Fine-Grained Synchronization using Global Task Dependencies in DASH

Joseph Schuchart, **José Gracia**

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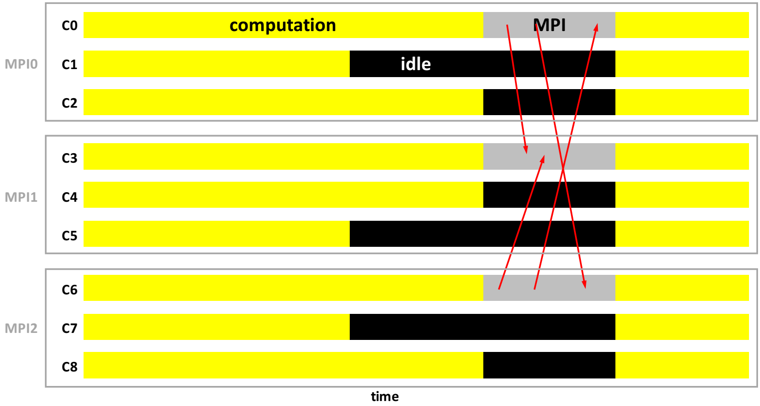
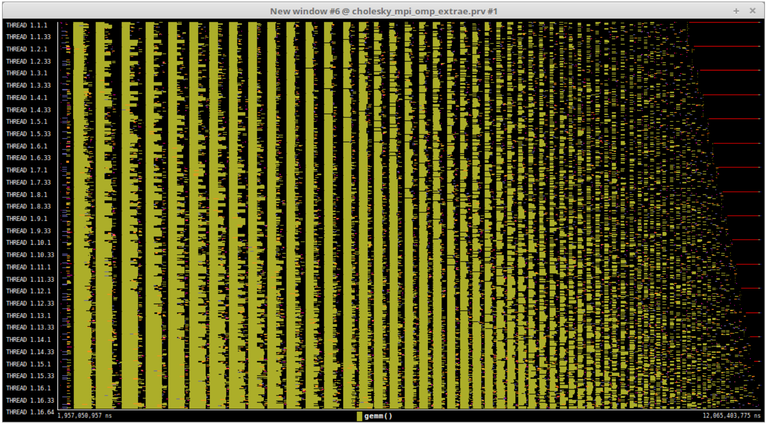
Motivation: Strong synchronisation in MPI applications



Motivation: Strong synchronisation in MPI applications



MPI+OpenMP
Oakforest PACS (KNL), 16 nodes, 64 Threads each

Outline

Background
- DASH – a C++ PGAS Model
- OpenMP Task Data-Dependencies

Global Data Dependencies with DASH

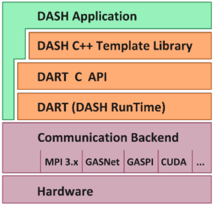
Preliminary Evaluation

Conclusion and Future Work

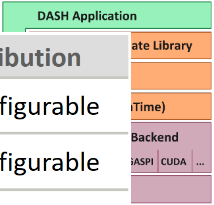
Background

DASH – a C++ PGAS Model

- Partitioned Global Address Space (PGAS)
- C++11/14 distributed data structures and C11 runtime (using MPI-3 RMA)
- Follows STL-principles
- Data-centric computation (*"owner computes"*)



DASH – a C++ PGAS Model



Container	Description	Data distribution
Array<T>	1D Array	static, configurable
NArray<T, N>	N-dim. Array	static, configurable
Shared<T>	Shared scalar	fixed, configurable
Directory*<T>	Variable-size, locally indexed Array	manual
CoArray*<T>	Similar to CAF	uniform

(*) Under construction

DASH – a C++ PGAS Model

- Partitioned Global Address Space (PGAS)
- C++11/14 distributed data structures and C11 runtime (using MPI-3 RMA)
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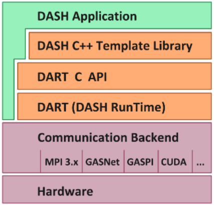

- Synchronization:
  - PGAS: decoupled synchronization and data transfer
  - Team-wide (global) synchronization
  - Distributed lock implementation
  - **No fine-grained synchronization! (yet)**

How to Achieve Fine-grained Synchronization?

