Towards Performance Portable GPU Programming with RAJA

Arpith Jacob, Samuel Antao, Hyojin Sung, Alexandre Eichenberger, Carlo Bertolli, Gheorghe-Teodor Bercea, Tong Chen, Zehra Sura, Georgios Rokos, Kevin O'Brien

IBM T. J. Watson Research Center

The RAJA Approach

- RAJA* is a C++ based programming approach that
  - Hides computing paradigm and parallel programming models from user
  - With minimum code disruption

- Expresses parallelism in inner loops
- Uses C++11 Lambdas and templates

* R. D. Hornung, and J. A. Keasler. 2014. The RAJA Portability Layer: Overview and Status. LLNL-TR-661403. Lawrence Livermore National Laboratory

The RAJA Approach

- **Fundamental concepts:** traversal template, execution policy, loop body

```
for (int i=0; i<len; i++) {
   bvc[i] = cls * (compression[i] + 1.0);
}
```

C/C++ style loop

Traversal Template — Policy

```
forall<simd_exec>(0, len,
   [&] (int i) {
      bvc[i] = cls * (compression[i] + 1.0);
   }
);
```

Body

RAJA loop

RAJA: SIMD Execution

- Exploit SIMD on CPU with the Clang compiler

```
template <typename LOOP_BODY>
inline
void forall ( simd_exec, int begin, int end,
                         LOOP_BODY loop_body) {
   #pragma clang loop vectorize(enable)
   for (int i = begin; i < end; i++) {
      loop_body(i);
   }
}
```

RAJA: Hardware Threads with OpenMP

```
forall<cpu_parallel_exec>(0, len,
    [&] (int i) {
        bvc[i] = cls * (compression[i] + 1.0);
    }
);
```

```
template <typename LOOP_BODY>
inline
void forall ( cpu_parallel_exec, int begin, int end,
                  LOOP_BODY loop_body) {
   #pragma omp parallel for
    for (int i = begin; i < end; i++) {
        loop_body(i);
    }
}
```

RAJA: Streaming Multiprocessors on a GPU

```
forall<gpu_parallel_exec>(0, len,
    [&] (int i) {
        bvc[i] = cls * (compression[i] + 1.0);
    }
);
```

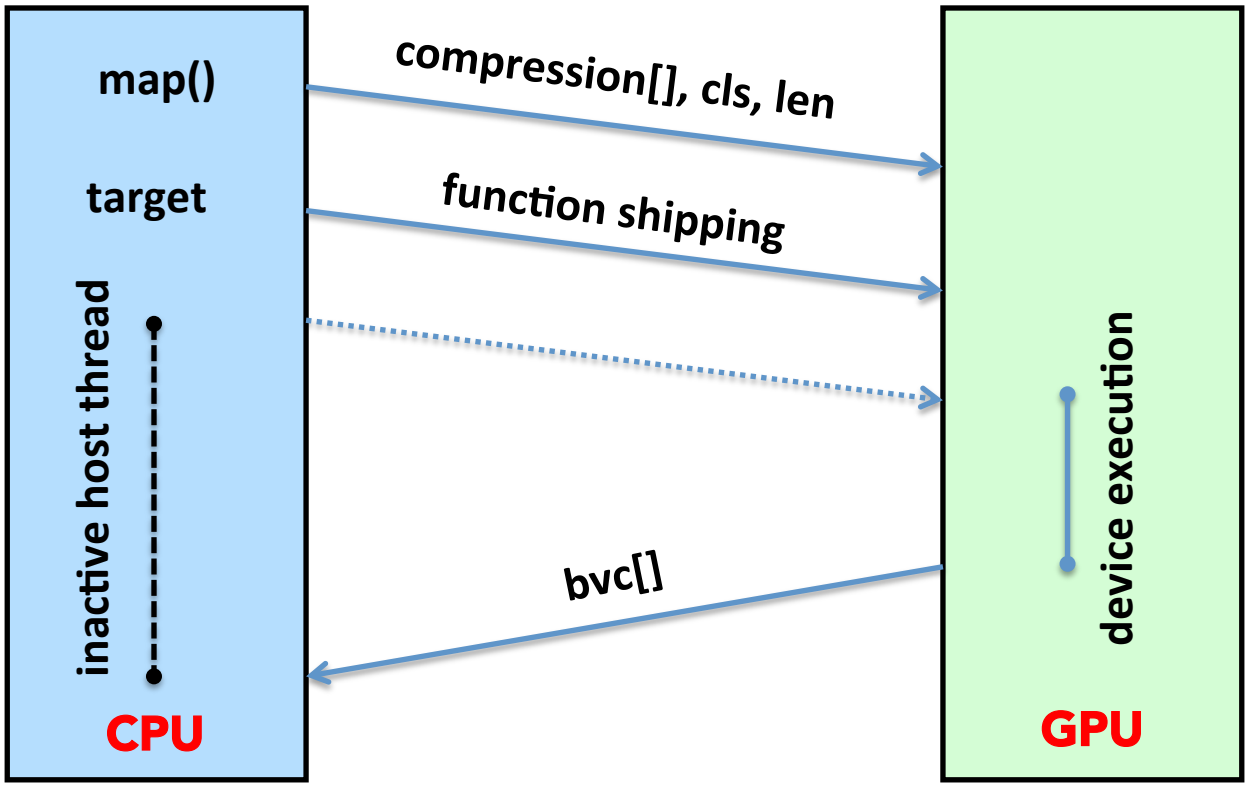
<gpu_parallel_exec> ?

