Parallelization of Multisegment Wells: Enhancing simulation flexibility

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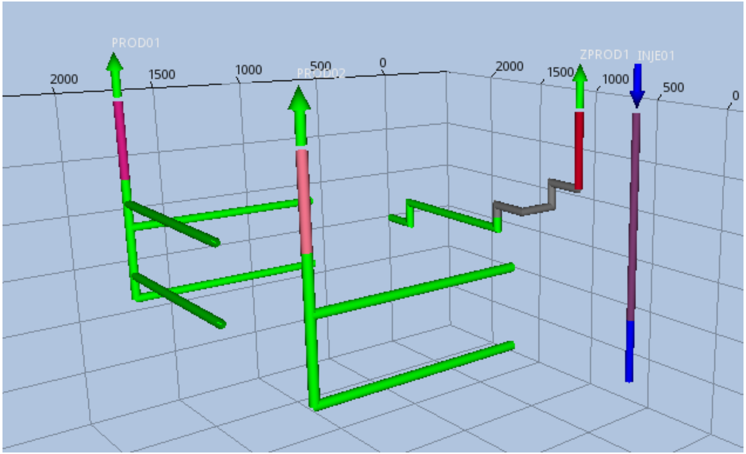
What are multisegment wells?



Simulation flexibility

- Partitions are critical for the performance!
- The new default partitioner handles well info better $\rightarrow$ performance improvement!
- Before: Partitions had to keep multisegment wells on one process.
- With distributed multisegment wells: Partitions can be independent of the wells.
- Enable with --allow-distributed-wells=true.
- Spoiler[1]: The well-independent version of the new default partitioner slightly outperforms the well-dependent one!

[1] for the cases I have tested

Steps to parallelize multisegment wells

A Linear system solved in each timestep in flow, Schur complement

B Equations and resulting part of the linear system for standard and multisegment wells

C Linear system for multisegment wells in parallel

D Performance results

E Outlook

A: Linear system

- reservoir + well equations define a large system of nonlinear equations

$$R(x) = \vec{0}$$

$$dim(x) = dim(R(x)) = \underbrace{\#\text{grid cells} \cdot \#\text{primary variables}^{1}}_{\#\text{reservoir unknowns}} + \underbrace{\#\text{wells} \cdot \#\text{unknowns per well}}_{\#\text{well unknowns}}$$

- solve $R(x) = \vec{0}$ using a Newton-Raphson type method, i.e., in each iteration: calculate Jacobian $J(\cdot) \in \mathbb{R}^{dim(x) \times dim(x)}$ of R and solve

$$J(x_n)(x_{n+1} - x_n) = -R(x_n)$$

[1] one primary variable for each phase, so 3 primary variables for a three-phase black oil system

A: Linear system

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$$J(x_n)x_{n+1} = J(x_n)x_n - R(x_n)$$

A: Linear system

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$$J(x_n)x_{n+1} = r_n$$

A: Linear system

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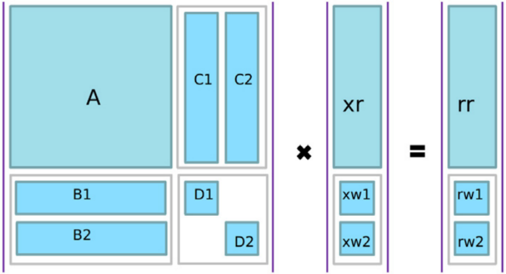
- solve $R(x) = \vec{0}$ using a Newton-Raphson type method, i.e., in each iteration: calculate Jacobian $J(\cdot) \in \mathbb{R}^{dim(x) \times dim(x)}$ of R and solve

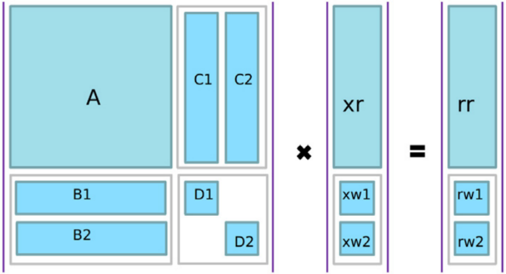
$$\begin{pmatrix} A & C \\ B & D \end{pmatrix} \begin{pmatrix} x_{reservoir} \\ x_{wells} \end{pmatrix} = \begin{pmatrix} r_{reservoir} \\ r_{wells} \end{pmatrix}$$

