DSLs and APIs for Dataflow Programming (over the PaRSEC runtime)

Thomas Herault, Joseph Schuchart, George Bosilca, Robert Harrison, Ed Valeev, Poornima Nookala, et al

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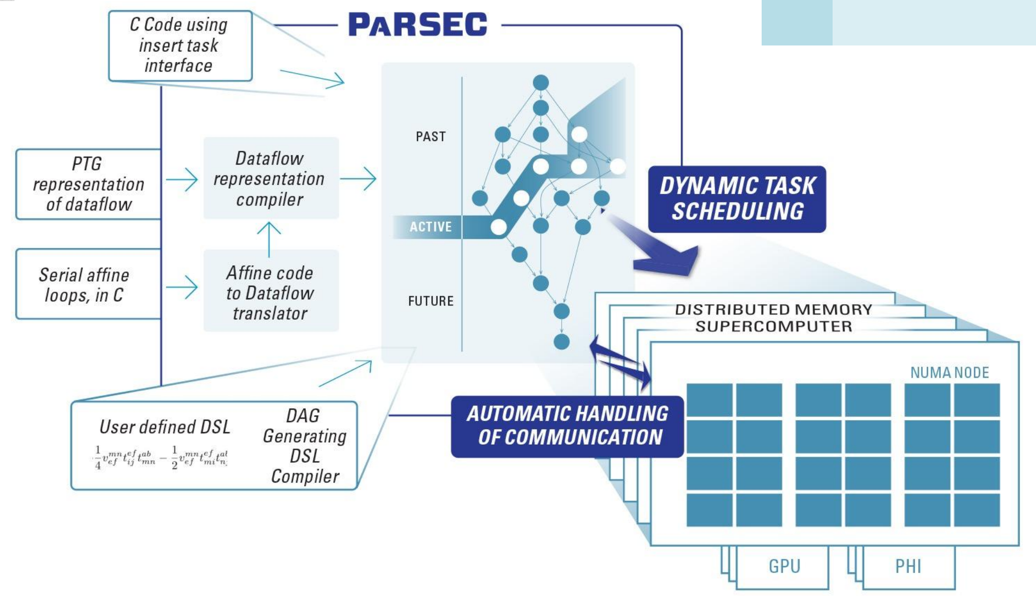
PaRSEC: a generic runtime system for asynchronous, architecture aware scheduling of fine-grained tasks on distributed many-core heterogeneous architectures



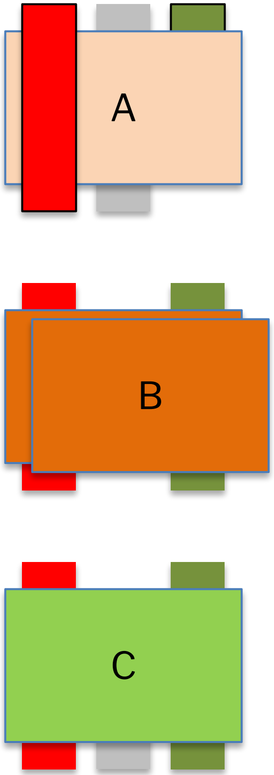
Concepts

- Clear separation of concerns: compiler optimize each task class, developer describe dependencies between tasks, the runtime orchestrate the dynamic execution
- Interface with the application developers through specialized domain specific languages (PTG/TTG, Python, insert_task, fork/join, …)
- Separate algorithms from data distribution
- Remove unnecessary control flow

Runtime

- Portability layer for heterogeneous architectures
- Scheduling policies adapt every execution to the hardware & ongoing system status
- Data movements between producers and consumers are inferred from dependencies. Communications/computations overlap naturally unfold
- Coherency protocols minimize data movements
- Memory hierarchies (including NVRAM and disk) integral part of the scheduling decisions

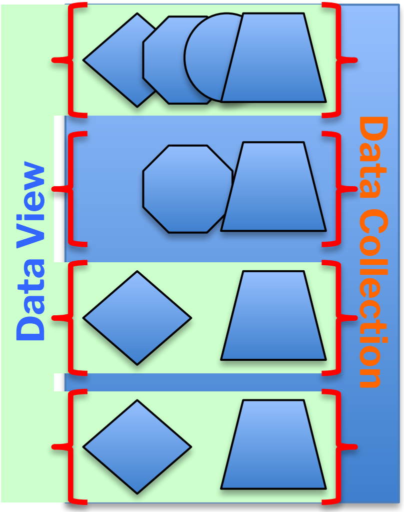
PaRSEC concepts: Tasks / Collections / Contexts



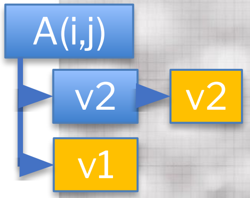
- A task-class is somewhat a familiar concept, a pure function with a well-defined number of terminals (input and outputs)
  - Terminals are tagged with properties R/RW/W/T
  - Depending on the DSL the outputs might be made available at any time
  - Task-classes can be extended with multiple incarnations (CPU, GPU, hierarch, OpenCL, JIT, …)
  - The execution device is dynamically selected at runtime among available incarnations
  - Specialized terminals exists (IO, redistributed, compress, low-rank, push/pull, validate)

