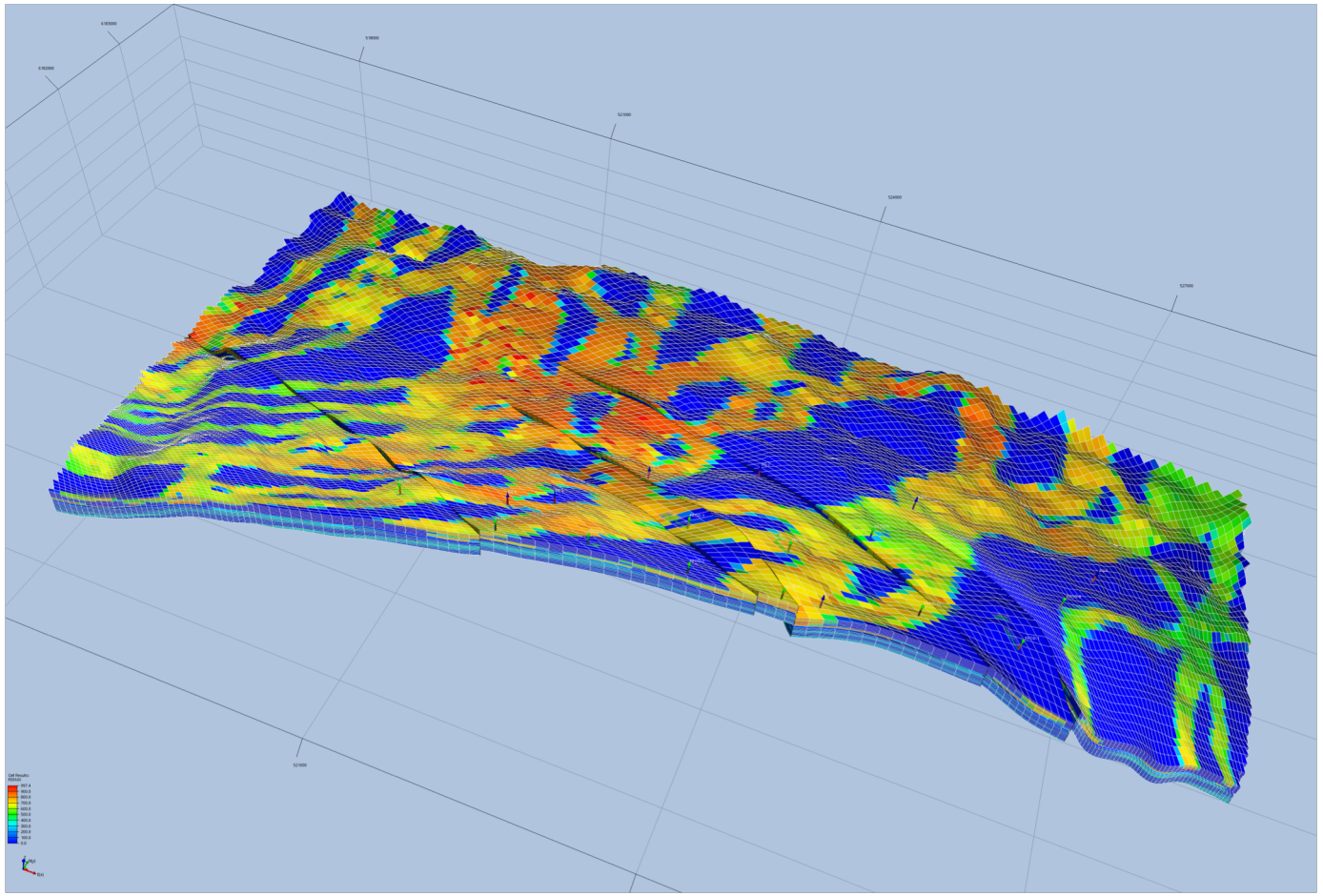
- One of eight research groups at the department of Mathematics & Cybernetics, SINTEF Digital
- 14 researchers/postdocs/PhD students
- Offices in Oslo, Norway
- Performs a mixture of basic and applied research
- Well known for our *open-source software*: MRST and OPM
- Internationally oriented
- Strong publication record
- Main clients: Equinor, ExxonMobil, Research Council of Norway, Wintershall, . . .

