The Design and Implementation of OpenMP 4.5 and OpenACC Backends for the RAJA C++ Performance Portability Layer

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Motivation

- Directive-based languages allow for *performance portability***
  - Relatively easy to integrate
  - Minimal SLOC changes
  - Adaptable to many architectures
- Not all Directive-based languages work across all toolchains
  - Need the right compiler + runtime
- Different codes may need to run on a particular platform with a specific toolchain (performance, reproducibility)
  - Cannot always rely on having OpenMP 4.5 or OpenACC everywhere
- Autotuning and optimization space exploration

OpenACC and OpenMP 4.5

- Language + Runtime describing parallelism for GPUs and accelerators

- OpenACC – Implicit + Explicit
- OpenMP – Explicit

- Tradeoffs
  - Do programmers always want full control?
  - Do users always know what's better?

RAJA Performance Portability Abstraction Layer

- Developed for codesign at Lawrence Livermore National Laboratory
- Embedded DSL in C++11 with several backends:
  - Intel TBB, OpenMP, CUDA, SIMD
- Three main components:
  1. Execution Policies
  2. Reductions
  3. Iterables

```
RAJA::forall(ExecPolicy(), iterable, [=] (int i) {
  // loop body
}
```

- This talk focuses on *Execution Policies*

Execution Policies in RAJA

- A C++ type
- Contains any information pertinent toward code generation
    - Sometimes just the type: `RAJA::seq_exec`
    - Sometimes with additional arguments: `RAJA::cuda_exec<128, false>`

- For OpenACC and OpenMP 4.5, we propose defining a set of *Execution Policy* building blocks

- Building blocks are composed to define high-level execution policies.

Adding a Directive-Based Language Backend

1. Define all pragma language grammar tokens as policy tags:

```
namespace omp::tags {
  // region-based tags
  struct Parallel {};
  struct BarrierAfter {};
  // ... BarrierBefore, etc.

  // construct- and clause-based tags
  struct For {};
  struct Static {};
  // ... Guided, Dynamic
}
```

Adding a Directive-Based Language Backend

2. Construct Policies for each high-level grammar rule

```
template <typename Inner>
struct Parallel : policy<tags::Parallel> {
  using inner = Inner;
};
```

```
template <typename... Options>
struct For : policy<tags::For>, Options... {};
```

List of optional clauses

Adding a Directive-Based Language Backend

3. Compose high-level Execution Policies

```
template <unsigned int N>
using omp_parallel_static_exec =
  omp::Parallel<
    omp::BarrierAfter<
      omp::For<omp::Static<N>>>>;
```

```
#pragma omp parallel
{
  {
    #pragma omp for nowait schedule(static, N)
    // loop and body emitted here
  }
  #pragma omp barrier
}
```

