Groute: An Asynchronous Multi-GPU Programming Model for Irregular Computations

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Overview

Motivation

- Prevalent method of multi-GPU programming: **Bulk Synchronous Parallel (BSP)**
  - Local computation $\rightarrow$ global communication
  - Underutilization particularly for irregular applications
  - Due to load imbalance and unpredictable communication
- **Asynchronous** programming models to the rescue
  - Processors can compute and communicate autonomously
  - Overlap computation and communication
  - But requires in-depth knowledge of underlying architecture and network

Goals

- Asynchronous programming model + runtime environment
- Provide communication constructs to efficiently express both regular and irregular programs
- Promote load balancing for heterogeneous GPUs
- Outperform existing state-of-the-art implementations (Gunrock, B40C)

Multi-GPU Architecture

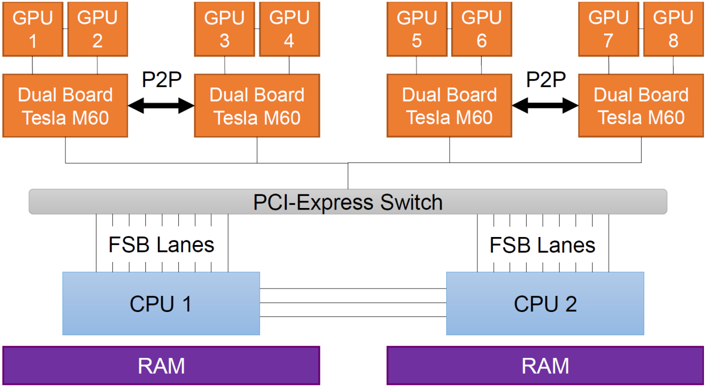


Figure: Multi-GPU Node Schematic[1]

[1]All figures were taken from the paper

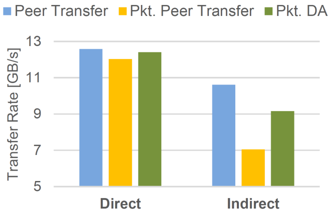
Inter-GPU Communication

- **Peer transfer**
  - Host-initiated
  - Executed explicitly
- **Direct access (DA)**
  - Device-initiated
  - Implemented with virtual addressing
  - Performance sensitive to alignment, coalescing, order of access
  - May not be available between all pairs of GPUs

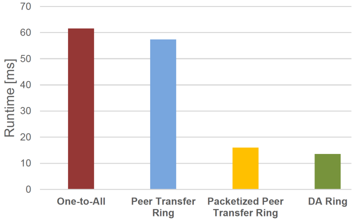
Packetization

- GPUs can only transmit to one destination at a time
- Hinders **responsiveness** of an asynchronous system, especially with large buffers
- Divide messages into **packets**
- Also used in collective communication
- But overhead exists

Packetization



(c) Packetized transfer rate



(d) Peer broadcast performance

Figure: Inter-GPU Memory Transfer Benchmarks

Groute Programming Model

- Dataflow graph construction + asynchronous computation
- **Endpoint:** a physical device (CPU/GPU) or a router
- **Router:** connects endpoints for dynamic communication
- **Link:** connects two endpoints
- **Routing policy** determines how routers behave

Example: Predicate-Based Filtering

- Filter data based on some condition (i.e. predicate)
- E.g. With a number of particles as input data, give me all the particles whose mass is larger than some threshold