Some OPM development stories

- Grid interfaces: a personal history
- Making Flow perform well

Grid interfaces: a personal history

Grids in simulation codes



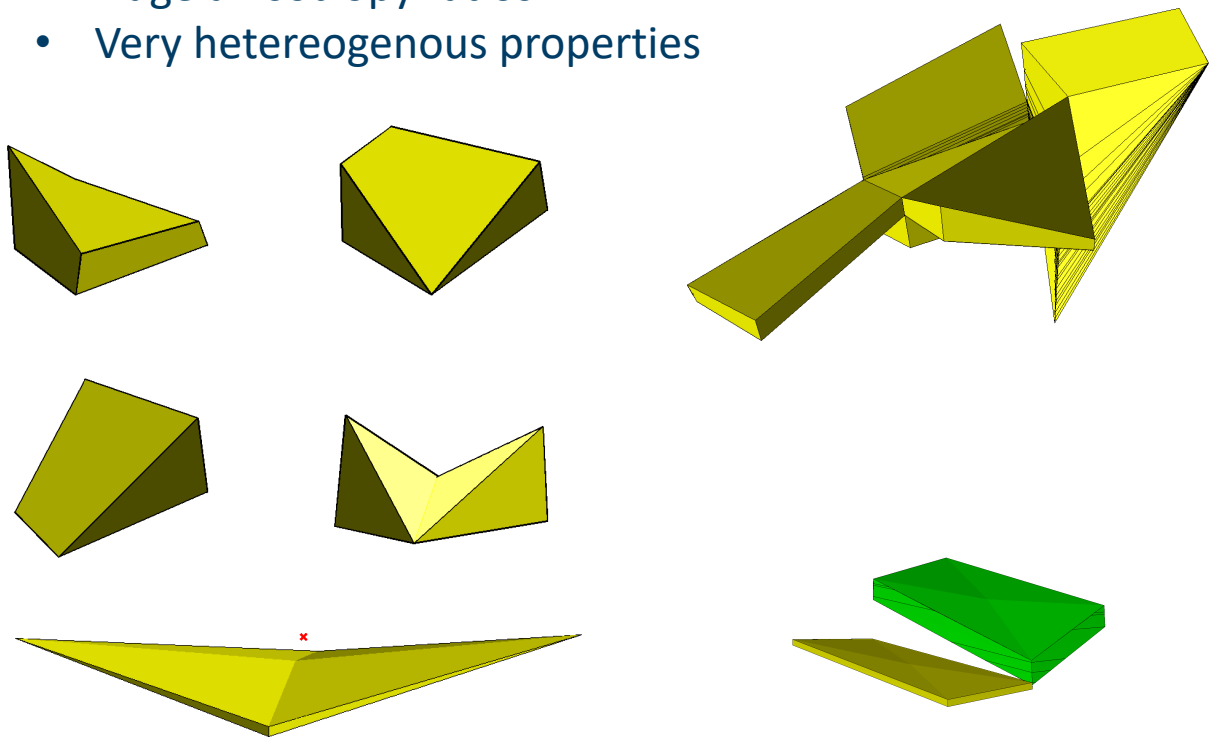
Computational grids discretize the spatial domain.