Task-based execution model for increased concurrency

Existing PGAS+Task approaches:

- Direct task synchronization, remote task invocation; HPX+UPC++ [3, 4]
- (Explicit) synchronization variables; Chapel [1]
- Explicit tags; XMP [5]
- Affinity instead of branches; PaRSEC [2]

```
upcxx::event e;
upcxx::async(rank, &e)(
    Function, args...);
e.wait();
```

```
var buffReady$: sync bool;
buffReady.readFE();
```

```
#pragma xmp tasklet \\
  get_ready(A, proc, tag)
...
#pragma xmp tasklet \\
  get(tag)
```

How to Achieve Fine-grained Synchronization?

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```
#pragma xmp tasklet \\
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...
#pragma xmp tasklet \\
  get(tag)
```

DASH requires:

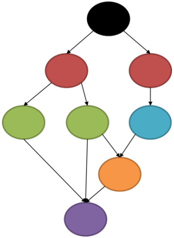
- Scalable distributed task creation
- Implicit, *data-centric* global synchronization
- Recurring dependency patterns

A step back: OpenMP Tasks

OpenMP supports asynchronous tasks since v3.0

Synchronization: Task data dependencies since v4.0

- Describe data flow to form task graph
- Implicit synchronization among *sibling tasks*
- Strict backward matching



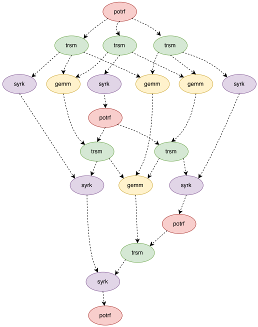
Blocked Cholesky Factorization

```
for (int k = 0; k < nt; k++) {
#pragma omp task out(A[k][k])
  potrf(A[k][k], ts, ts);

  for (int i = k + 1; i < nt; i++)
#pragma omp task in(A[k][k]) out(A[k][i])
    trsm(A[k][k], A[k][i], ts, ts);

  for (int i = k + 1; i < nt; i++) {
    for (int j = k + 1; j < i; j++)
#pragma omp task in(A[k][i], A[k][j]) out(A[j][i])
      gemm(A[k][i], A[k][j], A[j][i], ts, ts);

#pragma omp task in(A[k][i]) out(A[i][i])
    syrk(A[k][i], A[i][i], ts, ts);
  }
}
```



Blocked Cholesky Factorization

```
  for (int k = 0; k < num_blocks; ++k) {
    if (block_kk.is_local())
      potrf(block_kk);

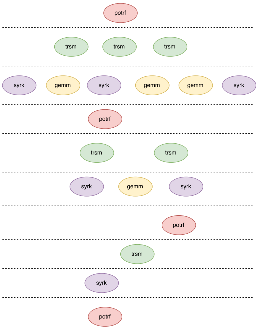
#pragma omp taskwait
    dash::barrier();

    for (int i = k+1; i < num_blocks; ++i)
      if (block_ki.is_local())
#pragma omp task
        trsm(block_kk, block_ki);

#pragma omp taskwait
    dash::barrier();

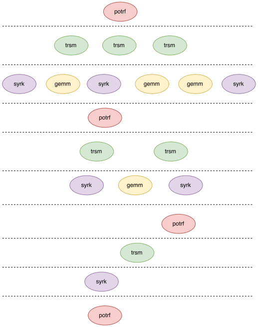
    for (int i = k+1; i < num_blocks; ++i) {
      for (int j = k+1; j < i; ++j)
        if (block_ji.is_local())
#pragma omp task
          gemm(block_ki, block_kj, block_ki);

