Task-Based Parallel Programming in Legion

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Acknowledgments

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Tutorial Materials

The slides, example program, and performance profiles are at:

http://theory.stanford.edu/~aiken/ecp

OVERVIEW

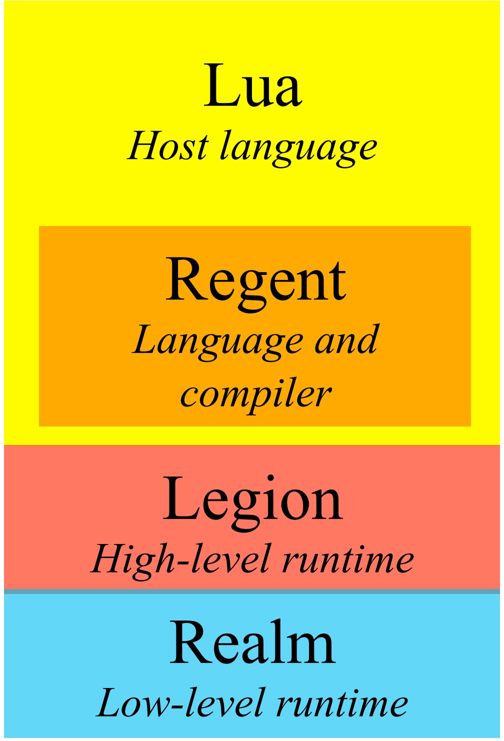
Legion & Regent

- *Legion* is
  - a C++ runtime
  - a programming model
- *Regent* is a programming language
  - For the Legion programming model
  - Current implementation is embedded in Lua
  - Has an optimizing compiler
- This tutorial focuses on Regent

Why Use Legion?

- Easy access to GPUs
  - Simplifies programming complex hardware
- Easy control over data
  - Partitioning, placement and layout in memory
- Automated scheduling and latency hiding
  - Asynchronous tasking
  - Throughput oriented
- Performance portability

Regent Stack



Regent in Lua

- Embedded in Lua
  - Popular scripting language in the graphics community
- Excellent interoperation with C
  - And with other languages
- Python-ish syntax
  - For both Lua and Regent

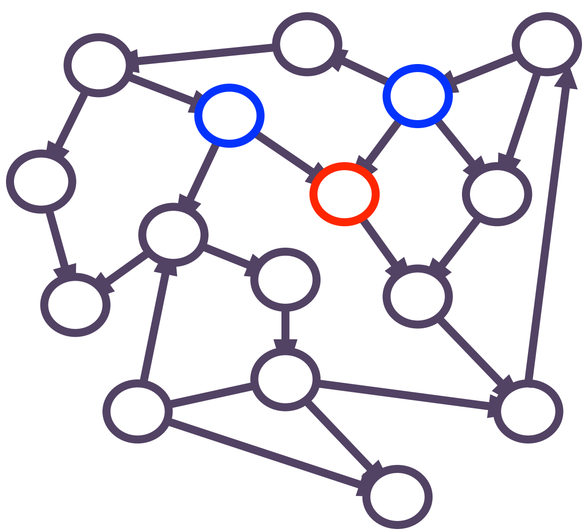
PAGERANK

PageRank

- Today's example
- Input: A directed graph.
- Output: The *rank* of each node
  - A measure of a node's importance
  - E.g., used for ranking web search results
    - Web pages are nodes
    - Hyperlinks are edges

PageRank Equation

rank(n) = (1 – α)/N + α × Σ p ε pred(n). rank(p)/|succs(p)|



TASKS

The PageRank Task

```
task pagerank(nodes: region(…), edges: region(…),
              pr_old: region(…), pr_new:region(…), alpha: float)
{



}
```

Tasks are the unit of parallel execution.

Logical regions are (typed) collections

Logical:
- no implied layout
- no implied location

The PageRank Task

```
task   pagerank(nodes: region(…), edges: region(…),
                 pr_old: region(…), pr_new:region(…), alpha: float)
{

}
```

The PageRank Task

```
task   pagerank(nodes: region(…), edges: region(…),
                   pr_old: region(…), pr_new:region(…), alpha: float)
  where reads(nodes, edges, pr_old), writes(pr_new)
{

}
```

Privileges declare how a task will use its region arguments.