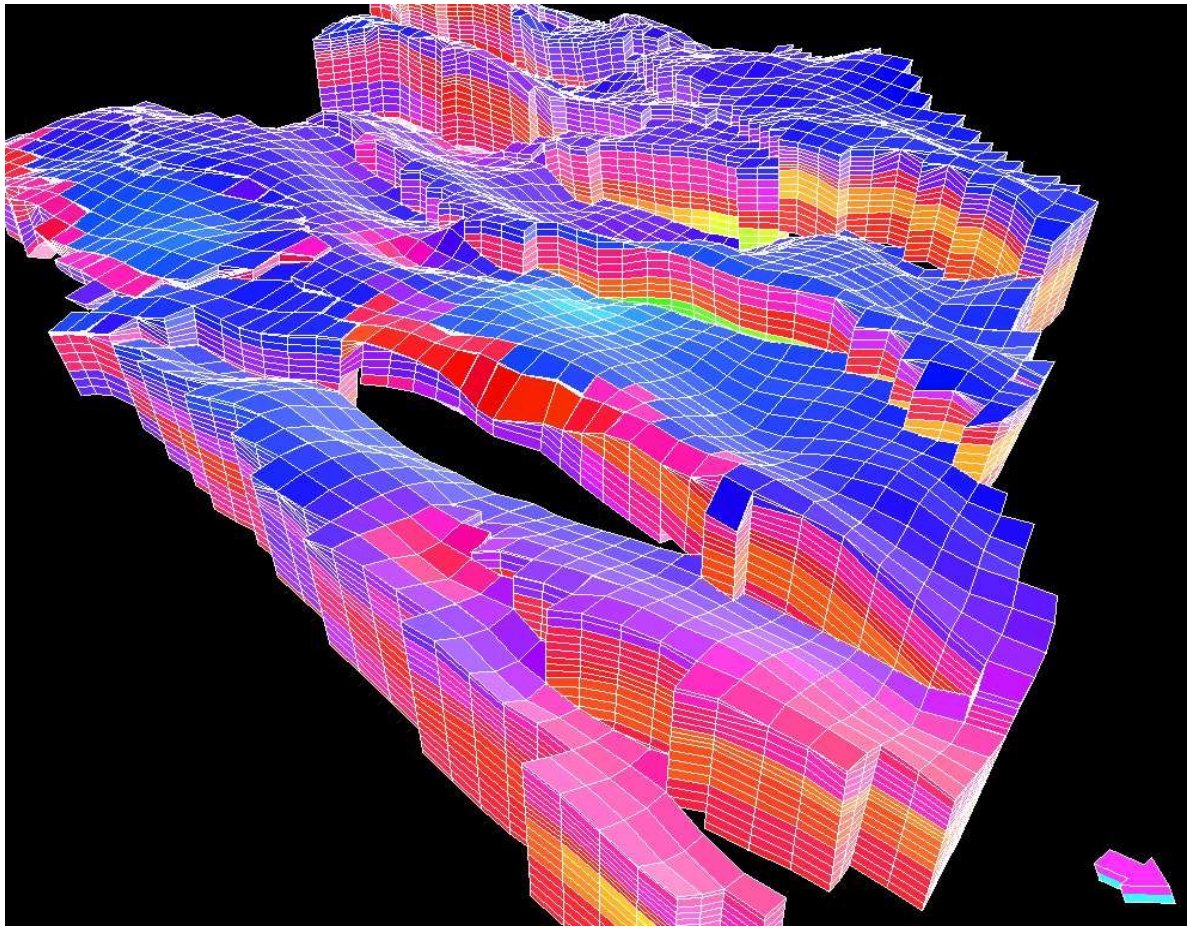
Broad topology categories:

- Structured/Cartesian
- Block-structured
- Unstructured/tetrahedral
- Fully unstructured

Reservoir grids are ”bad”

- Fully unstructured (arbitrary connectivity)
- Bad cell shapes
- Huge anisotropy ratios
- Very hetereogenous properties





