EXECUTORS ON CUDA GRAPHS

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AGENDA

Quick Executors review
Goals for project
Kernel Executor
Graph Executor
Conclusions

Diverse Libraries

`sort(...)` `for_each(...)`

`sgemm(...)` `train_network(...)`

`your_favorite_library_function(...)`

Multiplicative Explosion

✖

Diverse Resources

Operating System Threads

Thread pool schedulers

OpenMP runtime

SIMD vector units

GPU runtime

Fibers

Diverse Libraries	`sort(...)` `for_each(...)` `sgemm(...)` `train_network(...)` `your_favorite_library_function(...)`	
Uniform Abstraction	Executors	
Diverse Resources	Operating System Threads SIMD vector units	Thread pool schedulers GPU runtime OpenMP runtime Fibers

EXECUTORS

Like allocators for threads

Abstraction for creating threads*

Programmers need to control where applications execute

- Locality is critical to performance

Programmers need a uniform interface

- Dealing with multiple different execution APIs is complicated
- A single API organizes things

GRAPHS EXPLORATION

Project goals

Explore how to target graph runtimes (esp. CUDA Graphs) from Executors API

Explore Executors usage within a large application

- QMCPACK: Open-source quantum chemistry simulator

Explore “Senders & Receivers”

- C++ proposal for lazy execution on Executors
- wg21.link/P1194

Non-goal: Did not want to focus on the design an explicit graph abstraction

PROTOTYPE

Two executors

`kernel_executor`

- Implemented with traditional CUDA kernel launches
- Eager

`graph_executor`

- Implemented with CUDA graphs
- Associated ensemble of "Senders"
- Lazy

kernel_executor

Abstracts kernel launches

```
// a cuda_context owns resources
cuda_context ctx;

// get a CUDA stream from somewhere
cudaStream_t stream = ...

// create a kernel_executor
kernel_executor ex(ctx, stream);

// launch a kernel
ex.bulk_execute(...);

// wait for all kernels to finish
ex.wait();
```

kernel_executor

Launching kernels

```
grid_index shape = ...

ex.bulk_execute([] __device__ (grid_index idx, ...)
{
  int block_idx = idx[0].x;
  int thread_idx = idx[1].x;

  printf("Hello world from thread %d in block %d\n", thread_idx, block_idx);
},
shape,
...
);
```


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kernel_executor

Launching kernels

```
grid_index shape = ...

ex.bulk_execute([] __device__ (grid_index idx, int& grid_shared, int& block_shared)
{
  int block_idx = idx[0].x;
  int thread_idx = idx[1].x;

  printf("Hello world from thread %d in block %d\n", thread_idx, block_idx);
},
shape,
[] __host__ __device__ { return 42; }, // single variable shared by all threads
[] __host__ __device__ { return 13; } // shared variable per block of threads
);
```

graph_executor

Abstracts CUDA graphs

```
// get a CUDA stream from somewhere
cudaStream_t stream = ..

// create a graph_executor from the stream
graph_executor ex(stream);

// the root of the graph
void_sender root_node;

// make a kernel launch depend on the root
kernel_sender kernel = ex.bulk_then_execute(..., root_node);

// submit the kernel for execution
kernel.submit();

// wait for the kernel to finish
kernel.sync_wait();
```

`graph_executor`

A sender factory

Each method of `graph_executor` produces a different type of Sender targeting CUDA graphs

- `kernel_sender` ⇒ `cudaGraphAddKernelNode`
- `copy_sender` ⇒ `cudaGraphAddMemcpyNode`
- `host_sender` ⇒ `cudaGraphAddHostNode`

Senders represent nodes in a lazy task graph

- Mediate dependencies
- “Sends” its result down to its children

Senders are lazy

- Task description is separate from task submission

LAZY EXECUTION

Separating work description from submission

Proceeds in two* stages

Description: `executor.bulk_then_execute()` et al.