The PageRank Task

```
task   pagerank(nodes: region(…), edges: region(…),
                       pr_old: region(…), pr_new:region(…), alpha: float)
    where reads(nodes, edges, pr_old), writes(pr_new)
 {

   …
   for n in nodes do
        …
        score = 0
        for e in left, right do   -- indices of predecessor edges of n
            …
            score = score + pr_old[edges[e].src]
        end
        …
        score = (1 – alpha) / num_nodes + alpha * score
        pr_new[n] = score / out_degree
    end
}
```

REGIONS

Regions

- **A region is a (typed) collection**

- **Regions are the cross product of**
  - **An *index space***
  - **A *field space***

The region's field space

The region's index space

EDGES

	src	dst
0	a	x
1	b	x
2	c	x
3	a	y

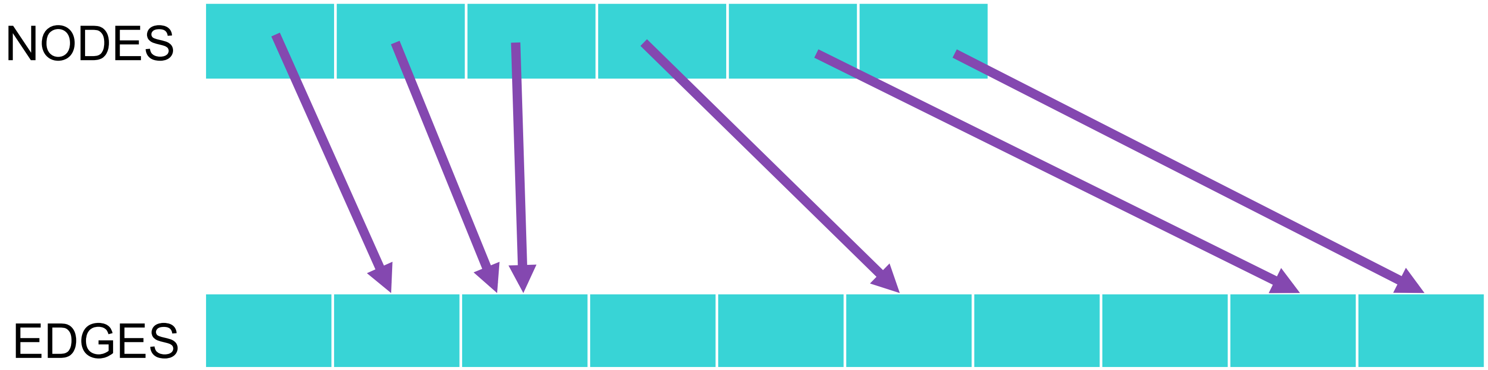
The edges region is constructed so that edges are grouped by dst node

Discussion

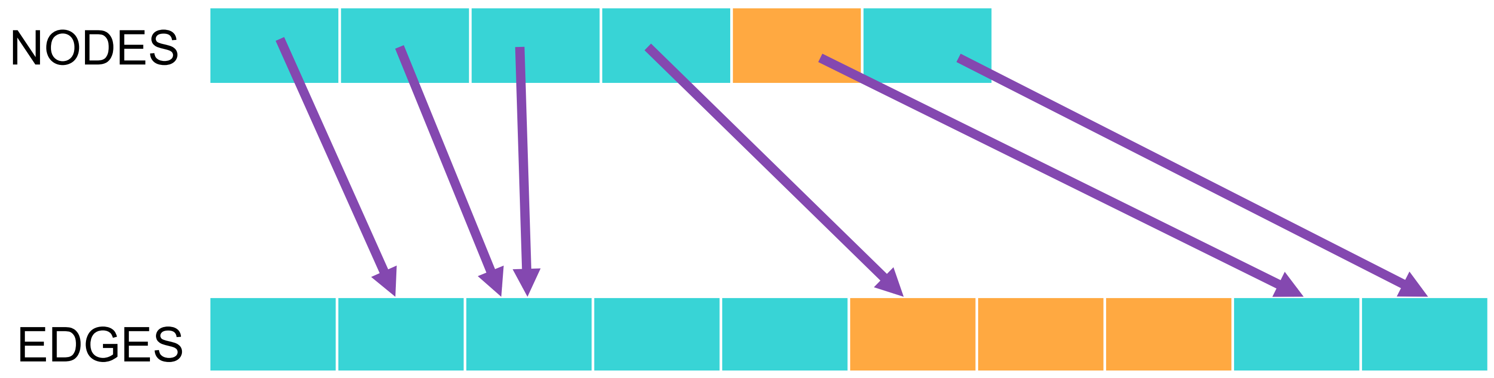
- Regions are *the* way to organize large data collections in Regent
- Regions can be
  - Structured (e.g., like arrays)
  - Unstructured (e.g., pointer data structures)
- Any number of fields
- Built-in support for multidimensional index spaces