- A task is a particular instance of a task-class (i.e. a task class with a unique task identifier)
  - The runtime was designed for tasks with ~10 μsec granularity
  - A collection of tasks and their dependencies is a taskpool
    - DSLs generate or populate taskpools

PaRSEC concepts: Tasks / Collections / Contexts



- A data is the basic logical element used in the description of the dataflow
  - Locations: have multiple coherent copies (remote node, device, checkpoint)
  - Shape: can have different memory layout
  - Visibility: only accessible via the most current version of the data
  - State: can be migrated / logged
- **Data collections** are ensemble of data distributed among the nodes
  - Can be regular (multi-dimensional matrices)
  - Or irregular (sparse data, graphs)
  - Can be regularly distributed (cyclic-k) or user-defined
  - Can be virtual (no content),
- **Data View** a subset of the data collection used in a particular algorithm (aka. submatrix, row, column,…)
- A data (version) is a promise, a data collection is a promise, a data view is a promise
- The promise will be delivered where it is expected by the task that will use it (distributed, GPU task on GPU, …)



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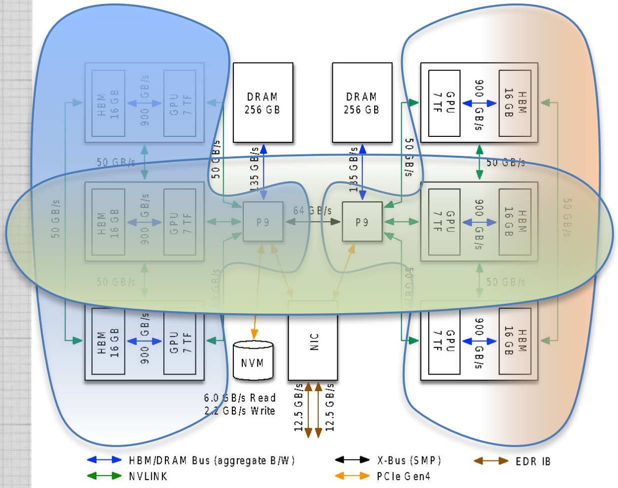
PaRSEC concepts: Tasks / Collections / Contexts



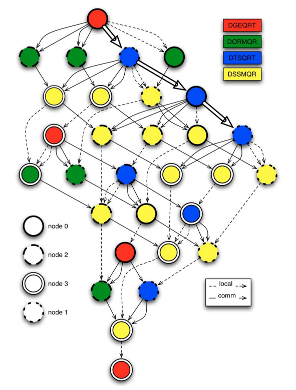
- A PaRSEC context is a distributed executor extended with a set of resources (core(s), accelerators, networks), memory allocators, and task schedulers
  - Multiple contexts could exist simultaneously, but the runtime does not police their use of resources
  - A given taskpool belongs to a specific context, and its tasks execute only on the resources belonging to the context

PaRSEC: task-based runtime system

- PaRSEC:
  - A runtime system
    - Distributed, accelerated, with multiple communication systems
  - A programming environment
    - Tools for profiling, debugging
  - A set of Domain Specific Languages / Extensions
    - Dynamic Task Discovery (DTD)
    - Parameterized Task Graph (PTG)
    - (SLATE API)
    - *Templated Task Graph (TTG)*

From the PaRSEC runtime perspective

- The runtime is agnostic to the domain specific language (DSL)
- Different DSL interoperate through the data collections
- The DSL share the infrastructure
  - Distributed schedulers
  - Communication engine
  - Hardware resources
  - Data management (coherence, versioning, …)
- They don’t share
  - The task structure
  - The internal dataflow depiction



Dynamic Task Discovery (DTD) aka. insert_task

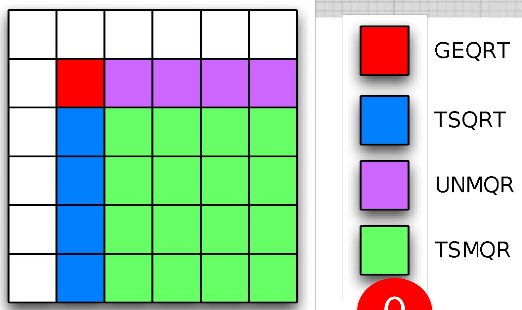
```
int task_hello(parsec_execution_stream_t *es,
               parsec_task_t *this_task)
{
  int *i;
  parsec_dtd_unpack_args( this_task, UNPACK_VALUE, &i);
  printf("Hello World, my index is %d\n", *i);
  return PARSEC_HOOK_RETURN_DONE;
}
int discover_tasks()
{
  for(int i = 0; i < 10; i++) {
    parsec_dtd_taskpool_insert_task( dtd_tp, task_hello,
                                     0, "hellow_world_task",
                                     sizeof(int), &i, VALUE,
                                     0); /* No more arguments
*/
  }
```