- Interacts with Senders to lazily describe work

Submission: `sender.submit()`

- Traverses sender DAG and communicates work to CUDA Graphs API
- Instantiates graph
- Launches graph

host_then_execute

Example executor implementation

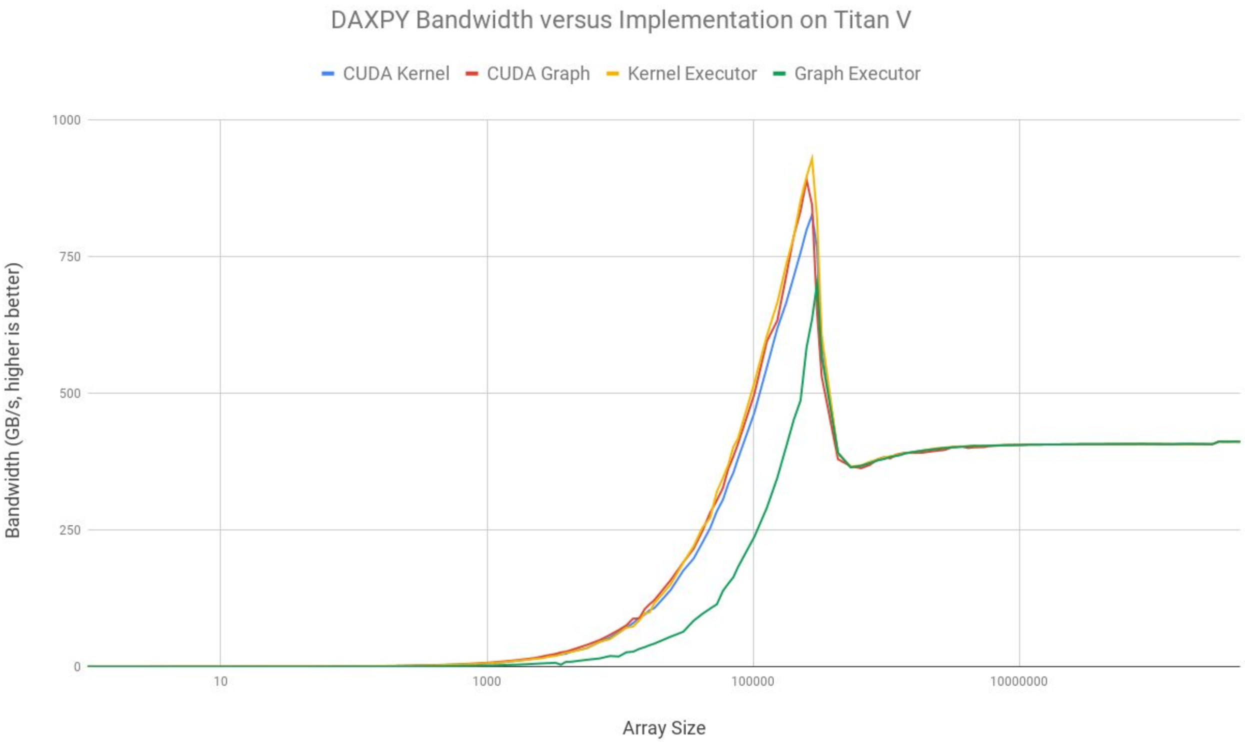
```
class graph_executor {
  private:
    cudaStream_t stream() const;
    ...

  public:
    template<class Function, class Sender>
    host_sender host_then_execute(Function f, Sender& predecessor) const {
      auto node_parameters_function = [=]()
      {
        // package f into parameters for the host node
        cudaHostNodeParams result = ...

        return result;
      };

      return host_sender{stream(), node_parameters_function, std::move(predecessor)};
    }
    ...
};
```

host_sender

Example sender implementation

```
class host_sender {
  private:
    std::function<cudaHostNodeParams()> node_params_function_;
    any_sender predecessor_;

    ...

  protected:
    cudaGraphNode_t insert(cudaGraph_t g) const {
      // insert the predecessor
      cudaGraphNode_t predecessor_node = predecessor_.insert(g);

      // generate the node parameters
      cudaHostNodeParams node_params = node_params_function_();

      // introduce a new host node
      cudaGraphNode_t result_node{};
      cudaGraphAddHostNode(&result_node, g, &predecessor_node, 1, &node_params);

      return result_node;
    }
};
```

OVERHEAD



DAXPY Bandwidth versus Implementation on Titan V
CUDA Kernel
CUDA Graph
Kernel Executor
Graph Executor
1000
750
500
250
0
Bandwidth (GB/s, higher is better)
10
1000
100000
10000000
Array Size

CONCLUSIONS

Enhancement opportunities

CUDA Graphs

- No memory management
- No deferred parameters
- Leads to out-of-band communication

Senders & Receivers

- Two-stage is awkward for systems like CUDA Graphs
- No support for replay
- Not clear how Receivers would leverage systems like CUDA Graphs

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