Nodes & Edges

Nodes have two fields: out_degree *and* index



Nodes & Edges



A node's index field points just beyond its last predecessor edge.

PAGERANK TASK

PARTITIONING

Partitioning

- To enable parallelism on a region, *partition* it into smaller pieces
  - And then run a task on each piece
- Partitioning is built in to Legion/Regent
  - A rich set of partitioning primitives
- Use the primitives to build partitioning algorithms

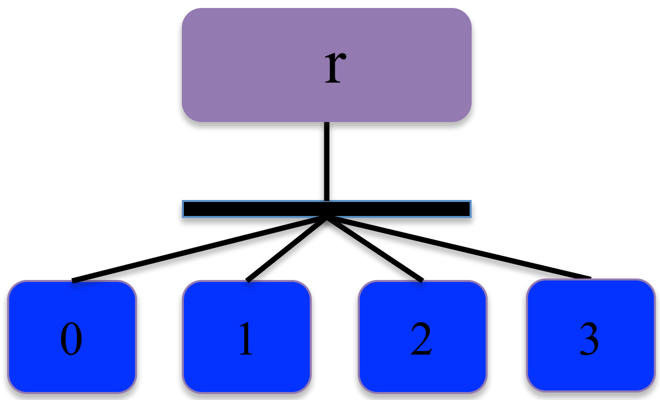
Equal Partitions

- One commonly used primitive is to split a region into a number of (nearly) equal size *subregions*

```
num_pieces = ispace(int1d, 4)
r = region(ispace(int1d, 12), int64)

p = partition(equal, r, num_pieces)
```

Region Trees

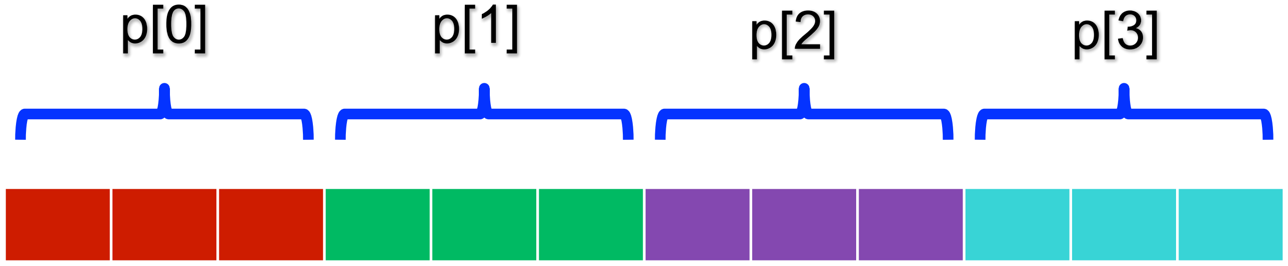


The Legion runtime knows and uses the region tree to manage mapping and automate parallelism and data movement.