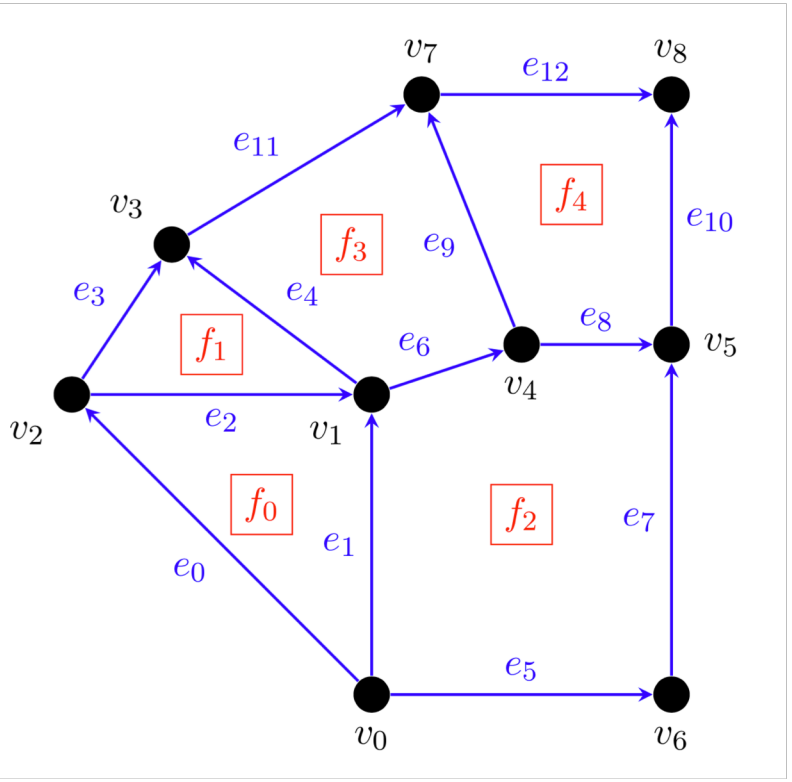
Important grid concepts

Topology:

- Cells, Faces, Edges, Vertices
  - *Entities* that make up the grid, *dimension* 3, 2, 1, 0.
  - Form a *cell complex:* (n-1)-dim entities are intersections of n-dim entities
  - Every entity is *oriented* (not always used)
- Adjacency relations
  - Which entities (of different dimension) are adjacent
  - Example: for face f_0, its neighbour edges are { $-e_0$, e_1, $-e_2$ }

Geometry:

- Positions, volumes, areas, normals, centroids…
  - Anything depending on the embedding in R^3



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Some grid interfaces I have used (1)

1. Interface used in our first upscaling codes (2006-2007)
   - A single class representing a fully unstructured grid
   - No templates
   - Grid assumed to be unchanging after construction
   - Example methods:

```
void getCellsForFace(Index f, Index& c1, Index& c2)
bool halfFaceIsFace(Index half_face_ix, Index face_ix) const
void halfFacesOfFace(Index face_ix, Index& hface1_ix, Index& hface2_ix) const
void coord(Index corner, FloatType* p) const
```

   - Main benefits: straightforward, random access.

Some grid interfaces I have used (2)

2. Interface used in our inhouse simulation codes (2007-2010)
   - Several grid class variants: Cartesian, Cornerpoint, Tetrahedral
   - Heavily templated! Very exotic to some.
   - Grid assumed to be unchanging after construction
   - Example code (adjacency relation: cells adjacent to a face):

```
typename grid_t::range_t cells_of_face
  = grid.template neighbours<FaceType, CellType>(face_index);
for (int cell_index : cells_of_face) {
  // Do something with cell_index
}
```

   - Main benefits: arbitrary topological relations, random access

Some grid interfaces I have used (3)

3. The Dune grid interface (2009-today)
   - Many grid class variants. CpGrid provides corner-point grids
   - Heavily templated!
   - Limited adjacency relations (but has cell->face and face->cell)

```
elemIt = gridView.template begin</*codim=*/ 0>();
for (; elemIt != elemEndIt; ++elemIt) {
  auto isIt = gridView.ibegin(*elemIt);
  const auto& isEndIt = gridView.iend(*elemIt);
  for (; isIt != isEndIt; ++isIt) {
    if (isIt->boundary()) {
      // deal with grid boundaries
    }
  }
}
```