Three instantiations of `RAJA::forall` at compile-time

Adding a Directive-Based Language Backend

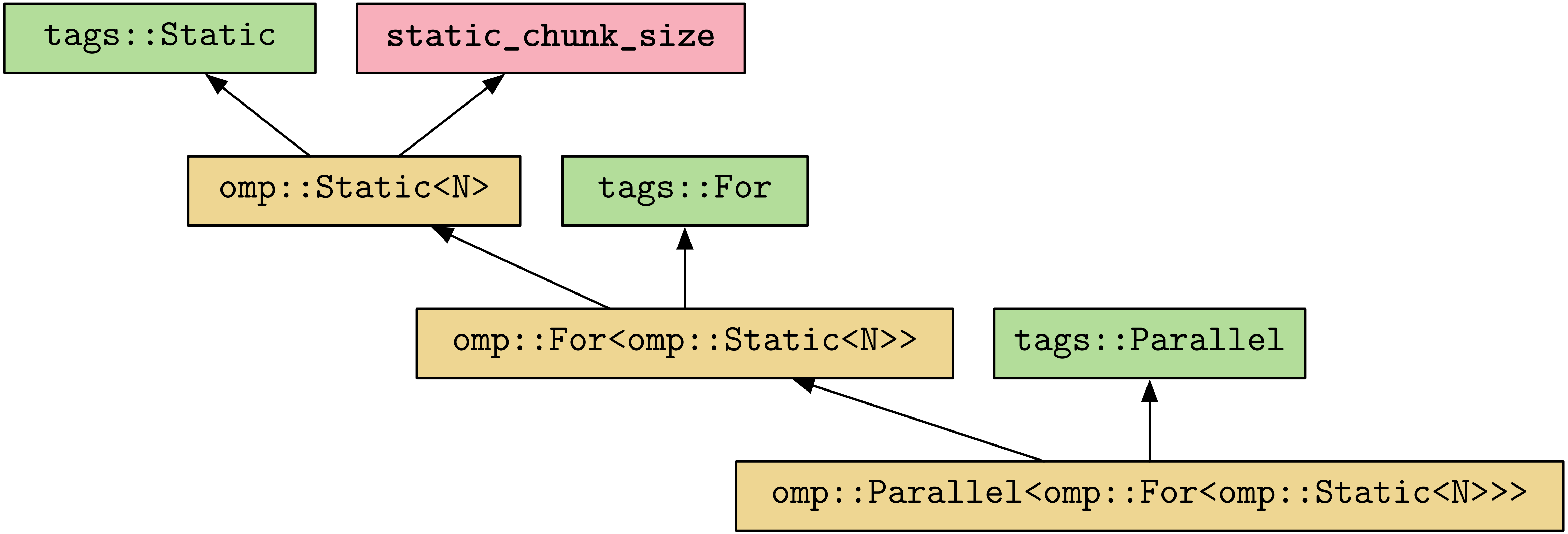
4. Provide Code Specializations for each Execution Policy

```
template <typename Exec, typename Iterable, typename Body>

exact<Exec, omp::tag_list, tags::For, tags::Static>
// does our execution policy exactly match For+Static ?

forall_impl(const Exec &&, Iterable && iter, Body && body) {
  auto size = iter.size();
  #pragma omp for nowait schedule(static, Exec::static_chunk_size)
  for (decltype(size) i = 0; i < size; ++i) {
    body(*(iter.begin() + i));
  }
}
```

Instantiated Type Hierarchy for omp_parallel_for_static<N>



Flat type for omp_parallel_for_static<N>

`tags::Parallel`	`tags::For`	`tags::Static`	`static_chunk_size`

- Code generation must be specialized for each possible permutation
  - `#pragma omp for nowait`
  - `#pragma omp for nowait schedule(static, N)`

- When writing options for OpenACC and OpenMP 4.5, there is state explosion
  - `#pragma acc loop`
  - `#pragma acc loop independent`
  - `#pragma acc loop gang`
  - `#pragma acc loop vector`
  - `#pragma acc loop worker`

OpenMP 4.5 Building Blocks

- All of the OpenMP Building Blocks PLUS:
  - `Target`, `Teams`, and `Distribute` tags
- Aggregate Policy definitions for:
  - `TargetTeamsDistribute`
  - `TargetTeamsDistributeParallelFor`
  - `TargetTeamsDistributeParallelStatic`
- Define a dispatch overload for forall with all OpenMP 4.5 policies
- Define built-in policies for some OpenMP 4.5 policies:
  - `OMP_Target`, `omp_target_teams_distribute_parallel_for`, and a few others.

OpenACC Building Blocks

- All OpenACC clause and directive names as tags:
  - `Parallel, Kernels, Loop, Independent, Gang, Worker, Vector, NumGangs, NumWorkers, VectorLength`
- Aggregate Policy definitions for each clause
  - Parallel, Loop, Independent, etc.
- Dispatch overload for OpenACC policies
- RAJA::forall specializations for:
  - `acc (parallel|kernels) (num_gangs)? (num_workers)? (vector_length)?`
    - 16 possible versions
  - `acc loop (independent)? (gang)? (worker)? (vector)?`
    - 16 possible versions

Evaluation Machine + Toolchains

- IBM POWER 8 + NVIDIA P100
  - CORAL EA System @ LLNL
  - 2x 10-core @ 4.0GHz
  - 256GB DDR3 RAM
  - NVLINK
- IBM Clang w/ OpenMP 4.5 support
- PGI Compiler 17.7 w/ OpenACC (nocopy lambda support)
- CUDA 8.0.61

Evaluation Benchmarks

- 9 Synthetic Kernels:
  - Jacobi-1D, Jacobi-2D, Heat-3D
  - Matrix-Matrix Multiplication
  - Matrix-Vector Multiplication
  - Vector Addition
  - Tensor-2D, Tensor-3D, Tensor-4D
- A C++ view class was used to represent multi-dimensional arrays
- No Reductions were used – emphasis on execution policies