Example: Predicate-Based Filtering

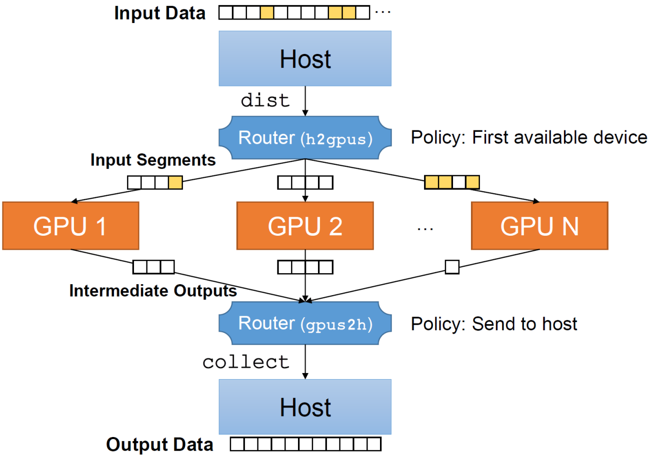


Figure: PBF Dataflow Graph

Example: Predicate-Based Filtering

```
std::vector<T> input = ...;
std::vector<T> output;
int packet_size = ...;

Context ctx;
auto all_gpus = ctx.devices();
int num_gpus = all_gpus.size();

Router h2gpus(1, num_gpus, AnyDevicePolicy);
Router gpus2h(num_gpus, 1, AnyDevicePolicy);

Link dist    (HOST, h2gpus, packet_size, 1);
Link collect (gpus2h, HOST, packet_size, 2);

for (device_t dev : all_gpus) {
  std::thread t(WorkerThread,
                Link(h2gpus, dev, packet_size, 2),
                Link(dev, gpus2h, packet_size, 2));
  t.detach();
}

dist.Send(input, input_size);
dist.Shutdown();

while(true) {
  PendingSegment output_seg = collect.Receive().get();
  if(output_seg.Empty()) break;
  output_seg.Synchronize();
  append(output, output_seg);
  collect.Release(output_seg);
}
//--------------------------------------------------------
```

```
EndpointList AnyDevicePolicy(
    const Segment& message, Endpoint source,
    const EndpointList& router_dst) {
  return router_dst;
}

void WorkerThread(device_t dev, Link in, Link out) {
  Stream stream (dev);
  T *s_out = ...;
  int *out_size = ...;

  while(true) {
    PendingSegment seg = in.Receive().get();
    if(seg.Empty()) break;
    seg.Synchronize(stream);
    Filter<<<...,stream>>>(seg.Ptr(), seg.Size(),
                           s_out, out_size);
    in.Release(seg, stream);
    out.Send(s_out, out_size, stream);
  }
  out.Shutdown();
}
```

Figure: PBF Pseudocode

Distributed Worklists

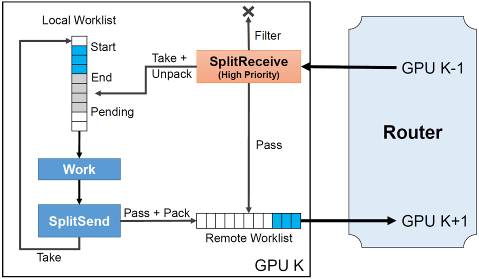


Figure: Distributed Worklist Implementation

- Global list of computations (work-items) to process
- Each item may generate new items
- Requires all-to-all communication

Distributed Worklists

- SplitReceive
  - Controlled by receive thread
  - High priority for responsiveness
  - Filter/take/pass
- Local worklist
  - Controlled by worker thread
  - Lock-free circular buffer
  - Newly generated work $\rightarrow$ local worklist or remote worklist
- Remote worklist: send to next GPU

Soft Priority Scheduling

- Stale information may be propagated due to asynchrony
- Can generate additional intermediate work
- Example: Asynchronous BFS
  - Path with least number of edges is located on a lagging device
  - ”Incorrect” path will be used to traverse the graph
  - After the lagging device completes, all traversed values will be recomputed
- Solution: assign **soft priorities** to each work-item
  - Defer items suspected to generate ”useless work”
  - Decreases amount of intermediate work

Kernel Fusion

- Small kernels cause underutilization and increases communication overhead
- Augment worker kernel to include entire control flow and communication with host and other GPUs
- Includes
  - Determining work-item priorities
  - Processing a batch of work-items in local worklist
  - Running SplitSend
- Decreases kernel launch overhead in high-diameter graphs
- Reduces CPU-GPU roundtrips

Performance Evaluation

1. Breadth-First Search (BFS)
2. Single-Source Shortest Path (SSSP)
3. PageRank (PR)
4. Connected Components (CC)

- Compared to **Gunrock** and **Back40Computing (B40C)**
  - Gunrock: multi-GPU graph analytics library using BSP
  - B40C: state-of-the-art hardcoded BFS
- Evaluated on multiple graphs

Graphs

Name	Nodes	Edges	Avg. Degree	Max Degree	Size (GB)
Road Maps					
USA [1]	24M	58M	2.41	9	0.62
OSM-eur-k [3]	174M	348M	2.00	15	3.90
Social Networks					
soc-LiveJournal1 [10]	5M	69M	14.23	20,293	0.56
twitter [8]	51M	1,963M	38.37	779,958	16.00
Synthetic Graphs					
kron21.sym [5]	2M	182M	86.82	213,904	1.40

Figure: Graph Properties

- Avg/max degrees vary significantly
- Partitioned using METIS, except *kron21.sym* and *twitter*