- Possible for each process to only discover local tasks, but data consistency **must** be maintained globally
- Data versioning and caching become a requirement
- Difficult to identify **collective patterns**
- Selecting the **window size** is difficult, all data movement must be known globally (and their order is critically important)

- Dynamic Task Discovery (DTD) enables simple DAG expression through sequential task discovery
- PaRSEC DTD engine builds the DAG of tasks, based on the dependencies of the data flow
- The semantics of sequential execution (the algorithm critical path) are enforced while keeping a DAG with maximal parallelism
- For distributed execution, all computing elements need to discover the same DAG, impairing the runtime scalability
- Only local tasks are kept, and a reference to last accessors / writers on given data to track remote dependencies
- The internal data structure representing the DAG is problem-size dependent, and task discovery window dependent

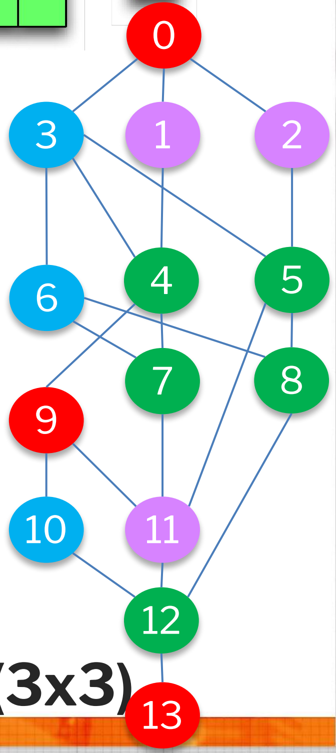
DTD: insert_task

```
for( k = 0; k < SIZE; k++ ) {
    parsec_insert_task( "GEQRT",
                        DATA_OF(A, k, k), INOUT|AFFINITY,
                        DATA_OF(T, k, k), OUTPUT|TILE_RECT)

    for( n = k+1; n < SIZE; n++ )
      parsec_insert_task( "UNMQR",
                          DATA_OF(A, k, k), INPUT|TILE_L,
                          DATA_OF(T, k, k), INPUT|TILE_RECT,
                          DATA_OF(A, k, n), INOUT|AFFINITY)

    for( m = k+1; m < SIZE; m++ ) {
      parsec_insert_task( "TSQRT",
                          DATA_OF(A, k, k), INOUT|TILE_U,
                          DATA_OF(A, m, k), INOUT|AFFINITY,
                          DATA_OF(T, m, k), OUTPUT|TILE_RECT)

      for( n = k+1; n < SIZE; n++ ) {
          parsec_insert_task( "TSMQR",
                              DATA_OF(A, k, n), INOUT,
                              DATA_OF(A, m, n), INOUT|AFFINITY,
                              DATA_OF(A, m, k), INPUT,
                              DATA_OF(T, m, k), INPUT|TILE_RECT)
      }
    }
}
```



A

0,0	0,1	0,2
1,0	1,1	1,2
2,0	2,1	2,2



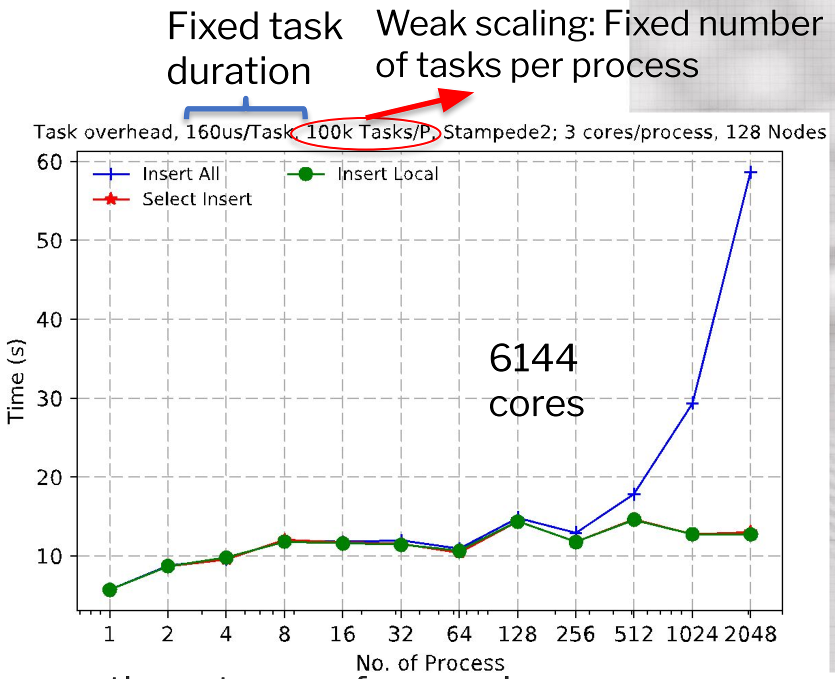
QR Factorization (3x3)

Challenge

- All participating nodes in distributed setting needs to discover the full task-graph (consistent view)
- DAG of large problem might not fit in memory