GPU Offloading with OpenMP 4.5

- Latest OpenMP specs support offloading to accelerators
- **How do we use OpenMP offload with RAJA?**

```
#pragma omp target map(to: cls, len, compression[0:len])   \
                   map(from: bvc[0:len])
#pragma omp parallel for
for (int i=0; i<len; i++) {
   bvc[i] = cls * (compression[i] + 1.0);
}
```

GPU Offloading with OpenMP 4.5




```
#pragma omp target map(to: cls, len, compression[0:len])   \
                    map(from: bvc[0:len])
#pragma omp parallel for
for (int i=0; i<len; i++) {
    bvc[i] = cls * (compression[i] + 1.0);
}
```

First Try: RAJA with OpenMP 4.5

```
forall<gpu_parallel_exec>(0, len,
   [&] (int i) {
      bvc[i] = cls * (compression[i] + 1.0);
   }
);
```

```
template <typename LOOP_BODY>
inline
void forall ( gpu_parallel_exec, int begin, int end,
              LOOP_BODY loop_body) {
   #pragma omp target
   #pragma omp parallel for
   for (int i = begin; i < end; i++) {
      loop_body(i);
   }
}
```

Data variables of loop body are not visible in template scope

Lambda function is not GPU code

Mapping LAMBDAs in the Compiler

```
forall<gpu_parallel_exec>(0, len,
    [&] (int i) {
      bvc[i] = cls * (compression[i] + 1.0);
    }
);
```

```
#pragma omp target
for (int i = begin; i < end; i++)
    loop_body(i);
```

map variables captured by lambda

```
struct <LAMBDA> {
  double* &bvc;
  double  &cls;
  double* &compression;

  void operator()(int i) {
    bvc[i] = cls * (compression[i] + 1.0);
  }
}
```

