Legion-based Scientific Data Analytics on Heterogeneous Processors

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Outline

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Motivation

- A scientific analytics workflow consists of multiple operations that intrinsically incur different communication or data movement requirements between compute nodes.
Motivation

• Legion: programming model + runtime system
  – Describe hierarchical organizations of both data and computation at an abstract level

• Legion assists a programmer in solving the common programming burdens
  – Discover/verify the correctness of parallel execution
  – Manage communication

• At a high level, mapping a Legion program needs making two kinds of decisions
  – For each task, select a processor on which to run the task by the **mapping interface**
  – For each **logical region**, a task needs to select a memory in which to create and use a physical instance of the logical region
Our Contribution

• Investigate the feasibility of using **Legion** to perform analytics for **large-scale** scientific data on **heterogeneous** processors

• Help users **simplify** programming on the **data partition, data organization, and data movement** for distributed-memory heterogeneous architectures

• Facilitate a simultaneous execution of **multiple analytics operations** on modern and future supercomputers

• Demonstrate the **scalability** and the **usability** of our approach using several representative analytics operations on a heterogeneous supercomputer
Mapper Interface

- We design a custom mapper based on Legion’s mapper interface
  - Map operations onto target processors
  - Specify which memories are used to host the physical instances of the logical regions requested by such operations
Region Construction and Task Scheduling

- Main steps of the process of our approach
  - Make an operation \( opi \) processed on heterogeneous processors

1. Construct an index space of the logical region for the input data of each operation.
2. Construct a field space of the logical region, and allocate the field space for each portion of data.
3. Create a logical region using the index space and the field space defined in the previous two steps.
4. Create a corresponding physical region to hold the physical instances (i.e., the real values for the input data).
5. Use coloring to partition a logical region (colorings are objects that describe an intended partition of an index space).
6. Execute operations on GPUs and CPUs according to the previous mapper interface we designed.
Listing 1
REGISTERING TASKS IN THE MAIN FUNCTION

```cpp
int main(int argc, char* argv[])
{
    HighLevelRuntime::set_top_level_task_id
        (TOP_LEVEL_TASK_ID);
    HighLevelRuntime::register_legion_task<
top_level_task>
        (TOP_LEVEL_TASK_ID,
            Processor::LOC_PROC, true/*single*/, false/*index*/,
            AUTO_GENERATE_ID, TaskConfigOptions(),
            "top_level");
    TaskHelper::register_gpu_variants<op_gi>();
    TaskHelper::register_epu_variants<op_ci>();
}

//TaskHelper namespace
namespace TaskHelper {
    template<typename T>
    FutureMap dispatch_task(T &launcher, Context ctx,
                              HighLevelRuntime *runtime)
    {
        FutureMap fm = runtime->execute_index_space(ctx,
                                                     launcher);
        return fm;
    }

    //CPU implementation of the operation
    template<typename T>
    void base_cpu_wrapper(const Task *task,
                          const std::vector<PhysicalRegion>&
                          regions,
                          Context ctx, HighLevelRuntime *
                          runtime)
    {
        T::cpu_base_impl(task, task->local_args, regions, ctx,
                         runtime);
    }
}
// GPU implementation of the operation

```cpp
template<typename T>
void base_gpu_wrapper(const Task *task,
                      const std::vector<PhysicalRegion> &regions,
                      T::gpu_base_impl(task, task->local_args, regions, ctx,
                                       runtime);
}
```

// register tasks on CPUs
```
template<typename T>
void register_cpu_variants(void)
{
    HighLevelRuntime::register_legion_task<base_cpu_wrapper<T>
        >(T::TASK_ID, Processor::LOC_PROC,
           false/*single*/, true/*index*/, CPU_LEAF_VARIANT,
           TaskConfigOptions(T::CPU_BASE_LEAF),
           T::TASK_NAME);
}
```

// register tasks on GPUs
```
template<typename T>
void register_gpu_variants(void)
{
    HighLevelRuntime::register_legion_task<base_gpu_wrapper<T>
        >(T::TASK_ID, Processor::TOC_PROC,
           false/*single*/, true/*index*/, GPU_LEAF_VARIANT,
           TaskConfigOptions(T::GPU_BASE_LEAF),
           T::TASK_NAME);
}
```
Examples

- **Sort-last** parallel volume rendering with entropy analysis
  - Mapper interface