Solution: Partially Unrolling the DAG

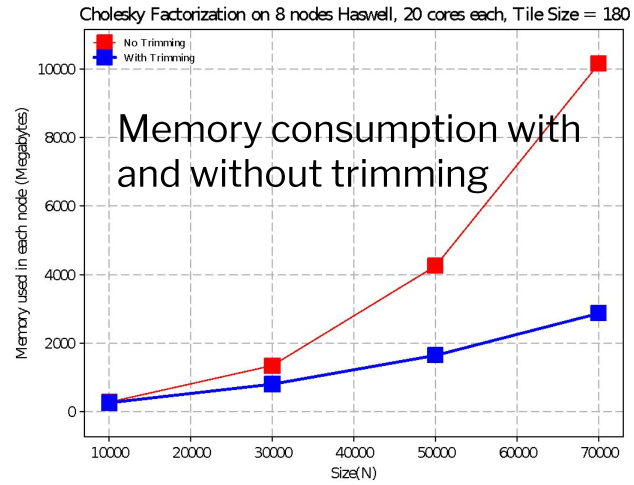
- Create partial DAG, progress, repeat (sliding window of DAG)
  - How the DAG is described directs the execution
- Memory usage is bound to the size of sliding window
- Size of window determines how far in future we can see both locally and remotely (affects performance)



- There are three types of scenario
  - Insert All: Each rank inserts all tasks, and executes only locals
  - Select Insert: Each rank inserts only local tasks but iterates over all tasks.
  - Insert Local: Each rank only inserts local tasks.

Other DTD optimizations

- Trimming (idea popularized by StarPU)
  - Removing remote tasks that do not have any impact locally
- Untying Task Insertion:
  - Users can insert task using one specific thread
  - Users can also insert task that can insert more tasks in the runtime, untying any specific thread from the responsibility of task insertion
  - Allow **recursive task insertion**
  - Allow users to generate independent tasks simultaneously
  - Eliminates performance drop in case of responsible thread being de-scheduled by OS
- Communication
  - Keep track of data version and cache them remotely to avoid sending the same version multiple times
    - What is the life expectancy of these remote copies ?
  - Recycle buffers to optimize memory usage
- PaRSEC Specific Extensions
  - Add collective communications, specialized tasks that operate on a variable number of data
  - Implement owner tracks uses – the opposite concept of tasks trimming



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SLATE API (templated C++)

```
for (int64_t k = 0; k < A.nt(); ++k) {
  PaRSEC::potrf_panel
      <HermitianMatrix<scalar_t>, scalar_t>(A, k, A.column(k));

  if (k+1 < A.nt())
     PaRSEC::broadcast_column
       <HermitianMatrix<scalar_t>, scalar_t>
            (A, k, A.column(k), A.column(k+1), A.column(A.nt()-1));
  }
  for (int64_t n = k+1; n < k+1+lookahead && n < A.nt(); ++n) {
    // lookahead column(s)
    PaRSEC::potrf_lookahead
       <HermitianMatrix<scalar_t>, scalar_t>
         (A, k, n, A.column(k), A.column(n));
  }
  if (k+1+lookahead < A.nt()) { // trailing submatrix
    PaRSEC::potrf_trailing_update
       <HermitianMatrix<scalar_t>, scalar_t>
         (A, k, k+1+lookahead, A.column(k), A.column(k+1+lookahead),
          A.column(A.nt()-1));
  }
  PaRSEC::data_flush(A.parsec_high_level_tp,
                     A.column_range(k, k, A.nt()-1));
}
```

- The SLATE-ish API targets regular algorithms: tile-based task discovery algorithms with explicit synchronization and communications
- Use of templating to manage multiple precision and data representations
- Task discovery based on maintaining the sequential semantic
  - Computing elements need to discover only local tasks
- Communications and synchronizations are both implicit and explicit
- The language/API expresses a control flow
- Explicit communication happens within the progress of these containers and in the background.