Partitions

- **Partitions are first class objects**
- **An array of the subregions formed by a partition**

p = partition(equal, r, num_pieces)



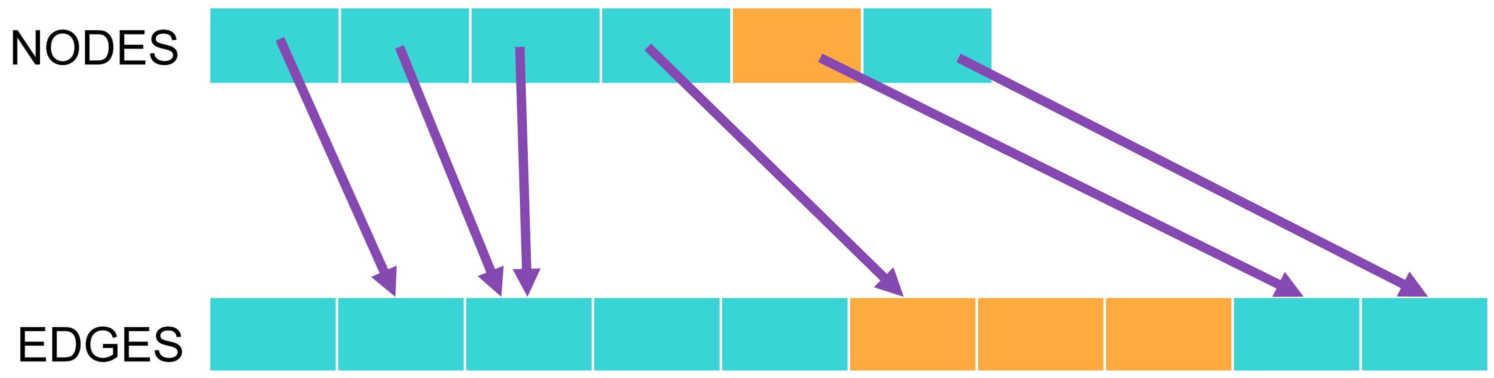
Discussion

- Partitioning and region creation are dynamic
  - Can be done at any time
  - Regions and partitions are first class values
- Regions trees can be any depth
  - Subregions can be partitioned, too
- Regions can be partitioned in multiple ways
  - A program can define multiple views of its data
- Defining regions/partitions does not materialize them
  - Gives names to subsets of the data
  - Actual computations access *physical instances* of regions

Partitioning Strategy for PageRank

- **Use *edge* partitioning**
  - **Approximately equal number of edges per subregion**
  - **Better than node partitioning if nodes can have very different out degrees**
- **But**
  - **Keep all predecessor edges of a given node in the same subregion**
- **So**
  - **Calculate the range of edges for each subregion**
  - **Partition the edges by range**
  - **Partition the nodes compatibly with the edge partition**

Nodes & Edges



a node's index field points just beyond its last predecessor edge

First Step: Calculate Edge Ranges

```
task init_partition( edge_range : region(ispace(int1d),rect1d),
                     edges : region(ispace(int1d), EdgeStruct),
                     avg_num_edges : E_ID,
                     num_parts: int)
where writes(node_range, edge_range), reads(nodes)
do
…
  for p = 0, num_parts do
    right_bound = min(avg_num_edges * (p + 1), total_num_edges)
    var my_dst: V_ID = edges[right_bound].dst
    -- extend the right bound to the last edge of the current node
    while (right_bound < total_num_edges) do
      var next_dst : V_ID = edges[right_bound+1].dst
      if (my_dst<next_dst) then break end
      right_bound = right_bound + 1
     end
     edge_range[p] = {left_bound, right_bound}
  end
```

DEPENDENT PARTITIONING

Partitioning, Revisited

- Why do we want to partition data?
  - For parallelism
  - We will launch many tasks over many subregions
- A problem
  - We often need to partition multiple data structures in a consistent way
  - E.g., given that we have partitioned the nodes a particular way, that will dictate the desired partitioning of the edges

Dependent Partitioning

- Distinguish two kinds of partitions

- *Independent partitions*
  - Computed from the parent region, using, e.g.,
    - partition(equals, …)

