

Solving Large Quantities of Small Matrix Problems on Cache-Coherent SIMD Architectures

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Abstract—Horizontal Explicit/Vertical Implicit (HE/VI) methods show promise as a scalable approach to solving global climate problems on cubed sphere geometries. When solving problems with a high horizontal-vertical aspect ratio HE/VI methods, it is necessary to perform a large number of small vertical implicit solves which are independent of each other. We present a performant approach for solving large quantities of independent matrix problems on cache-coherent SIMD architectures.

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OUTLINE

- Climate apps use HE-VI model 3D+1D. Also a pattern for 2D+1D and 3D+0D chemistry
- Results demonstrate importance of “batching” solves, MLK doesn’t do
- Cache coherency is important: IMEX RK accum, tiling
- Explicit part is HO stencil op, memory b/w bound (w/ ghost cells)
- Implicit part is non-linear solver: App requires different matrix at each i,j index
- Results in repeated vertical sparse banded solve
- Solve (tridiag, banded, dense) should vectorize on i (unit stride), tiled in pencils
- Considerations for vector alignment, tiling, and memory
- Performance results, scaling, comparison, by platform / parameter
- Future work: communication hiding, load imbalance, IMEX

(Bryce’s email comments) Looking over the outline:

It’s crucial that we clearly identify the optimizations that we believe are novel/high-impact, vs the optimizations that are well-known to the community (even if they were not well known to us). For example, on the outline, we have listed “IMEX RK accum, tiling”. Do we want to present the accumulation optimizations which removed unnecessary temporaries from the time integrator? Do we feel that optimization is novel, or is that just a common-sense thing that only affected us because of the Chombo programming model? Likewise, do we want to present tiling as a focal point in this paper? Tiling is a well-known technique; we certainly can’t claim tiling in general as novel work. Is some part of our tiling approach novel? (how about parallelizing the tile loop - is that fairly novel? I know Sam does this in HPGMG, but is this a widely used technique?)

We would be well served by applying the scientific method

at this juncture:

- Question: What concrete research question(s) are we answering?
 - Prior research indicates that HE-VI methods show promise as a scalable approach to solving global climate problems on cubed sphere geometries because [explanation] [cite prior studies]. How do we implement HE-VI methods which perform well on cache-coherent SIMD architectures?
 - When solving a problem with a high horizontal-vertical aspect ratio (e.g. the horizontal extents are much greater than the vertical extents) with HE-VI methods, it is necessary to perform a large number of small vertical implicit solves ([give examples of matrix sizes] [citation]) which are independent of each other. [explain the type of solves in the climate dycore - e.g. non-linear but nearly banded] [citation]. How can we efficiently solve large quantities of small non-linear bandedish/banded/tridiagonal matrices on cache-coherent SIMD architectures?
- Hypothesis: What theories did we come up with that would answer our research question(s)?
 - Optimal memory access patterns, management of working set sizes (e.g. staying in cache) and efficient use of vector units are necessary to achieve good performance on cache-coherent SIMD architectures.
 - * Optimal memory access patterns: moving through memory in unit stride, controlling the number of streams.
 - * Management of working set sizes: tiling, reducing size of temporaries/localizing temporaries (thread-local or otherwise)
 - * Efficient use of vector units: moving through memory in unit stride, controlling memory alignment, controlling array strides, annotation-assisted autovectorization
 - * TODO: List of individual, concrete optimizations from above.
 - Mainstream linear algebra libraries ([examples] [citation]) are not well-suited for solving large quantities of small non-linear bandedish/banded/tridiagonal matrices on cache-coherent SIMD architectures because [explanation] [cite prior studies if possible].

- Prediction: If our hypotheses are true, what results can we expect to see?
→ TODO: What performance characteristics should we see with and without each of the concrete optimizations from our hypothesis above?
- Experiment: Investigate the predictions we've made.
→ TODO: Methodology for benchmarking the optimizations identified above and measuring the performance characteristics we're interested in.
- Analysis: What were the results of our experiments?

List of figures from meeting on 8/11: For KNL, HSW, SNB(?)...

- 1) Baseline performance using MKL (and hand) using i-major data layout (not vectorized)
- 2) Performance as a function of 32b RCP NR (not needed on KNL), stored reciprocal (cuts divides in half) for fixed file size (4?)
- 3) Performance vs. Tile Size (jtile = 1,2,4,8,16,32)
- 4) Best Performance vs. MKL using same data layout vs. MKL using its best (include DRAM BW limit)
- 5) Performance as a function of total parallelism for constant tile size [optional time permitting]
- 6) Performance with 2,3,4 hyperthreads... maybe just prose comments?
- 7) effect of kdim != pow(2)... maybe just prose comments?

I. INTRODUCTION

Hans to write Argument for uniqueness:

- Different at every point: nonlinear iter, banded / sparse, tridiagonal, result of Schur complement
- Algorithm doesn't require pivoting (why?)
- Vectorized (in-place) banded/tri-diag MM
- Size of matrices 30 - 100
- SIMD architectures (not SIMT GPU)
- Mixed precision ops (float reciprocal vs. double divides)
- Tiled (experiment for non-tiled code blowing out cache)

Hans to write - put in science motivation

II. RELATED WORK

Hans to write - put in Is this unique? Have to look at batched / tiled sparse solvers, on Intel architecture.