A: Linear system



- A: Jacobian of reservoir equations w.r.t. reservoir unknowns
- B_j, C_j, D_j for each well, $j = 1, \ldots, \#$wells
- B_j: Jacobian of equations for well j w.r.t. reservoir unknowns
- C_j: Jacobian of reservoir equations w.r.t. unknowns of well j
- D_j: Jacobian of equations for well j w.r.t. unknowns of well j

A: Linear system



- Do not solve the whole system

$$\begin{pmatrix} A & C_1 & C_2 & \dots \\ B_1 & D_1 & & \\ B_2 & & D_2 & \\ \vdots & & & \ddots \end{pmatrix} \cdot \begin{pmatrix} x_r \\ x_{w_1} \\ x_{w_2} \\ \vdots \end{pmatrix} = \begin{pmatrix} r_r \\ r_{w_1} \\ r_{w_2} \\ \vdots \end{pmatrix}$$

as one, instead:

- For x_r solve

$$\left(A - \sum_{j=1}^{\#wells} C_j D_j^{-1} B_j \right) x_r = r_r - \sum_{j=1}^{\#wells} C_j D_j^{-1} r_{w_j}.$$

- For each x_{w_j}, solve the small system

$$x_{w_j} = D_j^{-1} \left(r_{w_j} - B_j x_r \right).$$

Steps to parallelize multisegment wells

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B: Well equations for a standard well

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- one conservation equation per phase α:

$$\underbrace{\frac{A_\alpha - A_\alpha^0}{\triangle t}}_{A_\alpha \text{ = amount of phase } \alpha \text{ in the wellbore}} + \underbrace{Q_\alpha}_{\text{flow rate of phase } \alpha} - \overset{\text{connections of the well}}{\sum_{i=1}} \underbrace{q_{\alpha,i}}_{\text{flow rate of phase } \alpha \text{ through connection } i} = 0$$

- for a three-phase black oil system: $\alpha \in \{\text{water, oil, gas}\} = \{\text{w, o, g}\}$
- one control equation, e.g. for a prescribed bottom hole pressure:

$$p_{bhp} - p_{bhp}^{target} = 0$$

- unknowns for each well for a three-phase black oil system:

$$\underbrace{Q_t}_{\text{weighted total flow rate}}, \quad \underbrace{F_w, F_g}_{\text{weighted fractions of water and gas}} \quad \text{and} \quad p_{bhp}$$

B: Well equations for a standard well

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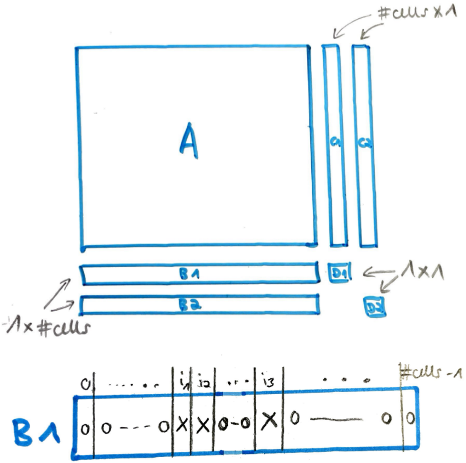
- unknowns for each well for a three-phase black oil system:

$$\underbrace{Q_t(Q_w, Q_o, Q_g)}_{\text{weighted total flow rate}},\ \underbrace{F_w(Q_t, Q_w), F_g(Q_t, Q_g)}_{\text{weighted fractions of water and gas}} \quad \text{and} \quad p_{bhp}$$

$\rightarrow$ four equations and four unknowns per standard well

B: Linear system for standard wells for 3 phases



- A is a $\#cells \times \#cells$ BCRS-matrix[1], inner matrices are 3×3
- B_j is a $1 \times \#cells$ BCRS-matrix, inner matrices are 4×3
- C_j is a $\#cells \times 1$ BCRS-matrix, inner matrices are 3×4
- B_j and C_j only contain entries for the cells that are perforated by the well j
- B_j and C_j^T have same sparsity pattern
- D_j is a 1×1 BCRS-matrix, inner matrix is 4×4

[1]BCRS = Blocked Compressed Row Storage
collection of small dense inner matrices

B: Well equations for a standard → multisegment well

- one conservation equation per phase α (water, oil, gas) :

$$\underbrace{\frac{A_\alpha - A_\alpha^0}{\triangle t}}_{\substack{A_\alpha \text{ = amount of phase } \alpha \\ \text{in the wellbore}}} + \underbrace{Q_\alpha}_{\text{flow rate of phase } \alpha} - \sum_{i=1}^{\text{connections}} \underbrace{q_{\alpha,i}}_{\substack{\text{flow rate of phase } \alpha \\ \text{through connection } i}} = 0$$

