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shaping tomorrow with you

Reservoir kernel code evaluation on A64FX

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Simone Rinco - Soham Sheth
Schlumberger

Fabrice Dupros
Arm ltd.

Takayuki Hoshiya
Fujitsu ltd.

Agenda

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- Reservoir simulation
  - Fundamental equations
  - Discretization
  - Evaluation model
  - kernel code structure
- Performance on A64FX
  - Tuning tips
- Take away/Future works

Reservoir Simulation

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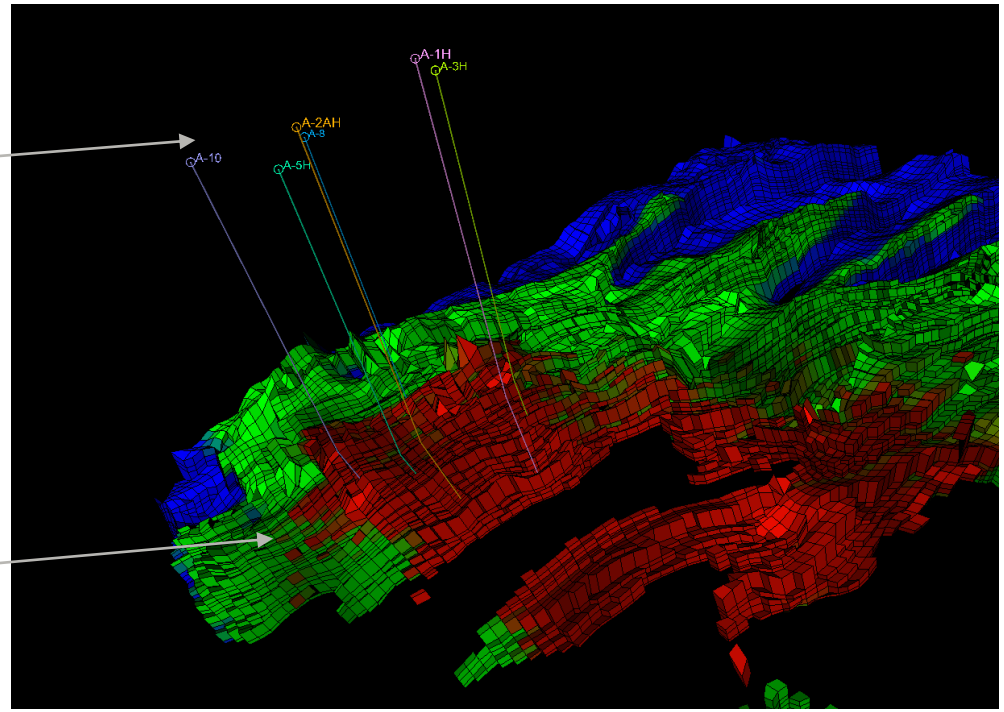
Wells
(producers/injectors)

Reservoir

Gas
Oil
Water



Petrel

Reservoir Simulation: predict the behaviour of the **reservoir** and the **wells** according to a specific strategy (well control).

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IX INTERSECT

Reservoir Simulation

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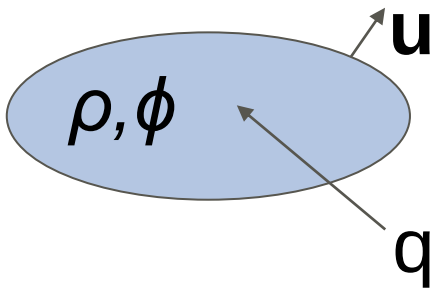
- Two fundamental equations
  - Conservation of mass:



Control volume is arbitrary

Fluid density

Rock porosity

Fluid speed

$$\frac{\partial}{\partial t}(\rho\phi) + div\,(\rho\mathbf{u}) = q \qquad \left[\frac{Kg}{m^3 s}\right]$$

Mass injected (wells)
Negative for producers

  - Darcy's law:

Rock permeability

$$\mathbf{u} = -\frac{\mathbf{K}}{\mu}(\nabla p - \rho g \nabla D) \qquad \left[\frac{m}{s}\right]$$

Fluid viscosity

Fluid pressure

Depth

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Reservoir Simulation

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- Combining the two equations:

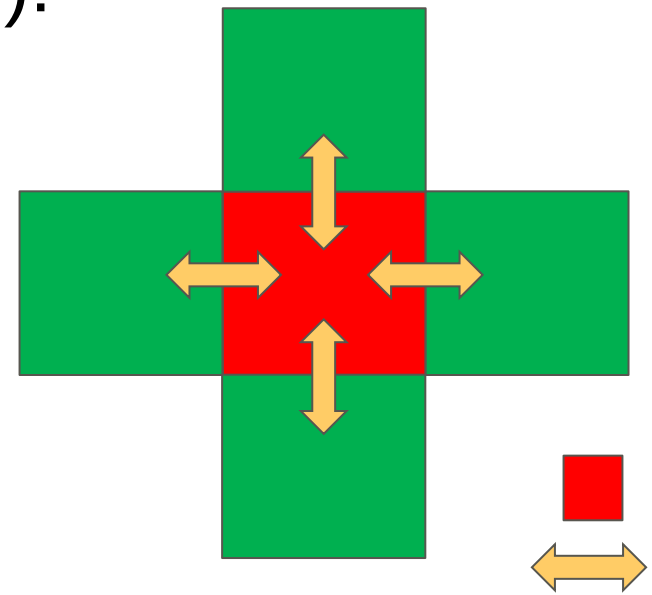
$$\underbrace{\frac{\partial}{\partial t}(\rho\phi)}_{\text{Mass accumulation}} - \underbrace{div\left(\rho\frac{\mathbf{K}}{\mu}(\nabla p - \rho g \nabla D)\right)}_{\text{Mass flux}} = \underbrace{q}_{\text{Well(s) contribution}}$$

One equation per component:
gas, oil, water (3 equations).
1 extra equation for thermal models

- Discretisation for the control volume (cell):
  - Mass accumulation:

    depends only on control volume
  - Mass flux:

    depends on control volume and neighbours
  - Wells: [ignored]



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Evaluation model

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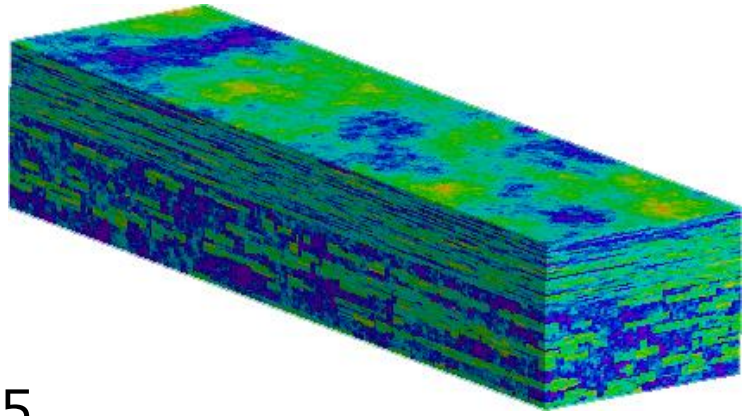
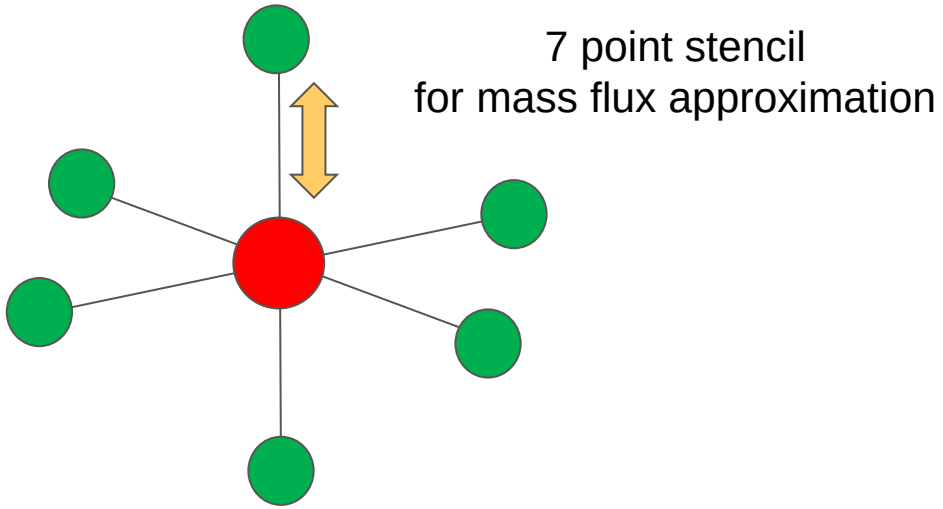
- SPE10 model 2
  https://www.spe.org/web/csp/datasets/set02.htm
- 60 x 220 x 85 cells
- Only the topology (connections) data is used
- Original model is oil-water (2 equations). The mock code assumes gas is present as well (3 equations)
- For each time step, mass accumulation and flux are calculated 5 times. This simulates an execution of 5 Newton iterations.