```
CPU = { cpu_1,...,cpu_m }
GPU = { gpu_1,...,gpu_n }

mapper interface
```

```
CPU = { cpu_1,...,cpu_m }
GPU = { gpu_1,...,gpu_n }

mapper interface
```
Examples

- **Sort-last** parallel volume rendering with entropy analysis
  - Region construction and task scheduling
Examples

- **Sort-first** parallel volume rendering with entropy analysis
  - Mapper interface
    - Ray casting task (GPUs)
    - Entropy task (CPUs)
  - Region construction and task scheduling
    - **Divide the 2D image** into uniform 2D grids
    - Each processor is responsible for the rendering of an image portion
    - **No need to divide the 3D volume data**
    - No need image compositing

- The sort-first and sort-last algorithms have **differences on data partitioning and distribution requirements**, but our solution provides a **simple and feasible** way to incorporate different operations in a unified framework using logical regions
Experiments and Results

• Conduct experiments on Titan, a Cray XK7 supercomputer located at the Oak Ridge Leadership Computing Facility
  – Each node of Titan contains one 16-core AMD Opteron CPU and a NVIDIA Tesla K20 GPU

• Test sort-first and sort-last parallel rendering

• Conduct scalability comparisons using a combustion dataset with the resolution of 1600x1375x430

• Test between 1 to 256 processors with two output image resolutions of 1024² and 2048²
Experiments and Results

- The overview time breakdown, **data partition time**, **rendering time**, and **data movement time** on a different total number of nodes for sort-first rendering and sort-last rendering.

![Fig. 1](image1.png)

(a) The time breakdown of sort-first parallel volume rendering for different number of nodes. (b) The data partition time. (c) The rendering time. (d) The data movement time. Two output image resolutions, $1024^2$ and $2048^2$, are used.

![Fig. 2](image2.png)

(a) The time breakdown of sort-last parallel volume rendering for different number of nodes. (b) The data partition time. (c) The rendering time. (d) The image compositing time. Two output image resolutions, $1024^2$ and $2048^2$, are used.
Experiments and Results

- Interactive rendering time and data movement time of sort-first parallel rendering for 64 nodes with image resolution of $1024^2$

Fig. 3: The rendering time and data movement time of sort-first rendering for 64 nodes from multiple view angles. The output image resolution is $1024^2$. 
Experiments and Results

- The rendering time results of sort-first and sort-last parallel rendering on any number of nodes from 1 to 256 with image resolution of $1024^2$

![Rendering time for a $1024^2$ image in sort_first parallel rendering](image)

![Rendering time for a $1024^2$ image in sort_last parallel rendering](image)

Fig. 4: The time results of sort-first (a) and sort-last (b) parallel rendering on any number of nodes from 1 to 256. The output image resolution is $1024^2$. 
Experiments and Results

- Legion job stealing scheduling performance
  - CPU ray casting time is 1.347 seconds (5%)
  - CPU entropy time is 0.936 second
  - GPU ray casting time is 2.833 seconds (95%)

- Given that each node has a 16-core CPU, we tested different ratios between ray casting and entropy operations

![Fig. 5: The time results of ray casting and entropy analysis with various ratios on allocation. The output image resolution is 1024².](image)
Conclusion

• A study for conducting scientific data analytics on distributed heterogeneous architectures by leveraging the Legion programming model and runtime system

• Consider both scalability and usability in our design

• Facilitate complex analytics operations with completely different data partitioning and distribution requirements in a nearly unified manner

• Perform operations across CPUs and GPUs and balance workload by automatic or manual scheduling strategies
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Thank You!