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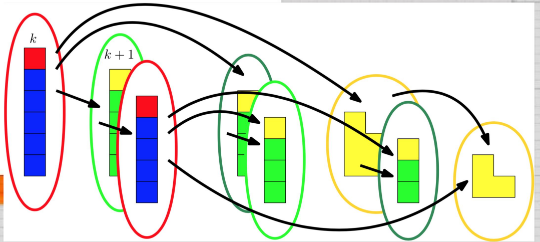
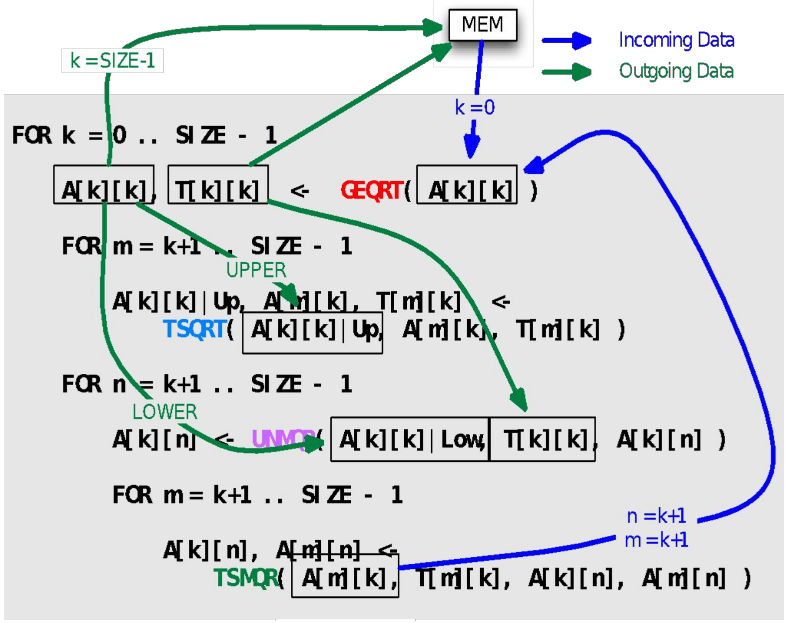
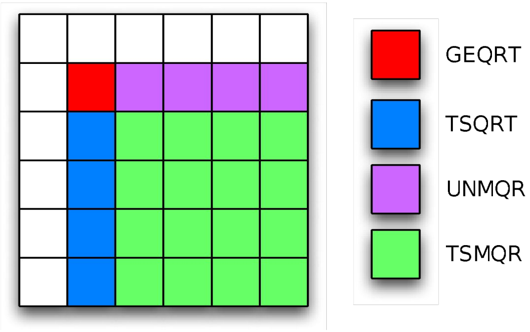


Parameterized Task Graph (PTG)





- A dataflow description based on data tracking
- A simple affine description of the algorithm can be understood and translated by a compiler into a control-flow free form (pure dataflow)
- Abide to all constraints imposed by current compiler technology

Parameterized Task Graph (PTG)

```
GEQRT(k)

 k = 0..( MT < NT ) ? MT-1 : NT-1 )

 : A(k, k)

 RW    A <- (k == 0)    ? A(k, k)
                        : A1 TSMQR(k-1, k, k)
        -> (k < NT-1)  ? A UNMQR(k, k+1 .. NT-1)  [type = LOWER]
        -> (k < MT-1)  ? A1 TSQRT(k, k+1)         [type = UPPER]
        -> (k == MT-1) ? A(k, k)                  [type = UPPER]
 WRITE T <- T(k, k)
        -> T(k, k)
        -> (k <  NT-1) ? T UNMQR(k, k+1 .. NT-1)

BODY [type = CPU]  /* default */
   zgeqrt( A, T );
END

BODY [type = CUDA]
   cuda_zgeqrt( A, T );
END
```

Control flow is possible but not necessary, maximum parallelism is exposed

Data-dependent problems (where the DAG structure depends on the data itself) are more challenging

- A concise parameterized dataflow language, with non-dense iterators and extended expressions via inlined C/C++ code to augment the language
- Only local tasks are instantiated: internal data structures size is inversely proportional to the number of nodes
- The language features multiple collective communication patterns
- Data flows can be typed, to transmit variable data elements
- Tasks can be specialized to target specific devices and refined to adapt to multiple granularities
- Termination mechanism part of the runtime (counting or distributed termination detection)