   - Main benefits: suitable for parallel and adaptive use, open source and not inhouse

Some grid interfaces I have used (4)

4. The UnstructuredGrid struct (2009-2015[ish])

- A simple C struct, similar to grid structure in MRST
- Access topological and geometric information as simple arrays
- CRS-like structure for unstructured adjacency relations

```
for (int i = grid.cell_facepos[cell]; i < grid.cell_facepos[cell+1]; ++i) {
  int f = grid.cell_faces[i];
  if (cell == grid.face_cells[2*f]) {
    flux = darcyflux[f];
  } else {
    flux = -darcyflux[f];
  }
}
```

- Main benefits: easy to integrate with MRST, simple (although some conventions used might surprise you)

Some grid interfaces I have used (5)

5. The free function grid interface in OPM (2014-today)

- All based on free functions taking a grid as one function argument
- Overloaded on grid class to support CpGrid and UnstructuredGrid

```
auto c2f = cell2Faces(grid);
for(auto it = c2f.begin(), end = c2f.end(); it != end; ++it) {
  const int face_index = *it;
  const double area = faceArea(grid, face_index);
}
```

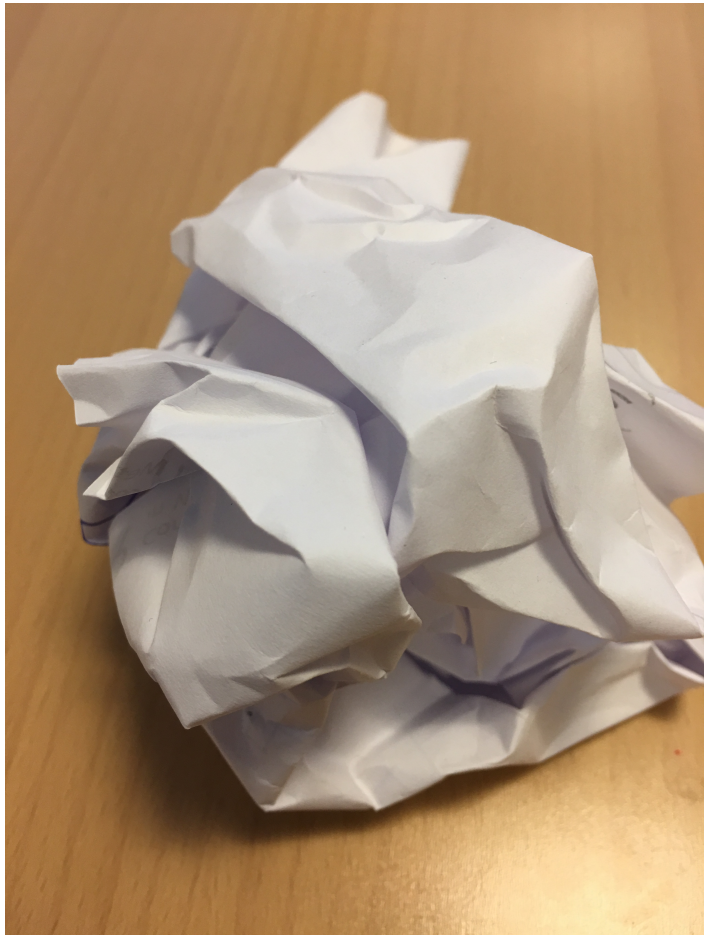
- Main benefits: allowed code to target both UnstructuredGrid and CpGrid (dune interface)

Even more grid interfaces I have used…

6. A grid used in an old corner-point GRDECL preprocessor (2006-2009)
7. A grid used in a colleague's old C++ code (2005-2009)
8. A grid interface used to wrap both our in-house (2) and Dune (3) grids, still used in the steady-state upscaling codes (2009-today)
9. An interface designed to both deal with Dune (3) and UnstructuredGrid(4), similar to (5), but abandoned since (5) was better for the parallel case.