- *Dependent partitions*
  - Computed using another partition

Dependent Partitioning Operations

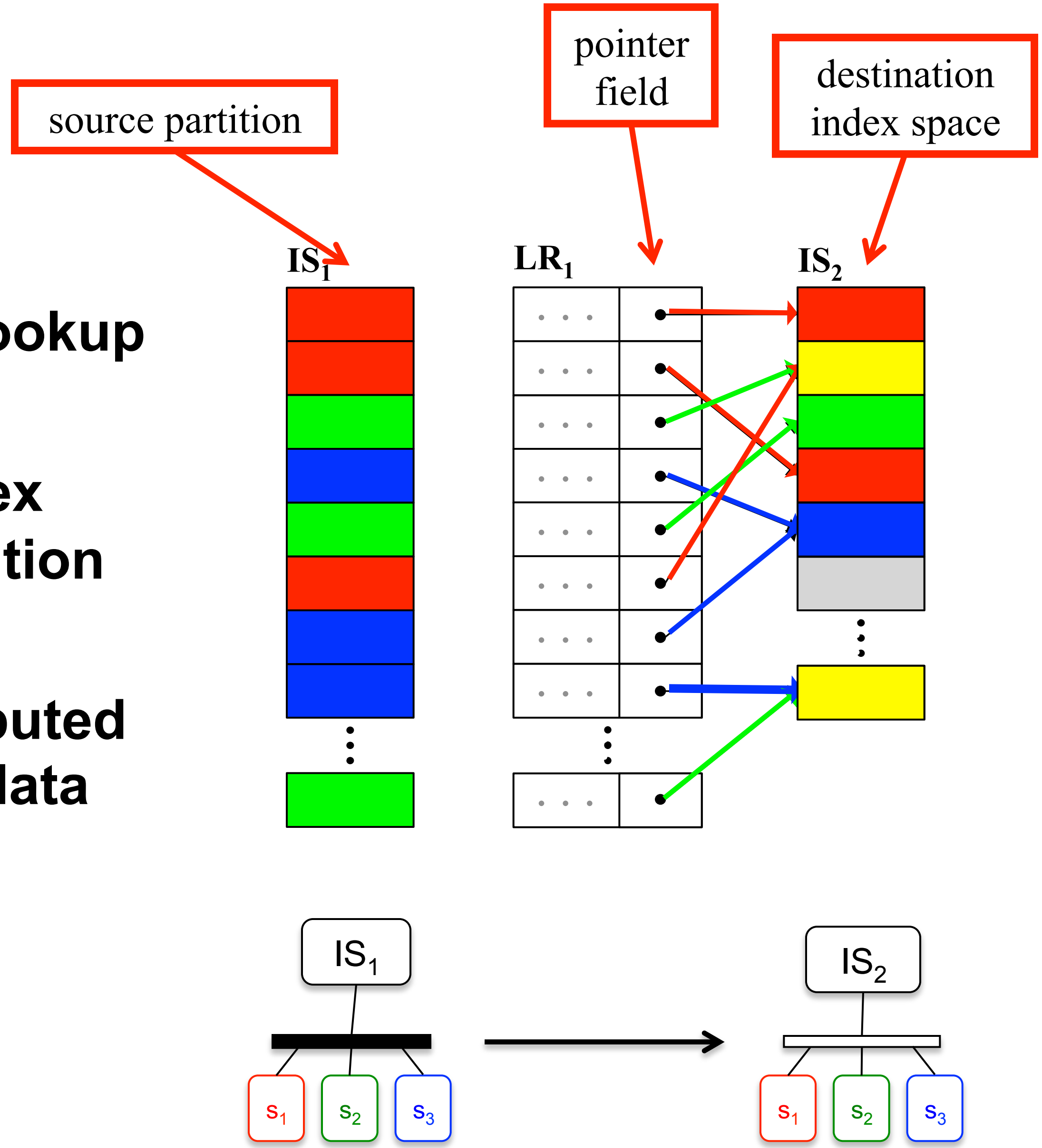
- Image
  - Use the image of a partition to define a new partition
  - E.g., the image of a field
  - E.g., or a range of values
- Preimage
  - Use the pre-image of a field in a partition …
- Set operations
  - Form new partitions using the intersection, union, and set difference of other partitions
  - Not illustrated today