create GPU function

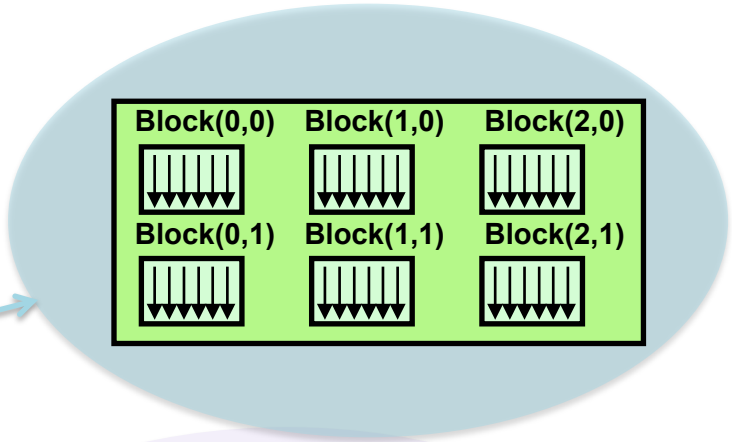
Establishing a GPU Data Environment

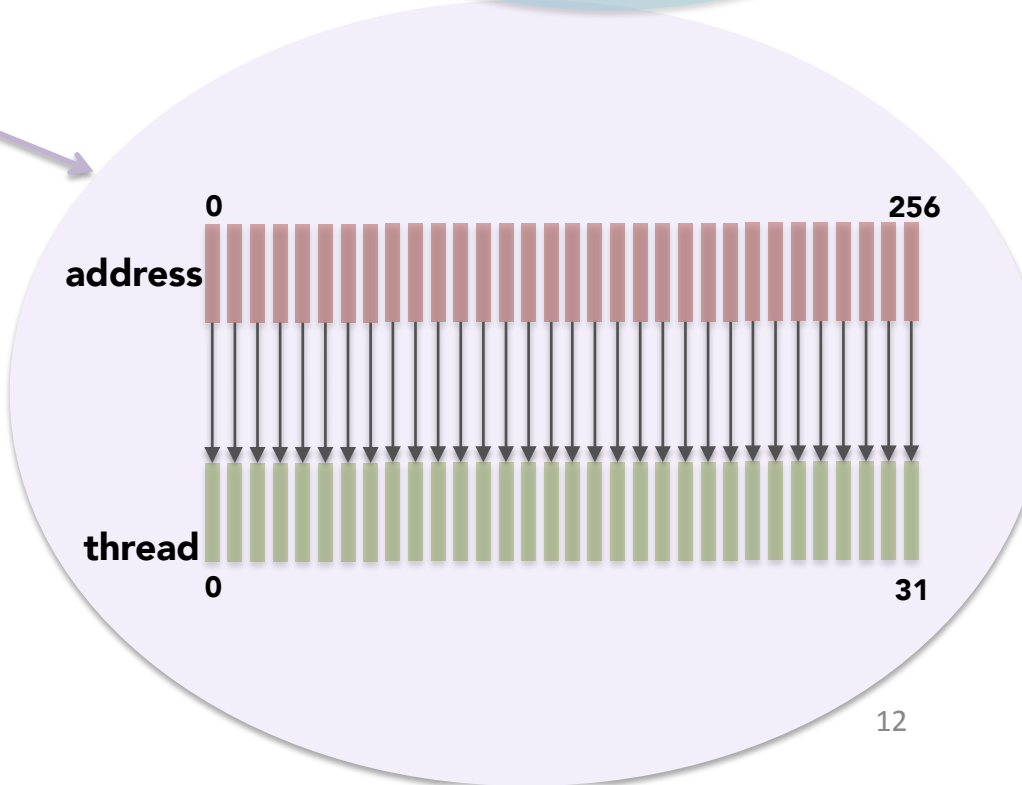
```
struct ADomain {
  ADomain(int ilen, int ndims ) {
      // Initialization code
      // Copy data onto the GPU
      #pragma omp target enter data \
              map(to: zones[0:n_zones])
  }
  UpdateHost() {
      // Retrieve from the GPU
      #pragma omp target exit data \
              map(from: zones[0:n_zones])
  }
 ~ADomain() {
      // Delete data from the device
      #pragma omp target exit data \
              map(delete: zones[0:n_zones])
      delete []zones;
  }
  ...
};
```

```
{
   ADomain domain(LENGTH, 2);

   ...

   forall<gpu_parallel_exec>()


   forall<gpu_parallel_exec>()

   domain.UpdateHost();
   ...
}
```

Optimizing RAJA OpenMP 4.5 Programs

```
template <typename LOOP_BODY>
inline
void forall ( gpu_parallel_exec, int begin, int end,
              LOOP_BODY loop_body) {
#pragma omp target teams distribute parallel for \
                  schedule(static, 1)
   for (int i = begin; i < end; i++) {
      loop_body(i);
   }
}
```