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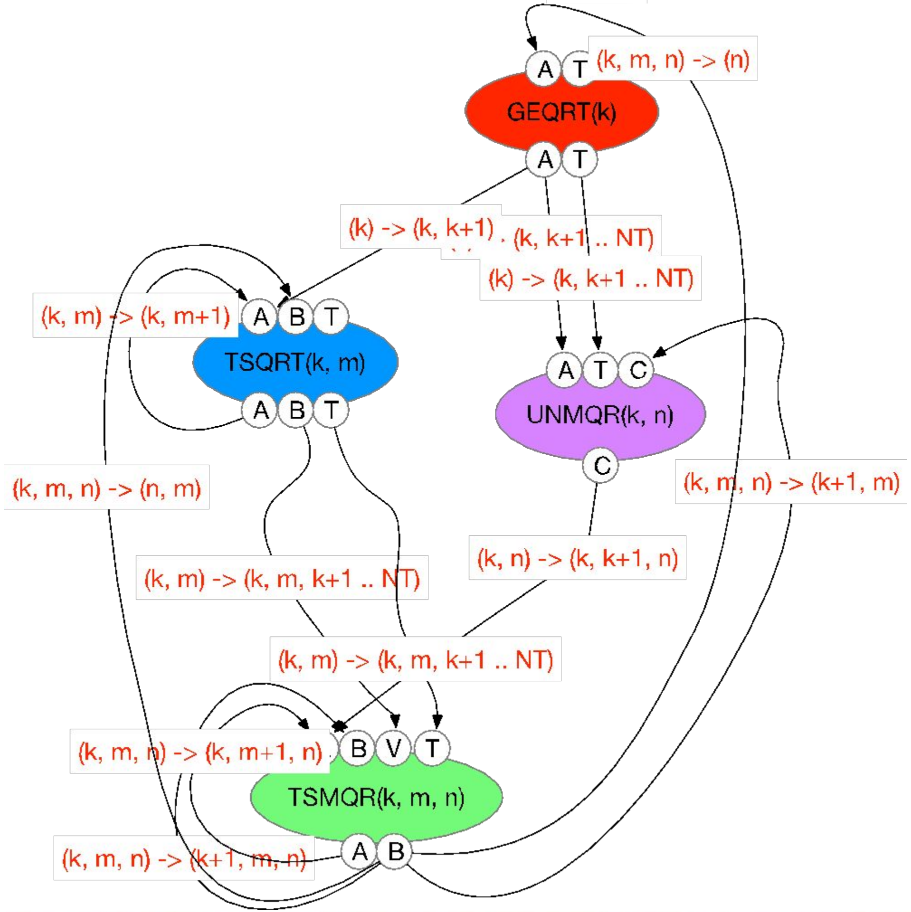
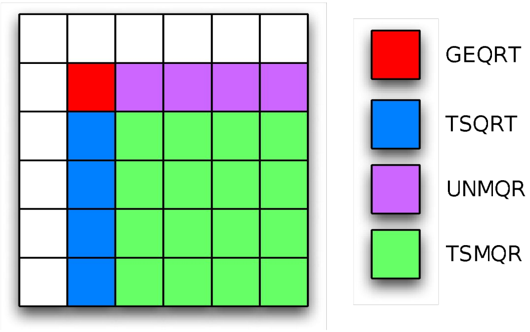
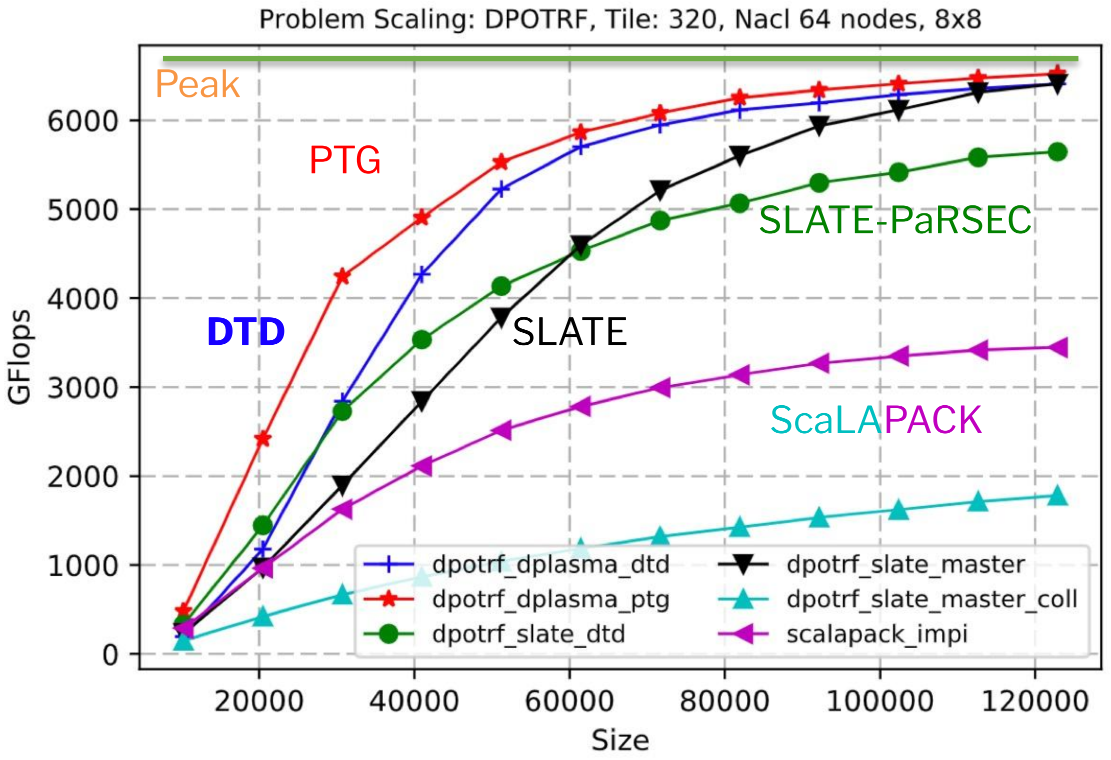