- one control equation for the top segment, e.g. for a prescribed bottom hole pressure:

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- unknowns for each standard well for a three-phase black oil system:

$$Q_t(Q_w, Q_o, Q_g), F_w(Q_t, Q_g), F_g(Q_t, Q_g) \quad \text{and} \quad p_{bhp}$$

→ four equations and four unknowns per standard well

B: Well equations for a multisegment well

- one conservation equation per phase α (water, oil, gas) and per segment n:

$$\underbrace{\frac{A_{\alpha,\mathbf{n}} - A^{0}_{\alpha,\mathbf{n}}}{\triangle t}}_{A_\alpha \text{ = amount of phase } \alpha \text{ in the segment n}} + \underbrace{Q_{\alpha,\mathbf{n}}}_{\text{flow rate of phase } \alpha \text{ in segment n}} - \sum_{i=1}^{\text{connections of segment n}} \underbrace{q_{\alpha,i}}_{\text{flow rate of phase } \alpha \text{ through connection } i} - \sum_{i=1}^{\text{inlets of segment n}} \underbrace{Q_{\alpha,i}}_{\text{flow rate of phase } \alpha \text{ in segment i}} = 0$$

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- one control equation for the top segment, e.g. for a prescribed bottom hole pressure:

$$p_{bhp} - p_{bhp}^{target} = 0$$

- one equation for all other segments with the pressure relationship to the outlet segment:

$$p_n - p_{\text{outlet of n}} - (\text{pressure drop between segment n and its outlet}) = 0$$

- unknowns for each standard well for a three-phase black oil system:

$$Q_t(Q_w, Q_o, Q_g), F_w(Q_t, Q_g), F_g(Q_t, Q_g) \quad \text{and} \quad p_{bhp}$$

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- unknowns for each multisegment well for a three-phase black oil system:

$$Q_{t,n}(Q_{w,n}, Q_{o,n}, Q_{g,n}), F_{w,n}(Q_{t,n}, Q_{g,n}), F_{g,n}(Q_{t,n}, Q_{g,n}) \quad \text{and} \quad p_{bhp}, \; p_n(n \neq \text{ top segment})$$

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B: Well equations for a multisegment well

- one conservation equation per phase α (water, oil, gas) and per segment n:

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- one control equation for the top segment, e.g. for a prescribed bottom hole pressure:

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- one equation for all other segments with the pressure relationship to the outlet segment:

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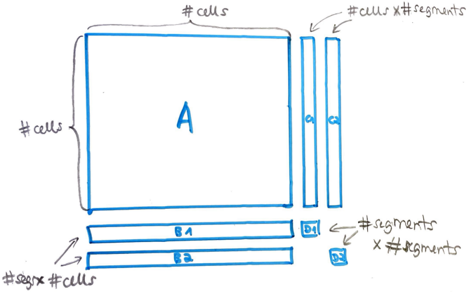
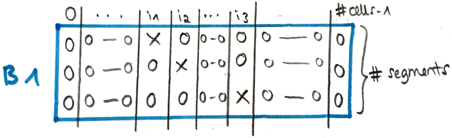
- unknowns for each multisegment well for a three-phase black oil system:

$$Q_{t,n}(Q_{w,n}, Q_{o,n}, Q_{g,n}), F_{w,n}(Q_{t,n}, Q_{g,n}), F_{g,n}(Q_{t,n}, Q_{g,n}) \quad \text{and} \quad p_{bhp}, \; p_n(n \neq \text{ top segment})$$

$\rightarrow$ four equations and four unknowns per segment of a multisegment well

B: Linear system for multisegment wells for 3 phases





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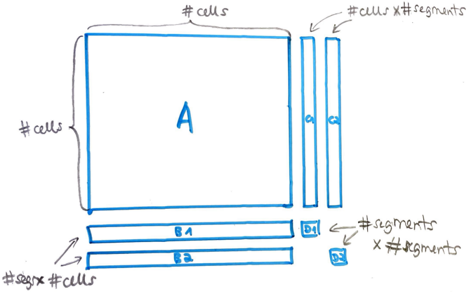
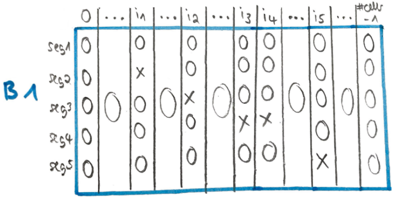
- C_j is a $\#cells \times \#segments$ BCRS-matrix, inner matrices are 3×4
- B_j and C_j contain entries for the cells that are perforated by the well j
- B_j and C_j^T have the same sparsity pattern
- standard wells: one row, all entries are in that one row
- multisegment wells: $\#$segments rows, each row has as many entries as the segment has perforations