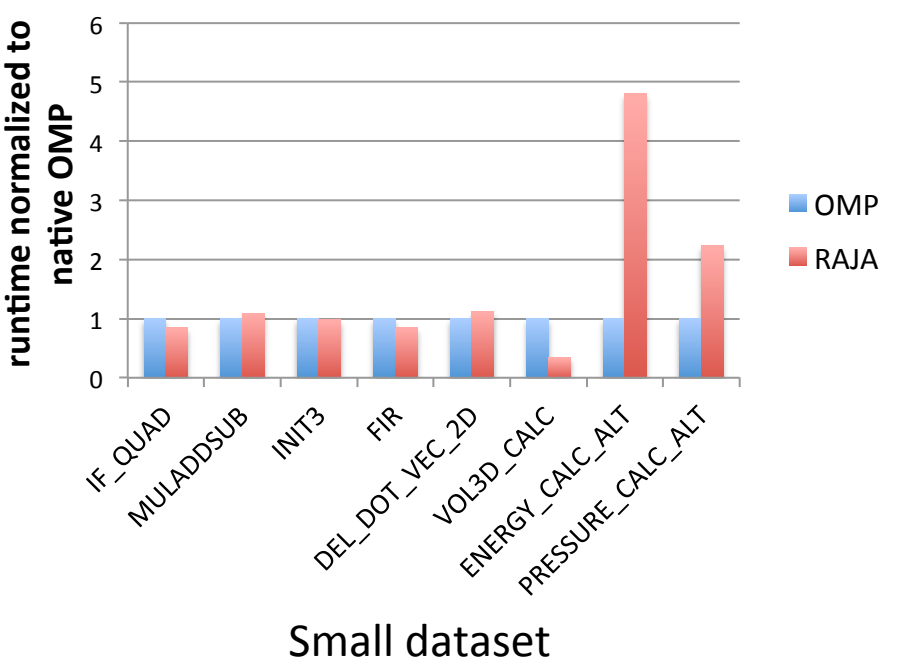
specialize parallel loop kernel call to remove OMP overheads

RAJA with GPUs

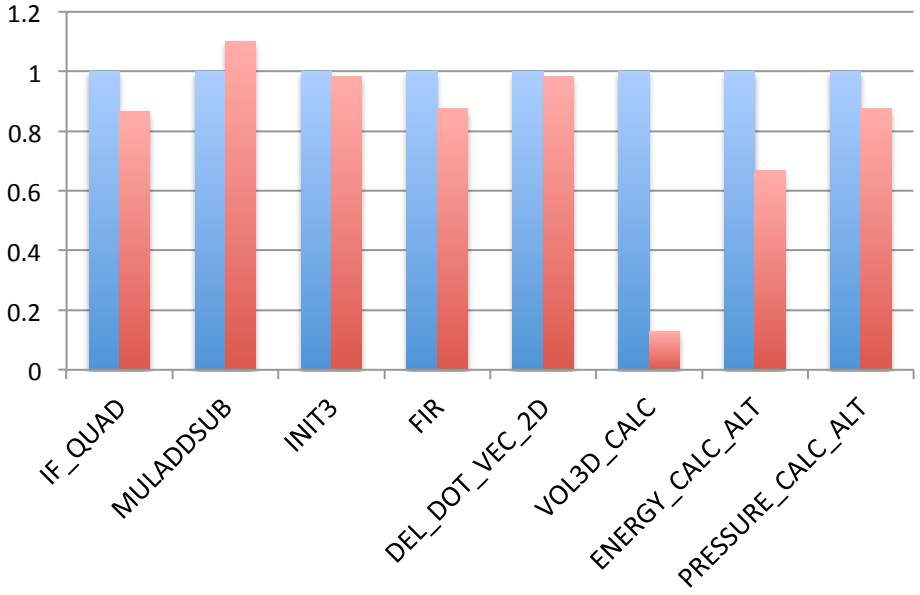
```
forall<gpu_parallel_exec>(0, len,
    [&] (int i) {
        …
    }
);
```

Results: RAJA vs. OMP

- Studied the LCALS benchmark, a collection of floating-point scientific kernels released by LLNL
- Ported to OMP4.5 and RAJA+OMP4.5
- Machine: NVIDIA Kepler K40m GPU and IBM Power8 CPU