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kernel code structure (mass flux)

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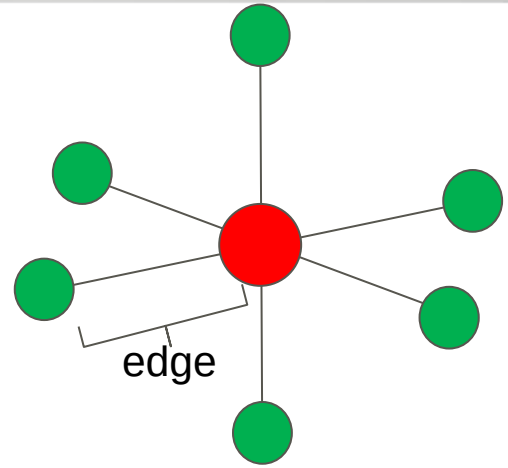
```
For each time step:
{
  For each Newton iteration (hardcoded 5 iterations):
  {
    For each edge (Parallelized by OpenMP):
    {
      - get source (src) and target (tgt) cell
      - get pressure in src and tgt cells and calculate pressure difference
      - get other properties in src and/or tgt cell
      For each equation (3 or 4):
      {
        calculate mass flux and update mass balance equation in
        src and tgt cell
      }
    }
  }
}
```



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Kernel loop performance (summary)

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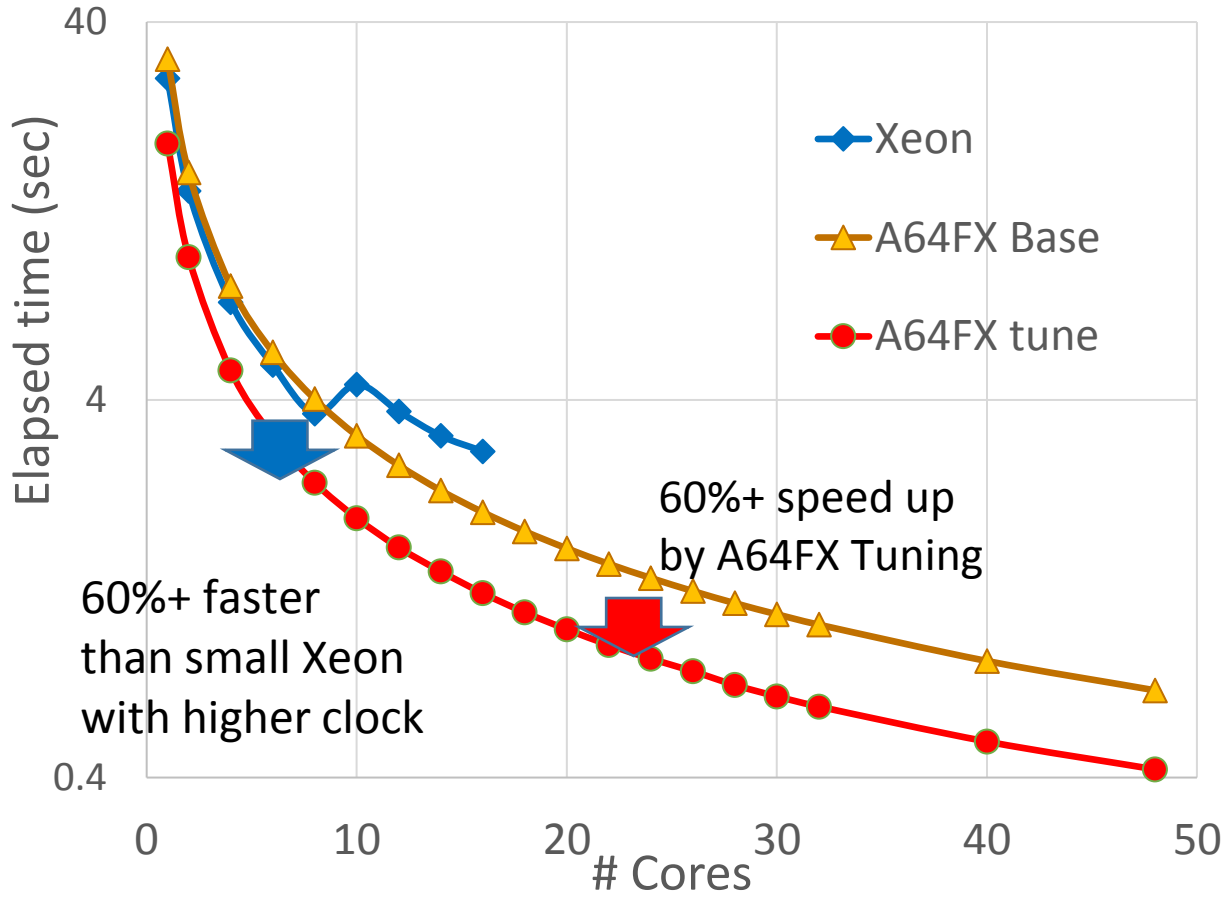
Conditions