B: Linear system for multisegment wells for 3 phases





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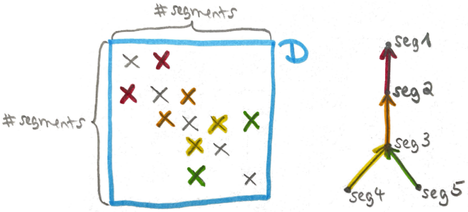

- D_j is a $\#segments \times \#segments$ BCRS-matrix, inner matrices are 4×4
- D_j contains entries on the diagonal and for all connections of the multisegment well
- D_j is generally **not** symmetric, only the sparsity pattern is symmetric

Steps to parallelize multisegment wells

A Linear system solved in each timestep in flow, Schur complement

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C: Linear system for multisegment wells in parallel

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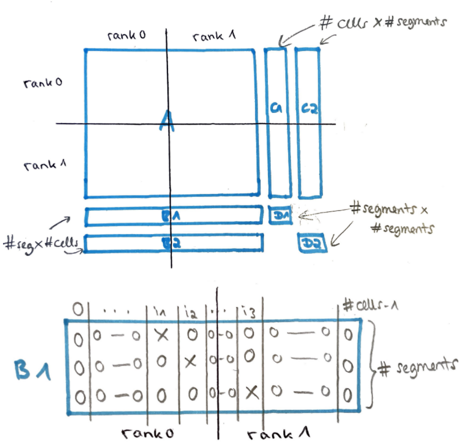
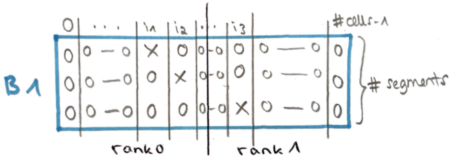
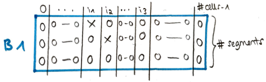
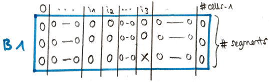


- Each process knows only its own parts of B_j and C_j, no overlap!
- D_j, x_{w_j}, and r_{w_j} are shared by all processes linked to the same well.
- Assembling B_j, C_j, D_j, and r_{w_j} requires **communication**, since entries depend on **all** perforations (e.g., pressure differences, averages, maxima, ...).
- One communicator per well!

C: Linear system for multisegment wells in parallel



rank 0: 

rank 1: 

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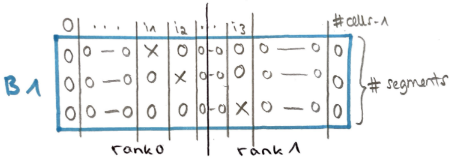
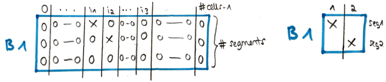
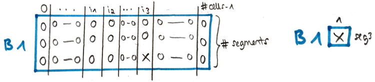


rank 0: 

rank 1: 

- Each process knows only its own parts of B_j and C_j, no overlap!
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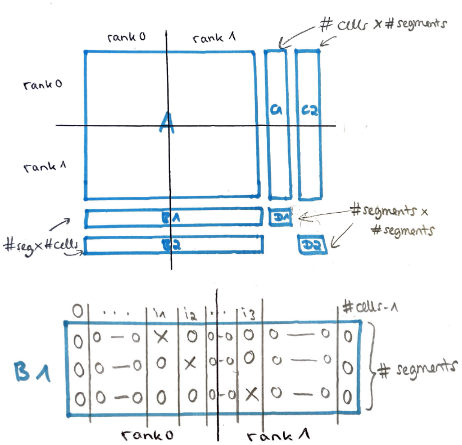
C: Linear system for multisegment wells in parallel



Recall the Schur complement approach:

- For each x_{w_j}, solve the small system

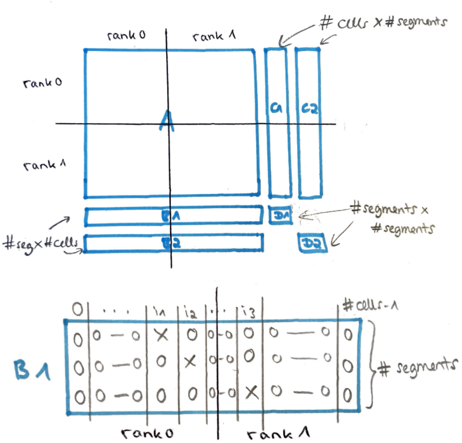
$$x_{w_j} = D_j^{-1} \left(r_{w_j} - B_j x_r \right) .$$

- For x_r, iteratively solve

$$\left(A - \sum_{j=1}^{\#\text{wells}} C_j D_j^{-1} B_j \right) x_r =$$

$$r_r - C_j D_j^{-1} r_{w_j} .$$

C: Linear system for multisegment wells in parallel



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- For each x_{w_j}, solve the small system

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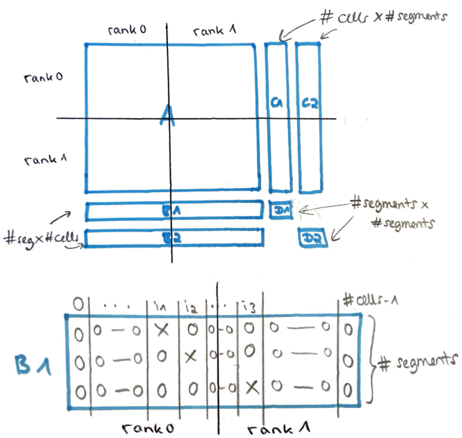
- For x_r, iteratively solve

$$A \cdot x_r - \sum_{j=1}^{\#\text{wells}} C_j D_j^{-1} B_j \cdot x_r = r_r - C_j D_j^{-1} r_{w_j} .$$

C: Linear system for multisegment wells in parallel



Recall the Schur complement approach:

- For each x_{w_j}, solve the small system

$$x_{w_j} = D_j^{-1}\left(r_{w_j} - \sum_{k=1}^{\substack{\text{all ranks}\\ \text{of well } j}} (B_j)_{|k} (x_r)_{|k} \right).$$

- For x_r, iteratively solve

$$A_{|k} \cdot (x_r)_{|k} - \sum_{j=1}^{\#\text{wells}} (C_j)_{|k}\, D_j^{-1} \left(\sum_{k=1}^{\substack{\text{all ranks}\\ \text{of well } j}} (B_j)_{|k} (x_r)_{|k} \right) =$$

$$(r_r)_{|k} - \sum_{j=1}^{\#\text{wells}} (C_j)_{|k} D_j^{-1} r_{w_j}.$$

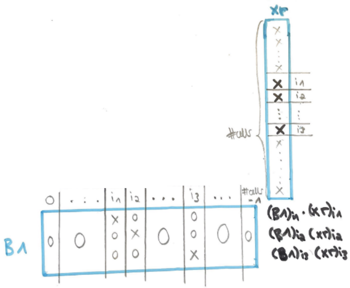
C: Linear system for multisegment wells in parallel

$$x_{w_j} = D_j^{-1}\left(r_{w_j} - \sum_{k=1}^{\substack{\text{all ranks}\\ \text{of well } j}} (B_j)_{|k}(x_r)_{|k}\right) \quad \Bigg| \quad A_{|k}\cdot(x_r)_{|k} - \sum_{j=1}^{\#wells}(C_j)_{|k}\, D_j^{-1}\left(\sum_{k=1}^{\substack{\text{all ranks}\\ \text{of well } j}}(B_j)_{|k}(x_r)_{|k}\right) = (r_r)_{|k} - \sum_{j=1}^{\#wells}(C_j)_{|k}\, D_j^{-1} r_{w_j}$$

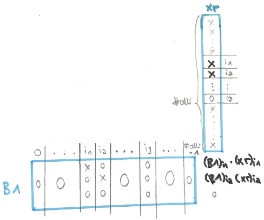
Where is communication needed when multiplying with B, D^{-1}, C?