MKL

Links Hans sent

- Built-to-order BLAS [1]
- Blaze [2]
- PLASMA [3]
- MAGMA [4]

etc...

III. IMPLEMENTATION

Bryce to write

To solve a positive-definite symmetric tridiagonal system **diagonally dominant?**, a simplified form of Gaussian elimination which does not perform any pivoting can be used. This method is known as the Thomas algorithm [], and it is $O(n)$ in

time, a significant improvement over full Gaussian elimination, which is $O(n^3)$ in time.

$$\begin{bmatrix} b_0 & c_0 & & & 0 \\ a_1 & b_1 & c_1 & & \\ & a_2 & b_2 & \dots & \\ & & \dots & \dots & c_{n-2} \\ 0 & & & a_{n-1} & b_{n-1} \end{bmatrix} \begin{bmatrix} u_0 \\ u_1 \\ \dots \\ \dots \\ u_{n-1} \end{bmatrix} = \begin{bmatrix} u_0 \\ u_1 \\ \dots \\ \dots \\ u_{n-1} \end{bmatrix}$$

Forward elimination:

```
for (index_type k = 1; k < n; ++k) {
    double const m = a[k] / b[k - 1];
    b[k] = b[k] - m * c[k - 1];
    u[k] = u[k] - m * u[k - 1];
}
```

Backward substitution:

```
u[n - 1] = d[n - 1] / b[n - 1];

for (index_type k = n - 2; k >= 0; --k) {
    u[k] = (u[k] - c[k] * u[k + 1]) / b[k];
}
```

TODO: Mention that algorithm is in-place and destroys the input matrix. Describe AI.

In the applications described in Section ??, we perform such a solve on each vertical (e.g. z) "column" in a 3D Cartesian grid (Figure ??). The matrix coefficients for each column depend on the problem state, so a unique matrix for each column needs to be constructed before each solve. There are two different approaches to computing these batch solves:

- **Solve Columns Independently:** The most straightforward approach is to deal with each tridiagonal solve separately, independent of the other solves. An $n_z \times n_z$ matrix is constructed for each column, and then the Thomas algorithm is used to solve the system formed by the matrix and the vertical column. Because the column solves are independent, different column solves can be executed concurrently via task-level parallelism. Additionally, vectorization can be attempted in the vertical (z) dimension for each independent solve.
- **Interleave Column Solves:** The alternative approach is to simultaneously solve multiple columns. For each $tw_x \times tw_y$ horizontal tile of the grid, a $tw_x \times tw_y$ sub-grid of $n_z \times n_z$ matrices (e.g. a 4D grid stored in a contiguous memory region) is constructed, and then a modified Thomas algorithm is used to simultaneously solve $tw_x \times tw_y$ independent vertical columns. Each tile is solved independently, so the tile solves can be executed concurrently via task-level parallelism. Data-level parallelism can be applied in one of the two horizontal dimensions (x or y).

The interleaved approach offers a major benefit over the independent approach; it allows vectorization in one of the horizontal dimensions. The independent approach is restricted to vectorizing in the vertical dimension. The extent of the vertical dimension (n_z) tends to be very small in the applications

TABLE I: **Comparison of Mixed-Precision and Double-Precision Algorithms:** To study the trade-off in performance and accuracy between the mixed-precision and double-precision variants of our algorithm, we solved a 1D diffusion problem with both codes on a single Intel Xeon ??? "Ivy Bridge" core. We used two measures to quantify error: the L2 norm of the difference between the analytic solution and the computing solution, and the absolute maximum of the residual vector of the tridiagonal solve. The test problem had storage requirements of approximately 4.3 GB. 10 sample runs were performed with each sample performing 5 time steps. The walltime and uncertainty metrics below are normalized to the double-precision results; the L2 norm and residual metrics specify order of magnitude.

Algorithm	Walltime (Normalized)	L2 Norm	Residual
Double-Precision	1.0 \pm 0.007	O(1e-07)	O(1e-16)
Mixed-Precision	0.836 \pm 0.006	O(1e-06)	O(1e-08)

we are concerned with (**HOW SMALL**). In this approach, the loops we are trying to vectorize will typically have iteration counts between 10 and 100. If we vectorize in one of the horizontal dimensions, we can control the iteration count of the loops via the tile size. Additionally, we cannot vectorize the forward-elimination loop, because it contains a read-after-write dependency (**ELABORATE**).

Thus, we pick one of the horizontal dimensions as our unit stride dimension. The vertical dimension will have the greatest stride.

IV. EXPERIMENTAL SETUP

Bryce to write Edison [5], Cori, etc... Compilers Problem Size

- 3x3 or 30x30 or 400x400
- Vectorized vs. MKL / non-vectorized
- Mixed precision
- Tiled (experiment for non-tiled code blowing out cache)

V. RESULTS AND ANALYSIS

Bryce to write

VI. CONCLUSION

Bryce to write The conclusion goes here.

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Comment this section out before submitting... Reformat before finalizing... Intel IPCC ack, too

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