Evaluation Environment

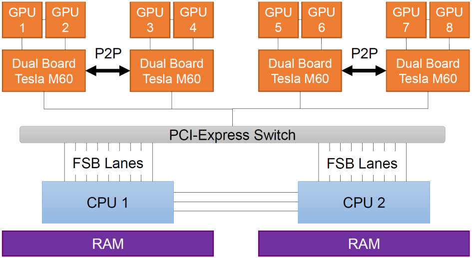


Figure: Multi-GPU Node Schematic

- 8-GPU server of 4 dual-board NVIDIA Tesla M60 cards
- 2 8-core Intel Xeon E5-2630 v3 CPUs
- 2 QPI links per CPU for PCI-E switch

Strong Scaling

- In communication intensive algorithms (BFS, SSSP), bus topology starts to affect performance when more than the single 4-GPU quadruplet is used
- Groute mitigates these issues but can still be seen in high-degree graphs such as *soc-LiveJournal1*

Breadth-First Search (BFS)

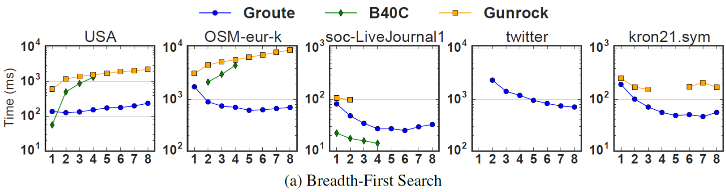


Figure: BFS Execution Time

- B40C
  - Requires direct memory access to all GPUs
  - No METIS partitioning
  - Failed on *twitter* and *kron21.sym*
- Gunrock
  - Ran out of memory on *twitter*
  - Produced incorrect results on *kron21.sym* and *soc-LiveJournal1*

Breadth-First Search (BFS)

- Groute significantly outperforms Gunrock in road networks due to kernel fusion
- B40C is faster on soc-LiveJournal1 as it contains a hybrid implementation that switches between kernels
  - Not implemented by Groute due to its highly specialized nature

Single-Source Shortest Path (SSSP)

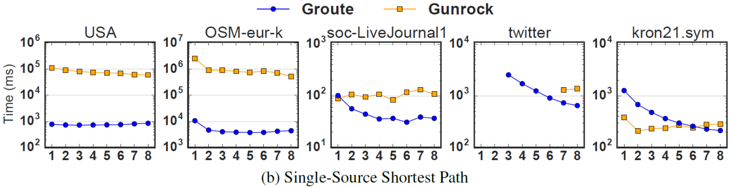


Figure: SSSP Execution Time

- Groute outperforms Gunrock in all cases except *kron21.sym*
- Asynchrony causes an inflation in number of atomic operations

PageRank (PR)

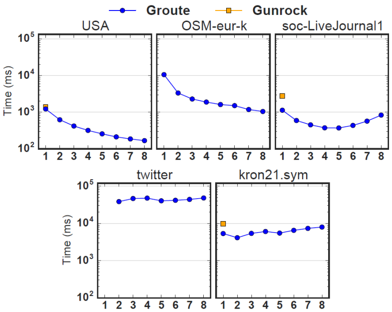


Figure: PR Execution Time

- Computationally intensive, unlike BFS and SSSP
- Groute outperforms Gunrock on all graphs
- Best scaling achieved with a high ratio of computation to communication (low-degree graphs)

Connected Components (CC)

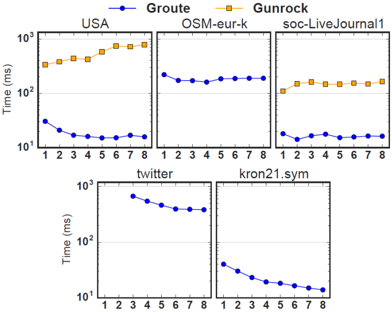


Figure: CC Execution Time

- Topology-driven, not worklist-driven
- Outperforms Gunrock on all counts
- Less memory consumption from not using worklists
- Gunrock runs out of memory

Conclusion

- A robust asynchronous multi-GPU programming model coupled with a runtime environment
- Expressive set of communication primitives capable of expressing both regular and irregular applications
- Outperforms existing graph analytics frameworks

Comments & Discussion

- Requires the programmer to explicitly implement threading (as in pseudocode)
- Limited to a single shared-memory node
- Lacks comparison to CPU-based implementations
- Will the ring topology be scalable in a distributed memory setting?
- All-to-all communication for distributed worklists likely to be a scalability bottleneck
- Soft priority scheduling: how do we know if items are likely to generate ”useless work”?
- Load balancing policy described in the paper is basically ’first available device’; how dœs Groute adapt to changing load during runtime? (E.g. imbalance in the number of generated work-items per GPU)

Thank You