C: Multiplying with B

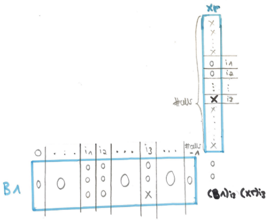
$$x_{w_j} = D_j^{-1}\left(r_{w_j} - \sum_{k=1}^{\text{all ranks of well } j} (B_j)_{|k}(x_r)_{|k}\right) \quad \Big| \quad A_{|k}\cdot(x_r)_{|k} - \sum_{j=1}^{\#\text{wells}}(C_j)_{|k}\, D_j^{-1}\left(\sum_{k=1}^{\text{all ranks of well } j}(B_j)_{|k}(x_r)_{|k}\right) = (r_r)_{|k} - \sum_{j=1}^{\#\text{wells}}(C_j)_{|k}\, D_j^{-1} r_{w_j}$$



rank 0:



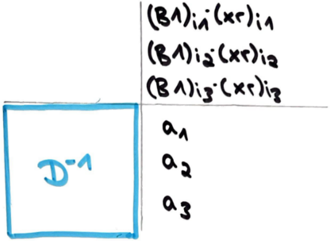
rank 1:



$\rightarrow$ Communicate to get the full vector $B \cdot x_r$ on all ranks perforated by that well!

C: Multiplying with D^{-1}

$$x_{w_j} = D_j^{-1}\left(r_{w_j} - \sum_{k=1}^{\text{all ranks of well } j} (B_j)_{|k}(x_r)_{|k} \right) \quad \Big| \quad A_{|k} \cdot (x_r)_{|k} - \sum_{j=1}^{\#\text{wells}} (C_j)_{|k}\, D_j^{-1} \left(\sum_{k=1}^{\text{all ranks of well } j} (B_j)_{|k}(x_r)_{|k} \right) = (r_r)_{|k} - \sum_{j=1}^{\#\text{wells}} (C_j)_{|k}\, D_j^{-1} r_{w_j}$$

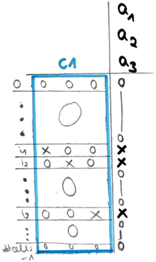


→ Calculate $D_j^{-1} \cdot (B \cdot x_r)$ and $D_j^{-1} \cdot r_{w_j}$ on each rank!

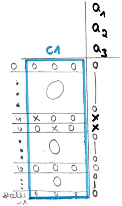
→ No communication needed, because D_j, $(B \cdot x_r)$ and r_{w_j} are the same across all ranks of well j!

C: Multiplying with C

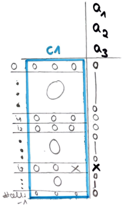
$$x_{w_j} = D_j^{-1}\left(r_{w_j} - \sum_{k=1}^{\substack{\text{all ranks}\\ \text{of well } j}} (B_j)_{|k}(x_r)_{|k} \right) \quad \Big| \quad A_{|k}\cdot(x_r)_{|k} - \sum_{j=1}^{\#\text{wells}} (C_j)_{|k}\, D_j^{-1}\left(\sum_{k=1}^{\substack{\text{all ranks}\\ \text{of well } j}} (B_j)_{|k}(x_r)_{|k} \right) = (r_r)_{|k} - \sum_{j=1}^{\#\text{wells}} (C_j)_{|k}\, D_j^{-1} r_{w_j}$$



rank 0:



rank 1:



$\rightarrow$ Multiplication with $(C_j)_{|k}$ will automatically reduce to rank k!

Steps to parallelize multisegment wells

A Linear system solved in each timestep in flow, Schur complement

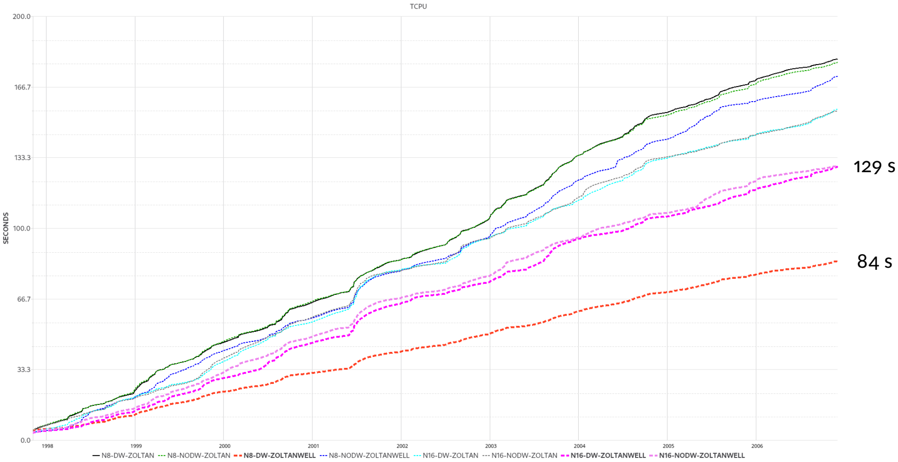
B Equations and resulting part of the linear system for standard and multisegment wells