Example: Heat-3D (OpenACC)

```
#pragma acc parallel num_gangs(16), vector_length(128)
{
  #pragma acc loop gang
  for (int i = 1; i < n - 1; ++i)
    #pragma acc loop worker
    for (int j = 1; j < n - 1; ++j)
      #pragma acc loop vector
      for (int k = 1; k < n - 1; ++k)
        B(i,j,k) = 0.125 * (A(i + 1, j, k) - 2.0 * A(i, j, k) + A(i - 1, j, k))
                 + 0.125 * (A(i, j + 1, k) - 2.0 * A(i, j, k) + A(i, j - 1, k))
                 + 0.125 * (A(i, j, k + 1) - 2.0 * A(i, j, k) + A(i, j, k - 1))
                 + A(i,j,k);
}
```

Example: Heat-3D (RAJA+OpenACC)

```
using ExecPol = RAJA::NestedPolicy<
  RAJA::ExecList<
    RAJA::acc::Loop<RAJA::acc::Gang>,
    RAJA::acc::Loop<RAJA::acc::Worker>,
    RAJA::acc::Loop<RAJA::acc::Vector>>,
  RAJA::acc::Parallel<RAJA::acc::NumGangs<16>, RAJA::acc::VectorLength<128>>>;
const RAJA::RangeSegment r (1, n - 1);
RAJA::forallN<ExecPol>(r, r , r, [=] (int i, int j, int k) {
  B(i,j,k) = 0.125 * (A(i + 1, j, k) - 2.0 * A(i, j, k) + A(i - 1, j, k))
           + 0.125 * (A(i, j + 1, k) - 2.0 * A(i, j, k) + A(i, j - 1, k))
           + 0.125 * (A(i, j, k + 1) - 2.0 * A(i, j, k) + A(i, j, k - 1))
           + A(i,j,k);
});
```

Evaluation Criteria

- Compilation Overhead (%)
  - RAJA + OpenACC backend vs. OpenACC
  - RAJA + OpenMP 4.5 backend vs. OpenMP 4.5
- Execution Overhead (%)
  - RAJA + OpenACC backend vs. OpenACC
  - RAJA + OpenMP 4.5 backend vs. OpenMP 4.5

$$\frac{(\mathrm{time}_{\mathrm{RAJA}} - \mathrm{time}_{\mathrm{Directive}})}{\mathrm{time}_{\mathrm{Directive}}}$$

Compilation Overhead

Kernel	OpenACC	OpenMP 4.5
Jacobi 1D	**17.50%**	**8.75%**
Jacobi 2D	50.24%	20.42%
Heat 3D	74.40%	**30.91%**
Matrix Matrix Multiplication	**80.28%**	31.24%
Matrix Vector Multiplication	45.41%	16.47%
Vector Addition	**15.20%**	**6.24%**
Tensor 1D	48.94%	17.57%
Tensor 2D	72.85%	27.53%
Tensor 3D	**120.74%**	**59.29%**
Average	**95.07%**	**38.78%**

Compilation Overhead

- Additional template instantiations (3 per `RAJA::forall`)
- Overload resolution goes from none to at least 8 per `forall` call
  - For OpenMP 4.5, 7 additional resolutions per `forall`
  - For OpenACC, 32 additional resolutions per `forall`
- 5 additional types created per nest level with `forallN`

- With a 3-nested loop with the OpenACC backend enabled:
  - > 18 type constructions
  - > 110 overload resolution attempts

Execution Overhead

Kernel	OpenACC	OpenMP 4.5
Jacobi 1D	**2.52%**	**1.94%**
Jacobi 2D	1.25%	1.14%
Heat 3D	1.08%	1.19%
Matrix Matrix Multiplication	**0.96%**	**1.01%**
Matrix Vector Multiplication	1.13%	1.38%
Vector Addition	**0.21%**	**0.38%**
Tensor 1D	0.98%	1.21%
Tensor 2D	1.34%	1.44%
Tensor 3D	**2.18%**	**2.14%**
Average	**1.66%**	**1.69%**

Conclusion and Future Work

- Proposed Execution Policy constructs for OpenACC and OpenMP 4.5
- Implemented OpenACC and OpenMP 4.5 backends for RAJA
- Showed significant compilation overhead when using RAJA
- Showed minor execution overhead when using RAJA

- Leverage/Propose conditional clause execution with directives
  - Avoids switchyard of SFINAE during compilation
- Add full reduction support to the proposed backends

http://www.github.com/LLNL/RAJA