What have I learned?

- Grid interfaces are too much fun to write
- I'll never find one that satisfies me 100%
  - I'd love to have one based on algebraic topology notation
- Do not generalize/abstract/wrap code until you are certain it is necessary
- Use the Dune interface, unless you really need something it does not provide
  - Random access, please…



How do we write our space discretizations?

Flow: FV order 1, upwind weighting

Requires:

- Connectivity graph
- Transmissibilities on graph edges (==faces)
- Cell depths and volumes

Ideal grid interface: only the above

High flexibility:

- Manipulate transmissibilities (faults)
- Manipulate connectivity graph (nnc, fake aquifers)
- Agnostic to actual grid type (CP, PEBI etc.)

Upscaling: mimetic method

Requires:

- Grid that is a cell-complex
- Face areas and centroids
- Cell volumes and centroids

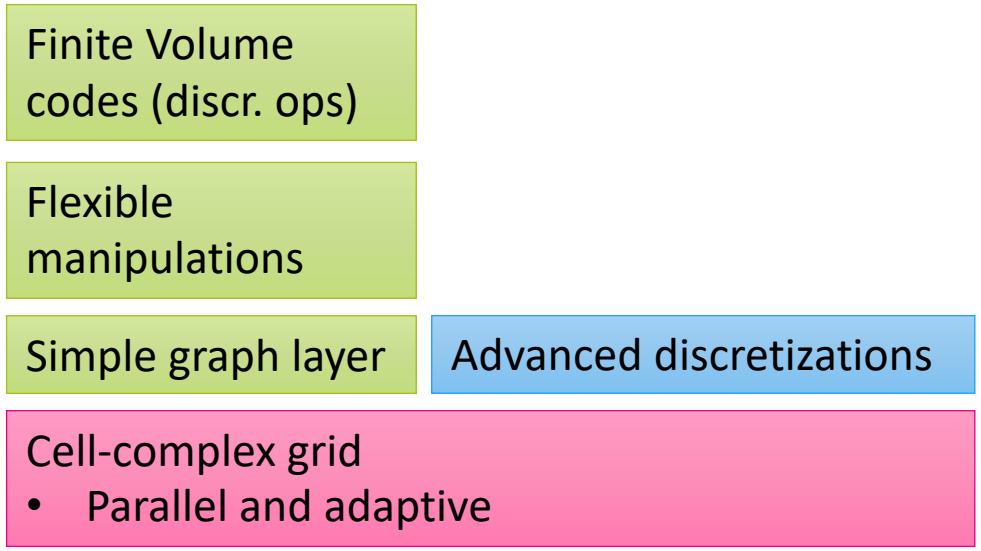
Ideal grid interface: a cell-complex interface

Can support other discretizations:

- Higher-order methods
- Streamline methods
- Virtual Element methods (and some FE)

How can we eat our cake and have it too? (1)

Sketch of an idea:



Some problems with this:

- Manipulations restrict adaptivity or vice versa
- Simple graph layer must also be parallel, partitioning must be done taking manipulations into account

How can we eat our cake and have it too? (2)

Another idea:

Finite Volume codes (discr. ops)

Advanced discretizations

Cell-complex grid
- Parallel and adaptive
- Additionally allows *fake neighbours*

Issues with this idea:
- Manipulations still restrict adaptivity or vice versa

Making Flow perform well

What is the main bottleneck?

A. Assembly of nonlinear equations?
B. Solving linear systems?
C. Input/output?
D. Other things?

Answer changes over time!

For OPM Flow and our target problems, always A or B.