- A64FX 1 node = 48cores (2.2GHz) 32GB(HBM2), Fujitsu compiler, OpenMP, numactl (interleave)
- Reference Xeon Cascade Lake 4cores/8threads x 2 sockets (3.8GHz), 128GB(DIMMx4), gcc 10.2, OpenMP, numactl(interleave)

Performance summary

- A64FX shows similar performance with 1-8cores Xeon even though A64FX has 60% lower clock rate. A64FX performance scales up to 48 cores
  - A64FX module used SVE for small iteration in inner loop(3).
  - Gcc generated SSE code (not AVX) for this small iteration.
- By tuning A64FX assembly code, A64FX speed up 60%+.
  (60% faster than small Xeon CPU even 60% lower clock)



Kernel loop performance (brief analysis)

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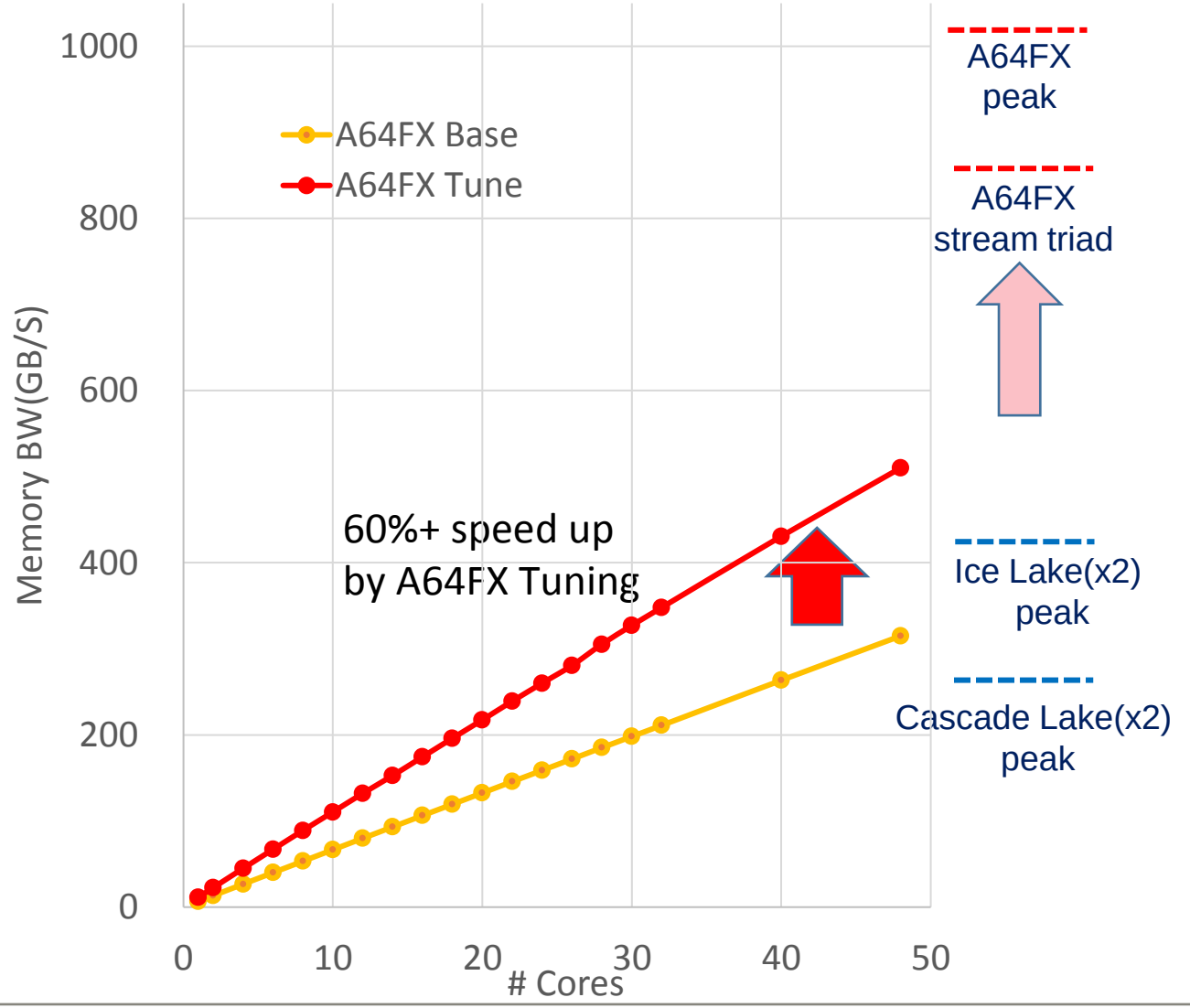
Memory Bandwidth