C Linear system for multisegment wells in parallel

D Performance results

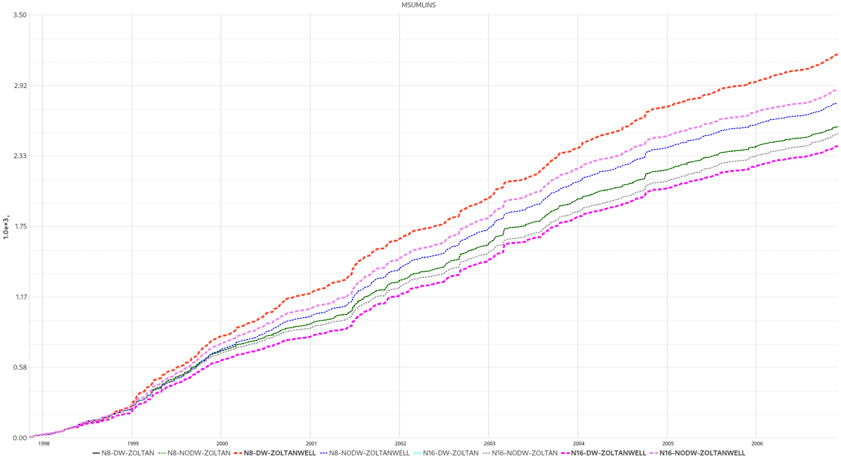
E Outlook

D: opm-tests/norne/NORNE_ATW2013.DATA



- **8**|**16 procs**, --**allow-distributed-wells**=true|false --**partition-method**=zoltan|zoltanwell --allow-splitting-inactive-wells=true
- Run on a machine with 32 cores, 64 threads, 4.55 GHz max frequency, 128 GB RAM.

D: opm-tests/norne/NORNE_ATW2013.DATA



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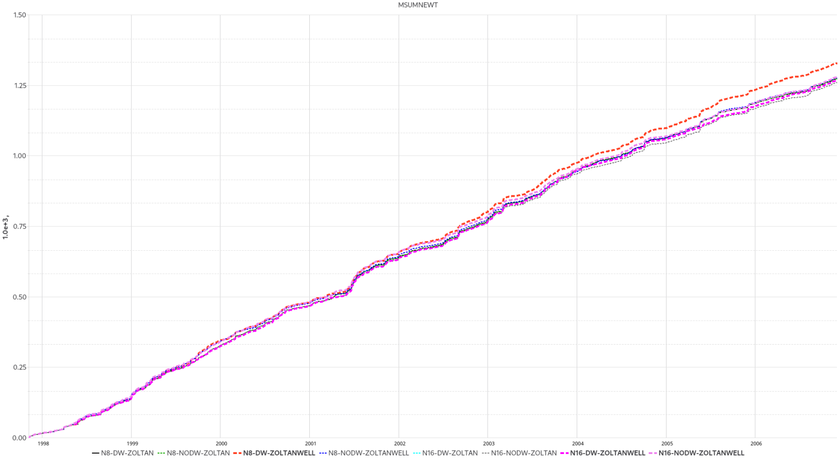
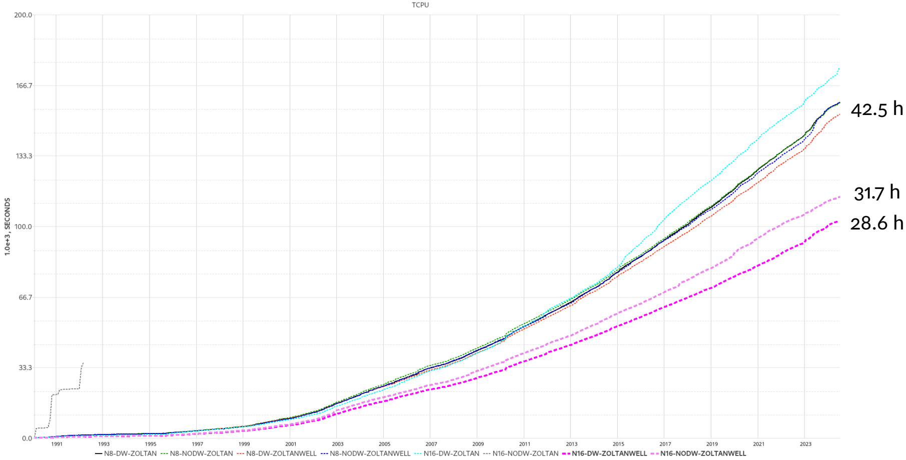
- Run on a machine with 32 cores, 64 threads, 4.55 GHz max frequency, 128 GB RAM.

