Extreme scale multi-physics simulations of the tsunamigenic 2004 Sumatra megathrust earthquake

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Methods and algorithms

Our code SeisSol uses an ADER-DG method, which is suitable for linear hyperbolic PDEs; e.g. the elastic wave equations:

$$\frac{\partial}{\partial t} \ddot{u} + c \cdot \nabla \ddot{u} + \rho \cdot \nabla \dot{u} - \nabla p = 0$$

The numerical scheme consists of element-local and small matrix chain multiplications. Data exchange only has to happen between immediate face-neighbours.

ADER time integration

$$\frac{\partial}{\partial t} Q_n + K_n \ddot{Q}_n - \nabla \cdot Q_n = 0$$

Element-local, matrix-based update scheme

$$Q_{n+1} = Q_n + K_n \ddot{Q}_n + \nabla \cdot Q_n$$

Local time stepping (LTS)

Static adaptivity, and especially low-quality elements may lead to severe time step restrictions, due to the CFL condition

$$\frac{c}{\Delta t} \leq \frac{C}{2r_0^2}$$

where $r_0$ is the element’s insphere radius. As a remedy we use clustered LTS [1, 2].

Code generation

We use an embedded domain-specific language (eDSL), specifically written for matrix chain products [3], to generate our computation-intensive kernels:

- Automatic detection of irrelevant matrix entries in matrix chain products
- Automatic determination of zero-paddings for aligned loads and stores
- Enabling block decompositions for structured sparse matrices
- Automatic solution of matrix chain ordering problem

To make our eDSL more broadly applicable, we are currently extending it to also support tensor contractions; e.g.

$$\mathbf{Q}(\mathbf{i}, \mathbf{j}) = \mathbf{A}(\mathbf{i}, \mathbf{k}) \cdot \mathbf{B}(\mathbf{k}, \mathbf{j})$$

generates a kernel for

$$D_{\text{local}} = \sum_k A_{i,k} B_{k,j} C_{k,l}$$

HW-SW-codesign: L2 cache efficiency

We use $F_{i,j} = D_{i,j}(R_{i,j})$.

The 2004 Sumatra-Andaman earthquake

An extreme event in every respect:
- Failure of 1300 km–1500 km of the Sumatra subduction zone
- 8 minutes of shaking
- 230,000–260,000 fatal victims
- Caused a tsunami up to 30 m high
- $M_{W} 9.1–9.3$

Largest model has 221 million elements (111 billion degrees of freedom) with 400 m fault resolution and 1.3–2.2 km material layer resolution [2].

ASCE modelling workflow

Performance

M SuperMUC Phase 2, 3072 nodes, 2x Intel Xeon E5-2697 v3 / node, Infintband FDR1 interconnect with 4:1 pruned fat tree topology
S Shaheen II, 6174 nodes, 2x Intel Xeon E5-2698 v3 / node, Cray Aries interconnect with Dragonfly topology
C Cori, 9688 nodes, 1x Intel Xeon Phi 7250 / node, Cray Aries interconnect with Dragonfly topology

Reproducible science

SeisSol is selected for the SC18 Student Cluster Competition: Reproducibility Challenge. The foundation is the artifact appendix in [2].

Continuous integration

Continuous integration (CI) strongly helps in the development process of SeisSol, simply because our software is tested automatically and thus more often.

Low effort CI for code consistency across developers and simple build or unit tests:

High effort CI for complex tests such as (sparse) build matrix of all configurations and nightly convergence tests:

References


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github.com/SeisSol/SeisSol

Figure 1: Elements are partitioned into time clusters for a more regular update scheme suitable for modern hardware.

Figure 2: Partial kernel before (top) and after (bottom) removing irrelevant entries in matrix chain products.

Figure 3: Comparison of simulated water height with satellite data [4]. Surface displacement output of SeisSol is used as initial condition.

Figure 4: Shared memory performance for 100000 elements.

Figure 5: Strong scaling with 221 million elements and 5th degree polynomials.

Figure 6: Local time-stepping reduces time to solution.