      if (block_ii.is_local())
#pragma omp task
        syrk(block_ki, block_ii);
    }
#pragma omp taskwait
    dash::barrier();
  }
```



Limitations of DASH + OpenMP

- Synchronization through collectives
  dependencies across nodes have to be enforces by barriers
- Synchronization may lead to imbalances
- Complex/impossible to further taskify



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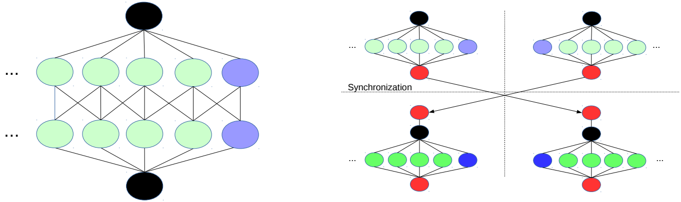
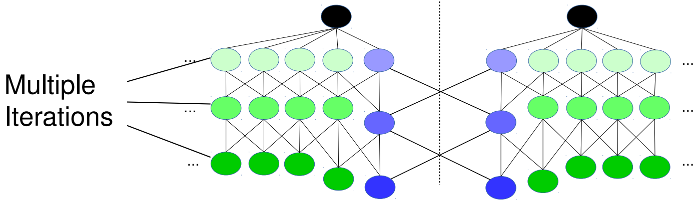
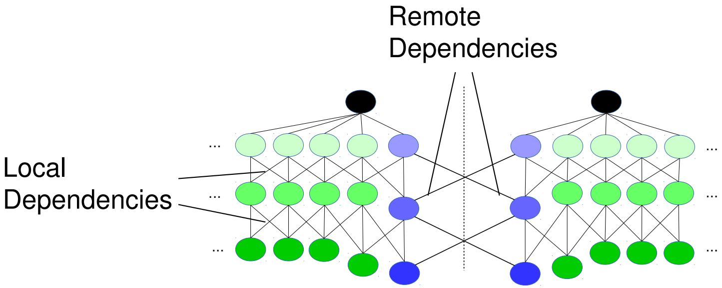


Global Data Dependencies with DASH

Global Data Dependencies



Global Data Dependencies



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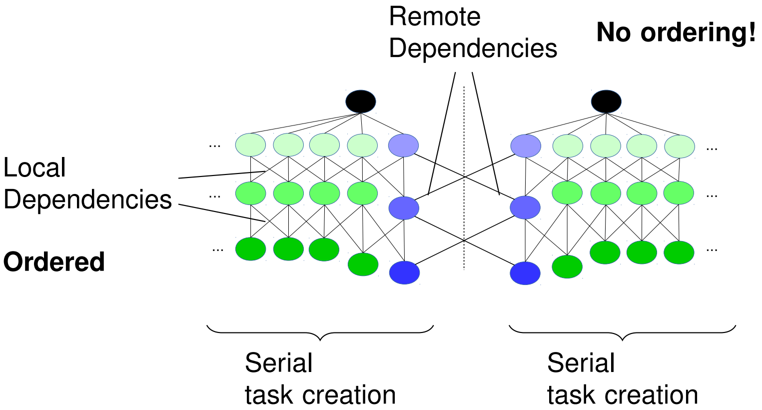
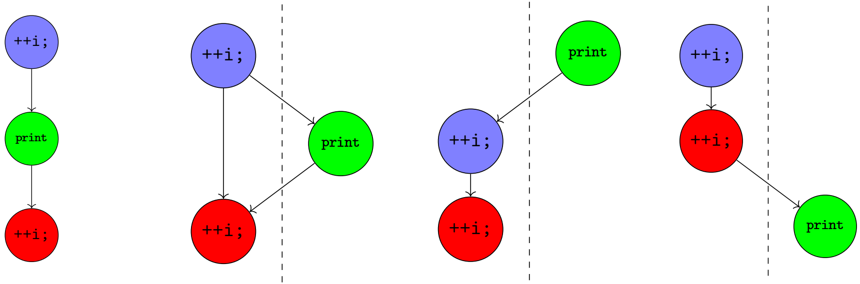


Global Task Ordering

Issue:
Remote dependency resolution depends on order of task instantiation across nodes

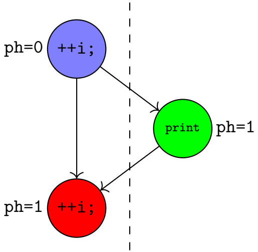


How to restore global task ordering?

Global Task Ordering

Proposed Solution: **Task Phases**

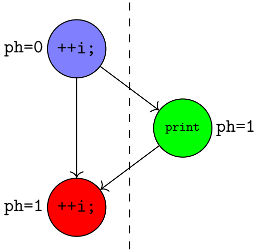
- *Logical clock* for tasks and dependencies
- Virtual barrier in task-based execution
- *Happens before*: `input` dependencies refer to earlier phase
- Additional information provided by the user

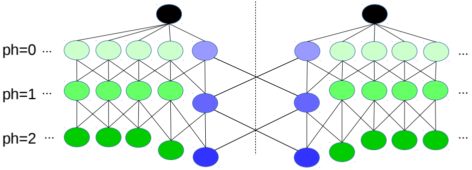


Global Task Ordering

Proposed Solution: **Task Phases**

- *Logical clock* for tasks and dependencies
- Virtual barrier in task-based execution
- *Happens before*: `input` dependencies refer to earlier phase
- Additional information provided by the user
- Overlapping iterations





DASH Prototype Implementation

- Nested tasking runtime using `pthreads`
- Preliminary C++ API

- Dependencies:
  - Local `in`/`out` dependencies (similar to OpenMP)
  - Remote `in`/`out` dependencies
  - Flexible `copyin`: 1-sided or 2-sided

- Active message queue based on MPI
- Re-scheduling `task-yield`
- Global task cancellation
- Task priorities

Blocked Cholesky Factorization (DASH)