- A64FX performance scales up to 48 cores.
- A64FX base performance was 30% of peak performance(1024GB/s). Memory latency looks bottle neck for these lower efficiency
- By the tuning, we could derive more than 50% of peak performance.
- We might have room to improve this performance in the viewpoint of memory bandwidth.



Example of kernel loop vectorization

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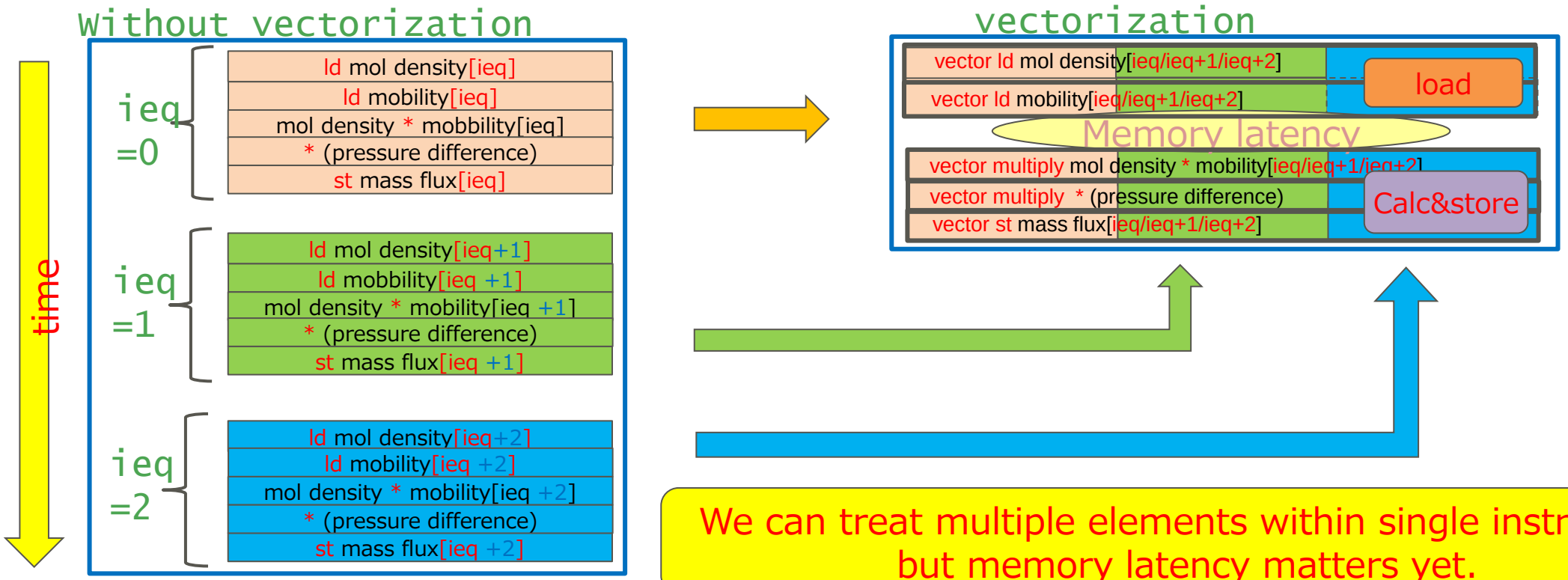
Vectorize inner loop

Predicate (mask) register in SVE enables vectorization
even 3 iterations within 512bit vector register

```
for each equation[ieq] (3 in this slide)
  mass flux[ieq] = mol density[ieq] * mobility[ieq]) * (pressure difference)
  (mass update follows)
```



We can treat multiple elements within single instruction
but memory latency matters yet.