(I/O performance has also been improved 3x)

Image from Joel McKelvey

Bottleneck 1

Linear solver horrendously slow

- UMFPACK, direct solver
- Works for very small systems (SPE1)
- Breaks down for a few thousand cells

Root cause: linear system not well suited for direct solver

Root cause: direct solvers do not scale well

	Pressure	Water sat	Gas mix/s	Well flux	Well bhp
Conserve W	W_p	W_{sw}	W_x	W_q	W_{bhp}
Conserve O	O_p	O_{sw}	O_x	O_q	O_{bhp}
Conserve G	G_p	G_{sw}	G_x	G_q	G_{bhp}
Well flow	Q_p	Q_{sw}	Q_x	Q_q	Q_{bhp}
Well control				C_q	C_{bhp}

Bottleneck 1 – addressed

Use Schur complement to eliminate well unknowns

Use iterative solvers from Dune

Use 2-stage CPR preconditioner

- Solve almost-elliptic system for pressure (with AMG precond.)
- Solve full system with ILU0 precond.

Results:

- SPE9 runtime 3 minutes (was 30 min)
- Norne case ~6 times Eclipse runtime

	Pressure	Water sat	Gas mix/s	Well flux	Well bhp
Conserve W	W_p	W_{sw}	W_x	W_q	W_{bhp}
Conserve O	O_p	O_{sw}	O_x	O_q	O_{bhp}
Conserve G	G_p	G_{sw}	G_x	G_q	G_{bhp}
Well flow	Q_p	Q_{sw}	Q_x	Q_q	Q_{bhp}
Well control				C_q	C_{bhp}

Figure: Schur complement eliminates well unknowns

Bottleneck 2

Assembly of nonlinear equations slow

- Functions implement residual equations
- AD class produces Jacobians

Root cause: simple operations too expensive

- Every +-*/ op triggers sparse matrix creation
- Even when matrix is diagonal or identity!

```
flux[phase] = upwind.select(b * mob) * (transi * dh);
```

Every multiplication, assignment and select() trigger sparse matrix creation.

Bottleneck 2 – addressed

Replace SparseMatrix in AD class with smart wrapper

- Wrapper treats zero, identity and diagonal matrices with custom code
- No change at all to the simulation code!

Result:

- Norne case ~3.5 times Eclipse runtime

```
flux[phase] = upwind.select(b * mob) * (transi * dh);
```

Now only select() trigger sparse matrix creation (since result depends on unknowns in multiple cells)

Bottleneck 3

Linear solver dominates runtime (again)

- Time-consuming setup of matrices for preconditioner and solver
- Outer linear solve of full system is slow

	Pressure	Water sat	Gas mix/s	Well flux	Well bhp
Conserve W	W_p	W_{sw}	W_x	W_q	W_{bhp}
Conserve O	O_p	O_{sw}	O_x	O_q	O_{bhp}
Conserve G	G_p	G_{sw}	G_x	G_q	G_{bhp}
Well flow	Q_p	Q_{sw}	Q_x	Q_q	Q_{bhp}
Well control				C_q	C_{bhp}

Bottleneck 3 – addressed

Change system matrix structure

- Use block-ILU0 instead of CPR
- Before: 3x3 system of NxN sparse matrices
- Now: NxN sparse matrix of 3x3 blocks
  (or 4x4 for polymer etc.)

Result:

- Norne case ~2.5 times Eclipse runtime

	Pressure	Water sat	Gas mix/s	Well flux	Well bhp
Conserve W	W_p	W_{sw}	W_x	W_q	W_{bhp}
Conserve O	O_p	O_{sw}	O_x	O_q	O_{bhp}
Conserve G	G_p	G_{sw}	G_x	G_q	G_{bhp}
Well flow	Q_p	Q_{sw}	Q_x	Q_q	Q_{bhp}
Well control				C_q	C_{bhp}

Bottleneck 4

Assembly of residual and Jacobians dominate (again)