```
for (int k = 0; k < num_blocks; ++k) {
  if (block_kk.is_local()) {
    potrf(block_kk);

  }
  dash::barrier();

  for (int i = k+1; i < num_blocks; ++i) {
    if (block_ki.is_local()) {
      trsm(block_kk, block_ki);

    }
  }
  dash::barrier();

  for (int i = k+1; i < num_blocks; ++i) {
    for (int j = k+1; j < i; ++j) {
      if (block_ji.is_local()) {
        gemm(block_ki, block_kj, block_ki);

      }
    }
    if (block_ii.is_local()) {
      syrk(block_ki, block_ii);

    }
  }
  dash::barrier();
}
```

Global synchro-nization to ensure happens-before relation

Blocked Cholesky Factorization (DASH Tasks)

```
for (int k = 0; k < num_blocks; ++k) {
  if (block_kk.is_local()) {
    dash::async([=](){ potrf(block_kk); },
      dash::out(block_kk));
  }
  dash::async_barrier();

  for (int i = k+1; i < num_blocks; ++i) {
    if (block_ki.is_local()) {
      dash::async([=](){ trsm(block_kk, block_ki); },
        dash::in(block_kk), dash::out(block_ki));
    }
  }
  dash::async_barrier();

  for (int i = k+1; i < num_blocks; ++i) {
    for (int j = k+1; j < i; ++j) {
      if (block_ji.is_local()) {
        dash::async([=](){ gemm(block_ki, block_kj, block_ki); },
          dash::in(block_ki), dash::in(block_kj), dash::out(block_ji));
      }
    }
    if (block_ii.is_local()) {
      dash::async([=](){ syrk(block_ki, block_ii); },
        dash::in(block_ki), dash::out(block_ii));
    }
  }
  dash::async_barrier();
}
dash::complete();
```

`async` introduces new task using C++ lambda notation

Blocked Cholesky Factorization (DASH Tasks)

```
for (int k = 0; k < num_blocks; ++k) {
  if (block_kk.is_local()) {
    dash::async([=](){ potrf(block_kk); },
      dash::out(block_kk));
  }
  dash::async_barrier();

  for (int i = k+1; i < num_blocks; ++i) {
    if (block_ki.is_local()) {
      dash::async([=](){ trsm(block_kk, block_ki); },
        dash::in(block_kk), dash::out(block_ki));
    }
  }
  dash::async_barrier();

  for (int i = k+1; i < num_blocks; ++i) {
    for (int j = k+1; j < i; ++j) {
      if (block_ji.is_local()) {
        dash::async([=](){ gemm(block_ki, block_kj, block_ji); },
          dash::in(block_ki), dash::in(block_kj), dash::out(block_ji));
      }
    }
    if (block_ii.is_local()) {
      dash::async([=](){ syrk(block_ki, block_ii); },
        dash::in(block_ki), dash::out(block_ii));
    }
  }
  dash::async_barrier();
}
dash::complete();
```

Non-blocking phase barrier to ensure happens-before relation

Blocked Cholesky Factorization (DASH Tasks)