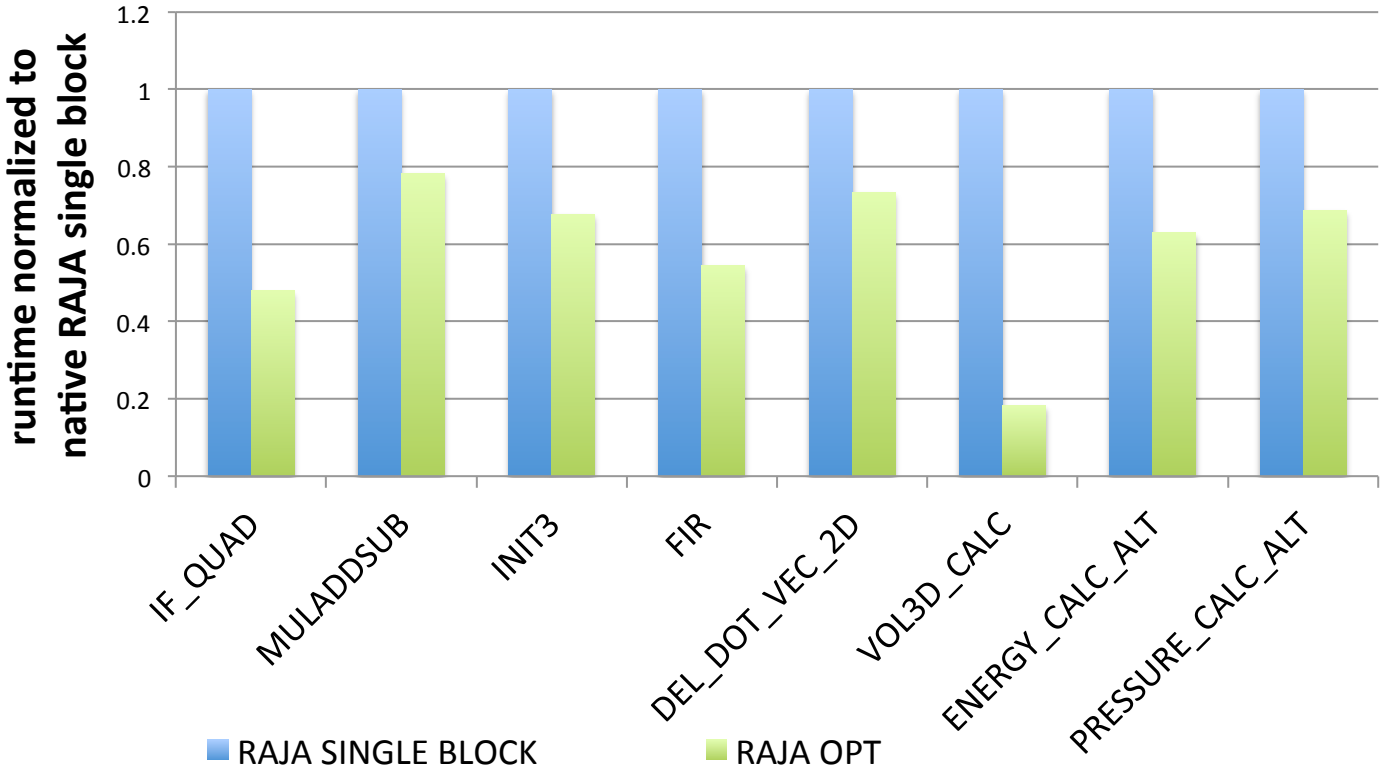
Small dataset



Large dataset

Results: Impact of GPU-specific directives

- Baseline: Single thread block
- Optimized: Multiple thread blocks, minimized overhead



LAMBDA Patterns Supported

a)

```
forall<gpu_parallel_exec>(0, len,
    [=, &c] (int i) {
        c[i] += a[i]+b[i];
    }
);
```

b)

```
forall<gpu_parallel_exec>(0, m,
    [&] (int i) {
        forall<simd_exec>(0, n,
            [&] (int j) {
                c[i*n+j] += a[i*n+j]+b[i*n+j];
            }
        );
    }
);
```

c)

```
forall<cpu_serial_exec>(0, m,
    [=] (int i) {
        forall<gpu_parallel_exec>(0, n,
            [=] (int j) {
                forall<simd_exec>(0, p,
                    [=] (int k) {
                        ....
                    }
                );
            }
        );
    }
);
```

Conclusions & Future Work

- Extended RAJA for GPU execution with OMP4.5
- Required additional support from the compiler
- High performance requires GPU-specific OMP directives and clauses, but they can be hidden in RAJA
- Focus on inner loop has performance advantages
- Explore asynchronous offloading to reduce GPU invocation overhead

- Download and install LLVM/OpenMP 4.x compiler and runtime for NVIDIA GPUs from:

www.ibm.biz/ykt-omp

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