PaRSEC Domain Specific Languages

simplicity — flexibility

- Dynamic Task Discovery
- SLATE – C++
- Parameterized Task Graph



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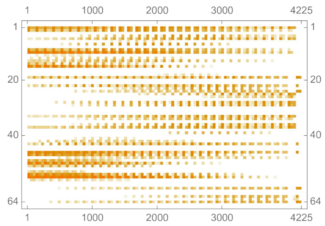
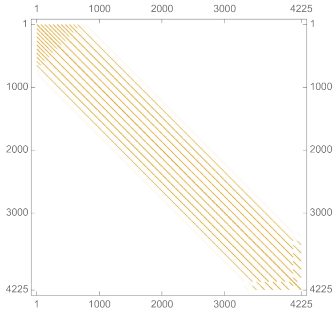
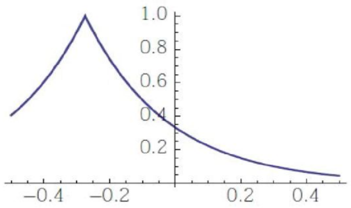
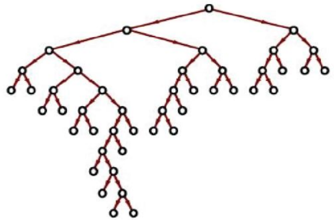
TTG: Motivation





- Some algorithms work on irregular data
  - Block-sparse matrices
  - Sparse matrices
- Others work on irregular data and the DAG is data-dependent
  - Approximative representation of functions using trees
- PTG is not well suited for the latter case (SLATE isn't either)
- DTD has scalability issues
  - All processes need to discover a consistent view of the DAG
  - DAG Pruning is sometimes complex to get right for programmers, especially if the DAG is data-dependent





- TTG: a C++ API to dynamically discover the DAG, with process-local discovery only

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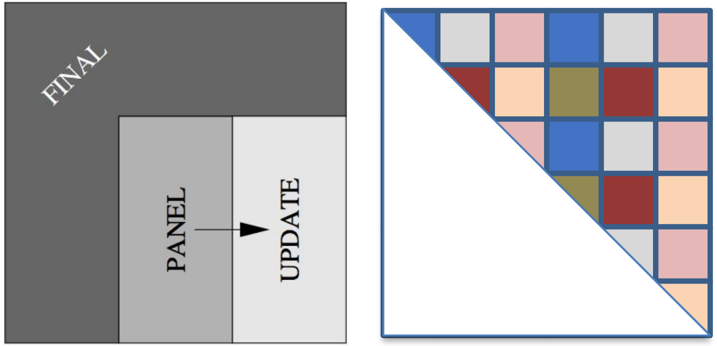
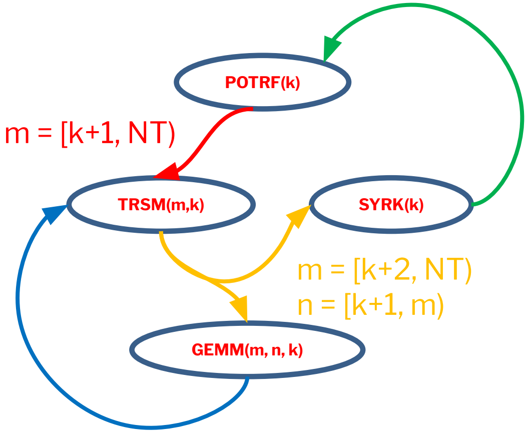
Cholesky in TTG

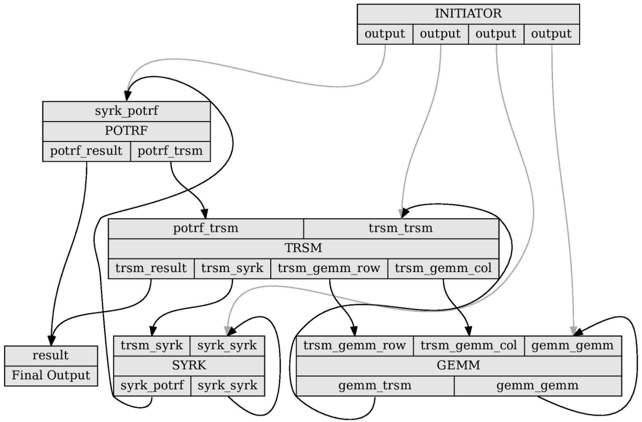





```
/* Edges with 1-tuple task IDs */
ttg::Edge<Int1, Tile> init_potrf;
/* Edges with 2-tuple task IDs */
ttg::Edge<Int2, Tile> potrf_trsm, trsm_result,
                      trsm_syrk, gemm_trsm;
/* Edges with 3-tuple task IDs, encodes the iteration K */
ttg::Edge<Int3, Tile> trsm_gemm_row, trsm_gemm_col;

auto POTRFOp = ttg::make_tt(potrf_fn /* not shown here */,
                            /* input edges */
                            ttg::edges(init_potrf),
                            /* output edges */
                            ttg::edges(potrf_results,
                                       potrf_trsm));

auto trsm_fn =
    [](const Int2& id,
       const Tile<T>&  tile_kk,
       Tile<T>&& tile_mk,
       std::tuple<ttg::Out<Int2, Tile<T>>,
                  ttg::Out<Int2, Tile<T>>,
                  ttg::Out<Int3, Tile<T>>,
                  ttg::Out<Int3, Tile<T>>>& out){
  const auto [I, J] = id;
  const auto K = J;

  /* call LAPACK library's tsrm function */
  TRSM(tile_kk, tile_mk);

  std::vector<Int3> row_ids, col_ids;
  /* ids for gemms row I */
  for (int n = J+1; n < I; ++n)
    row_ids.push_back(Int3(I, n, K));

  /* ids for gemms column I */
  for (int m = I+1; m < NROWS; ++m)
    col_ids.push_back(Int3(m, I, K));

  /* broadcast the result to 4 output terminals:
   * 0: to final output task writing back the tile;
   * 1: to the SYRK kernel;
   * 2: to the gemm tasks on in row I;
   * 3: to the gemm tasks in column K; */
  ttg::broadcast<0, 1, 2, 3>(
    std::make_tuple(id, Int2(I, K), row_ids, col_ids),
    std::move(tile_mk), out);
};
auto TRSMOp = ttg::make_tt(trsm_fn,
                           /* input edges */
                           ttg::edges(potrf_trsm, gemm_trsm),
                           /* output edges */
                           ttg::edges(trsm_result, trsm_syrk,
                                      trsm_gemm_row,
                                      trsm_gemm_col));
```