D: opm-tests/norne/NORNE_ATW2013.DATA



- **8|16 procs**, --**allow-distributed-wells**=true|false --**partition-method**=zoltan|zoltanwell --allow-splitting-inactive-wells=true
- Run on a machine with 32 cores, 64 threads, 4.55 GHz max frequency, 128 GB RAM.

D: Case with ≈ 1.64 M active cells, 338 active wells



- **8**|**16 procs**, --**allow-distributed-wells**=true|false --**partition-method**=zoltan|zoltanwell --allow-splitting-inactive-wells=true
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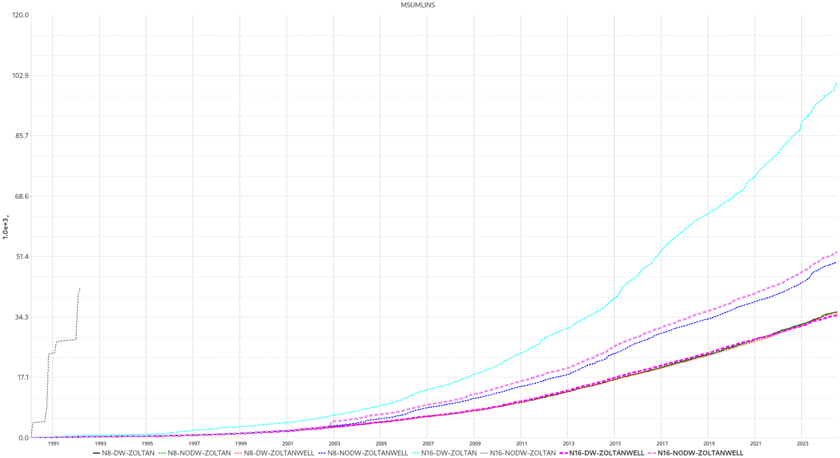

- **8**|**16 procs**, --**allow-distributed-wells**=true|false --**partition-method**=zoltan|zoltanwell --allow-splitting-inactive-wells=true
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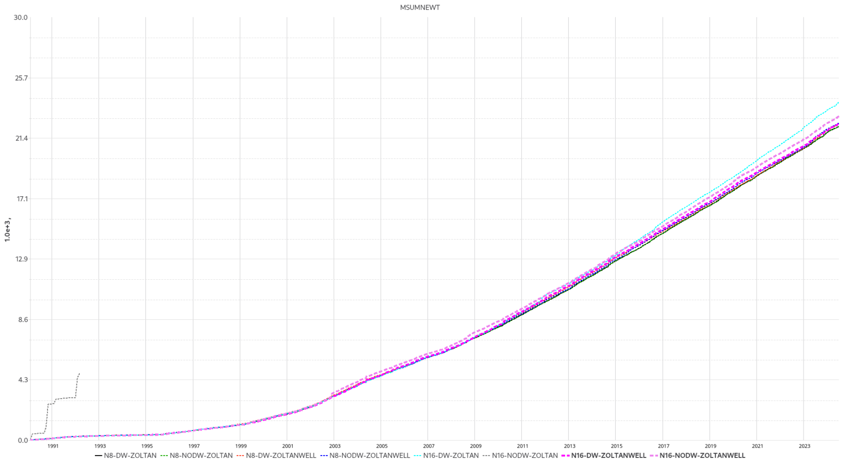

- **8|16 procs**, --**allow-distributed-wells**=true|false --**partition-method**=zoltan|zoltanwell --allow-splitting-inactive-wells=true
- Run on a machine with 32 cores, 64 threads, 4.55 GHz max frequency, 128 GB RAM.

E: Outlook

- Currently works for several test cases, but not for all ☹!
- More thorough verification of correctness needed!
- General problem with distriuted wells:

```
Load balancing distributed the wells as follows:
  well name            ranks with perforated cells
----------------------------------------------------
          PROD1        0        1
          PROD2        0        1        2
          PROD3        0        1        2
```

→ Careful with throws inside a loop over wells!

- Next steps: alternative solvers or preconditioners for the well equations?
- Many thanks to Markus Blatt, Michal Tóth, Vegard Kippe, Kai Bao and Halvor Møll Nilsen! ♡