```
for (int k = 0; k < num_blocks; ++k) {
  if (block_kk.is_local()) {
    dash::async([=](){ potrf(block_kk); },
      dash::out(block_kk));
  }
  dash::async_barrier();

  for (int i = k+1; i < num_blocks; ++i) {
    if (block_ki.is_local()) {
      dash::async([=](){ trsm(block_kk, block_ki); },
        dash::in(block_kk), dash::out(block_ki));
    }
  }
  dash::async_barrier();

  for (int i = k+1; i < num_blocks; ++i) {
    for (int j = k+1; j < i; ++j) {
      if (block_ji.is_local()) {
        dash::async([=](){ gemm(block_ki, block_kj, block_ki); },
          dash::in(block_ki), dash::in(block_kj), dash::out(block_ji));
      }
    }
    if (block_ii.is_local()) {
      dash::async([=](){ syrk(block_ki, block_ii); },
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    }
  }
  dash::async_barrier();
}
dash::complete();
```

`input` dependency refers to `output` dependency in previous phase

Blocked Cholesky Factorization (DASH Tasks)

```
for (int k = 0; k < num_blocks; ++k) {
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Wait for completion of all tasks

Blocked Cholesky Factorization (DASH Tasks)

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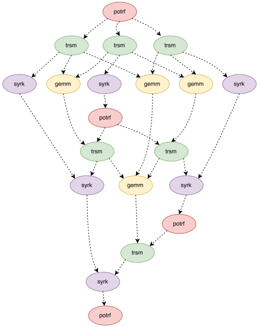


Preliminary Evaluation

Platforms

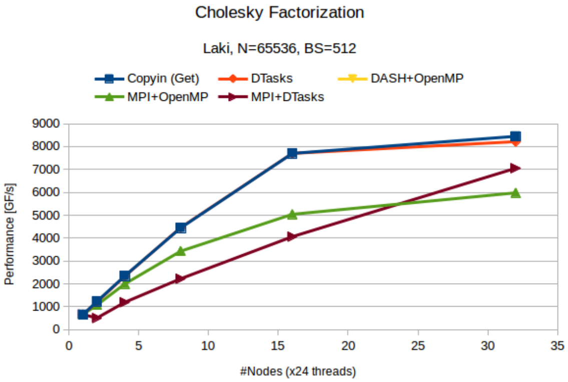
Systems under test:

- Laki (HLRS):
  2 x 'Haswell' E5-2680v3 12-core,
  IB, GCC 7.1.0
- Oakforest PACS (U Tsukuba):
  Intel Xeon Phi 7250 (KNL)
  OmniPath, Intel 18.0.1

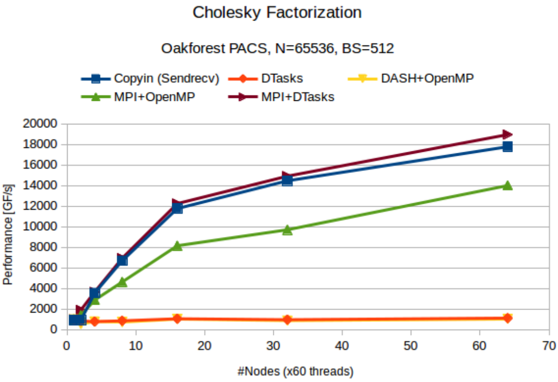
Evaluation Kernel

- Blocked Cholesky Factorization
  - 4 operations: `potrf`, `trsm`, `syrk`, `dgemm`
  - Fine-grained task dependencies
  - Scheduling-sensitive
- Implementations:
  - `DTasks`: DASH Tasks w/ manual block prefetching
  - `Copyin`: DASH Tasks w/ `copyin` dependency
  - `DASH+OpenMP`: OpenMP tasks between global sync
  - `MPI+OpenMP`: single commuication task
  - `MPI+DTasks`: block-wise communication tasks (test-yield-loop)