Root cause: cache-unfriendly use of AD class

Root cause: (still) too many sparse matrix ops

```
flux[phase] = upwind.select(b * mob) * (transi * dh);
```

The multiplication ”`b * mob`” requires writing the result vector to memory before doing the next operation

Bottleneck 4 – addressed

Completely change assembly approach to use local AD

- Meaning: only handle fixed number of local derivatives for each variable
- Much better cache performance
- Matrix assembly is separate
- Clever trick to get derivatives for fluxes (that depend on two cells)
- Was gradually prototyped by A. Lauser for 2-3 years before switching

Results:

- Norne case ~1.7 times Eclipse runtime (~1.1 or better by now)

Consequences:

- Assembly no longer resembles MRST
- More complex code structure to understand for programmers

How to find the next bottleneck?

- Common sense and intuition? Often fails…
- Linuxbenchmarking.com
- Profiling:

Weight		Self Weight	Symbol Name
14.97 min	100.0%	5.00 ms	▼Opm::SimulatorReport Opm::BlackoilModelEbos<Ewoms::Properties::TTag::EclFlowProblem>::nonlinearIteration<Opm::NonlinearSolverEbos<Ewom
7.43 min	49.6%	4.00 ms	▶Opm::BlackoilModelEbos<Ewoms::Properties::TTag::EclFlowProblem>::assemble(Opm::SimulatorTimerInterface const&, int) flow
7.32 min	48.8%	1.00 ms	▶Opm::BlackoilModelEbos<Ewoms::Properties::TTag::EclFlowProblem>::solveJacobianSystem(Dune::BlockVector<Dune::FieldVector<double, 3>, s
9.43 s	1.0%	0 s	▶Opm::BlackoilModelEbos<Ewoms::Properties::TTag::EclFlowProblem>::getConvergence(Opm::SimulatorTimerInterface const&, int, std::__1::vectc
3.20 s	0.3%	0 s	▶Ewoms::BlackOilNewtonMethod<Ewoms::Properties::TTag::EclFlowProblem>::update_(Dune::BlockVector<Ewoms::BlackOilPrimaryVariables<Ewo
747.00 ms	0.0%	3.00 ms	▶void Opm::NonlinearSolverEbos<Ewoms::Properties::TTag::EclFlowProblem, Opm::BlackoilModelEbos<Ewoms::Properties::TTag::EclFlowProblem>
208.00 ms	0.0%	208.00 ms	_platform_bzero$VARIANT$Haswell libsystem_platform.dylib
65.00 ms	0.0%	3.00 ms	▶Opm::BlackoilWellModel<Ewoms::Properties::TTag::EclFlowGasOilProblem>::postSolve(Dune::BlockVector<Dune::FieldVector<double, 2>, std::__
8.00 ms	0.0%	2.00 ms	▶std::__1::chrono::steady_clock::now() libc++.1.dylib
5.00 ms	0.0%	0 s	▶free_large libsystem_malloc.dylib
4.00 ms	0.0%	0 s	▶operator new(unsigned long) libc++abi.dylib
3.00 ms	0.0%	1.00 ms	▶free libsystem_malloc.dylib
2.00 ms	0.0%	2.00 ms	Opm::WellCollection::groupControlActive() const flow
2.00 ms	0.0%	0 s	▶Opm::Logger::addMessage(long long, std::__1::basic_string<char, std::__1::char_traits<char>, std::__1::allocator<char> > const&) const flow
1.00 ms	0.0%	1.00 ms	DYLD-STUB$$MPI_Allreduce flow
1.00 ms	0.0%	1.00 ms	Opm::SimulatorReport::operator+=(Opm::SimulatorReport const&) flow
1.00 ms	0.0%	1.00 ms	Opm::UgGridHelpers::numCells(Dune::CpGrid const&) flow
1.00 ms	0.0%	0 s	▶free_tiny libsystem_malloc.dylib

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