Cholesky in TTG

- Dense regular matrix
- Tile-based algorithm
- Comparisons:
  - Chameleon: runtime system StarPU; ‘Sequential Task Flow’ DAG representation (equivalent to DTD in PaRSEC)
  - DPLASMA: PaRSEC runtime with PTG DAG representation
  - SLATE: native SLATE implementation
  - ScaLAPACK: machine-provided ScaLAPACK implementation

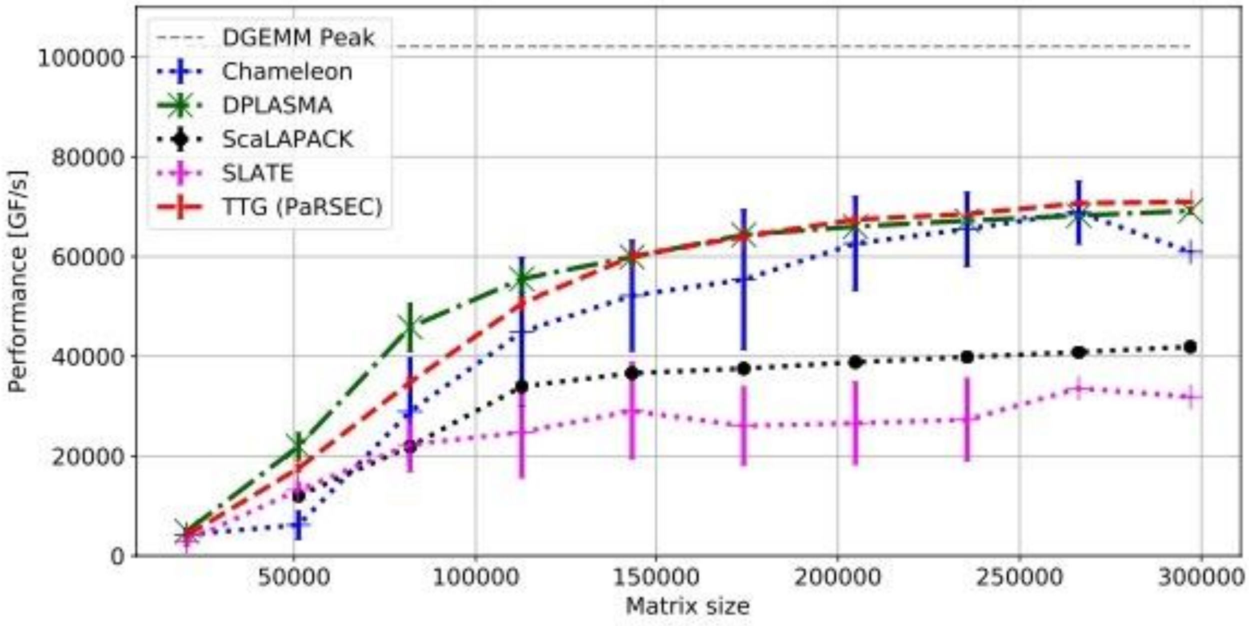


PaRSEC Domain Specific Languages

simplicity ⟵ ⟶ flexibility

- Dynamic Task Discovery
- SLATE – C++
- Parameterized Task Graph
- Template Task Graph

Problem scaling on 64 nodes / 3840 cores (tile size 512x512)



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Conclusion

- PaRSEC is a distributed task-based runtime system targeting hybrid large scale platforms
- It supports multiple DAG of tasks input languages / APIs
  - Centered around the idea of a task class that features multiple alternative implementations and can be instantiated into tasks by providing an identifier
    - Build a graph of task classes, at compile time or at runtime
    - Tasks instantiated during execution unfold the DAG of tasks in a distributed way
  - Data centric runtime: manages data lifecycle and movement for the user
- New interface to program task systems, TTG
  - Fully functional over PaRSEC and MADNESS
  - Targets irregular applications and C++ environments
- Performance oriented runtime for TTG: PaRSEC
  - Work in progress
  - performance is on-par with state of the art implementations at reasonable scale
  - Adding accelerator support in TTG

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