Unrolling outer loop to hide memory latency

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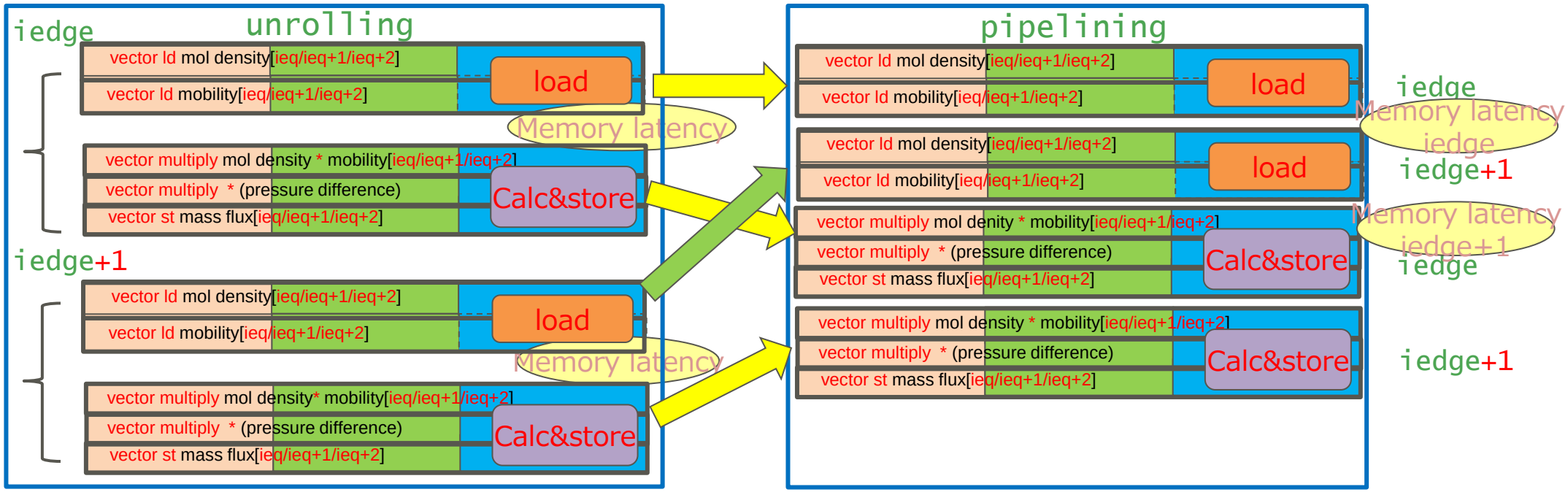
Loop unrolling is effective to hide memory latency in this kernel loop

```
for each edge [iedge] // unroll outer loop
  for each equation [ieq] // 3 iteration in this model // inner loop (vectrized)
     mass flux[ieq] = mol density[ieq] * mobility[ieq]) * (pressure difference)
  (mass update follows)
```

Memory latency could be hidden by moving load for iedge + 1



Take away/Future work

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- A64FX shows good performance with SVE(Scalable Vector Extension) and HBM(High Bandwidth Memory)
  on a reservoir kernel code.
- We needed hand assembly tuning to derive A64FX hardware potential as of now, because inner loop has small iteration.

- We'll proceed more practical application evaluation (hopefully without hand assembly tuning)

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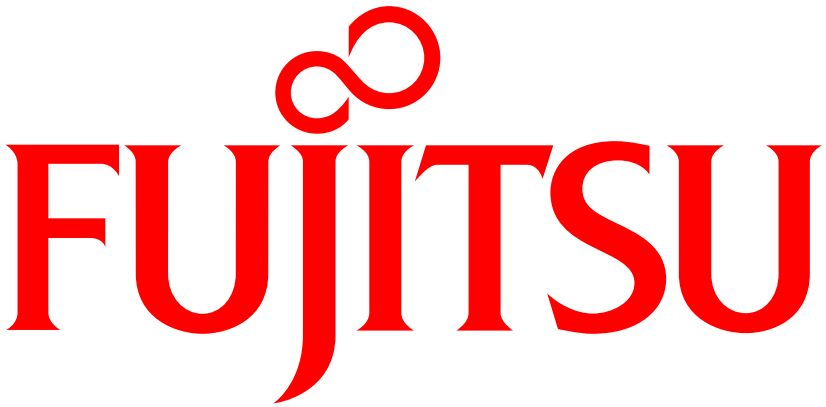

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