Results: Laki



Results: Oakforest PACS



Conclusion and Future Work

Conclusion

Global task data dependencies:

- Concept known from OpenMP
- Distributed task creation and synchronization
- Fine-grained, data-centric synchronization
- (Some) Ordering information required from user
  - Replace blocking `barrier()` with `async_barrier()`
- Promising first results (even on systems that poorly support RDMA)

Future Work

- Work on distributed scheduler
  - Advanced dependency types (`concurrent`, `commutative`)
  - Performance optimizations
  - Edge out bugs
- Tool support
- Interoperability with OpenMP (OmpSs?)
- Applications
  - Lulesh (Shock Hydrodynamics, already ported to DASH)
  - Ideas are welcome (preferably C/C++)

Thank you for your attention!

Questions?

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github.com/dash-project/

dash-project.org

dash

SPPEXA

Deutsche Forschungsgemeinschaft DFG

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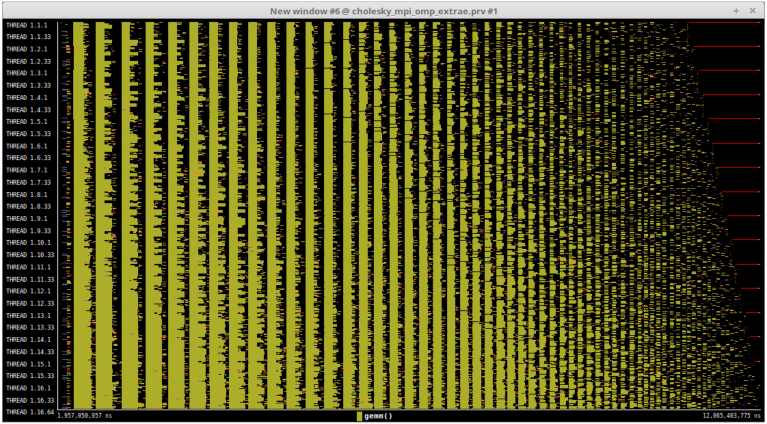
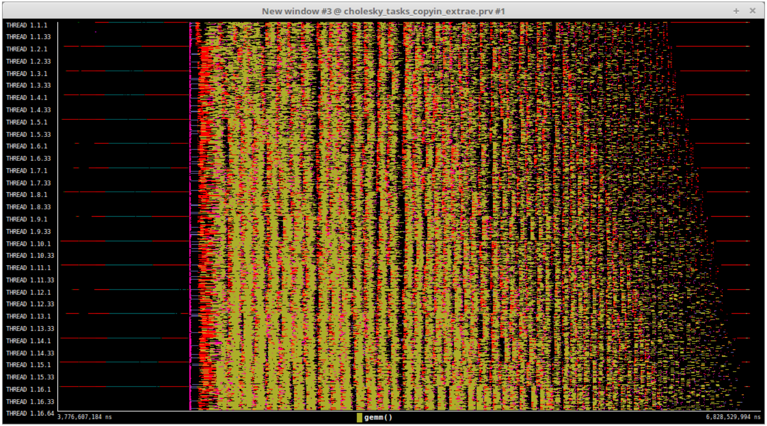
Cholesky: MPI+OpenMP



N = 32,768, bs = 512, `column-wise distribution`, MPI+OpenMP (10s)
Oakforest PACS (KNL), 16 nodes, 64 Threads each, w/ block pre-fetching

Cholesky: DASH+Tasks+Copyin



N = 32,768, bs = 512, `column-wise distribution`, DASH+Tasks+Copyin (3.0s)
Oakforest PACS (KNL), 16 nodes, 64 Threads each, w/ block pre-fetching