Image

- Computes elements reachable via a field lookup

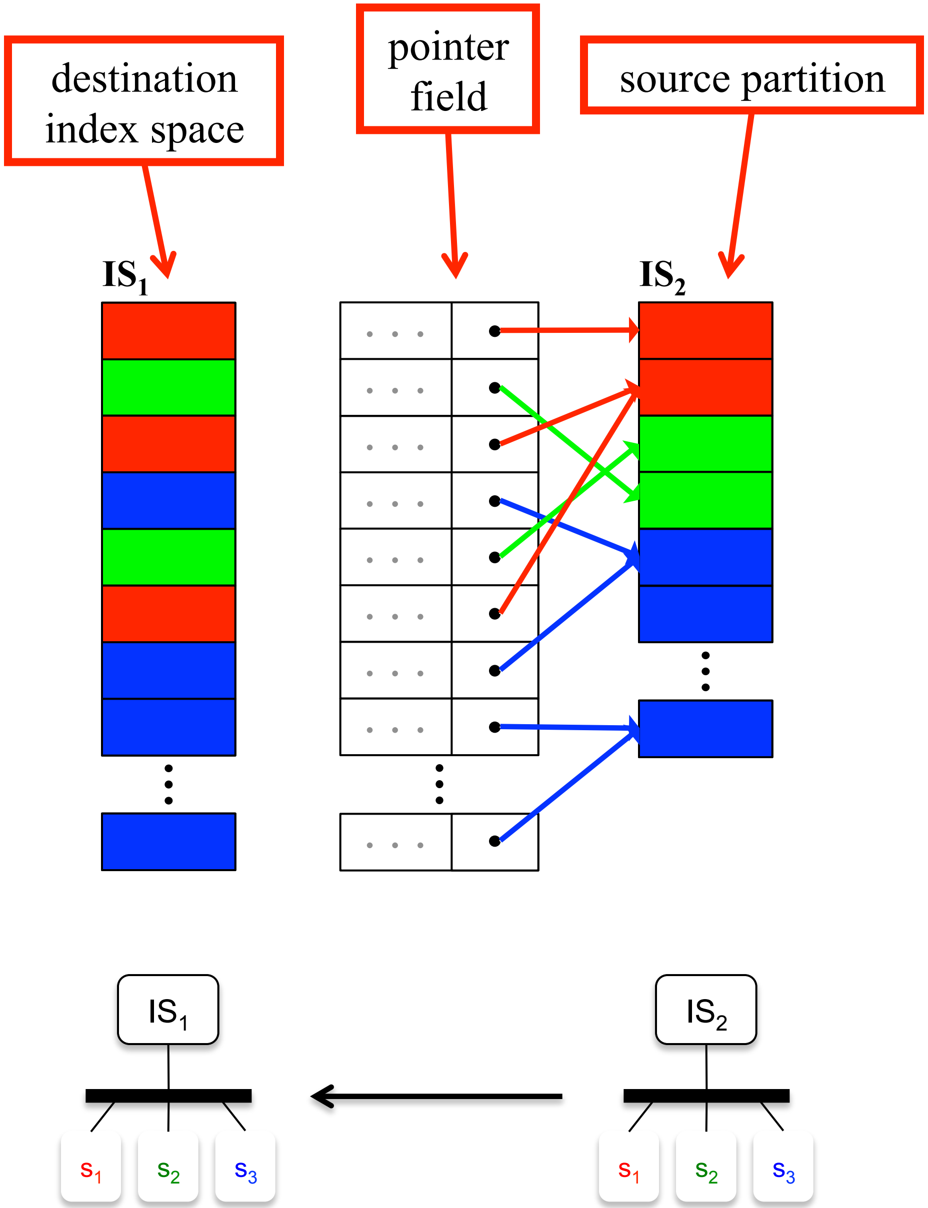
- Can be applied to index space or another partition

- Computation is distributed based on location of data



Preimage

- Inverse of image
  - Computes elements that reach a given subspace
  - Preserves disjointness
- Multiple dependent partitioning operations can be combined
  - Capture complex task access patterns



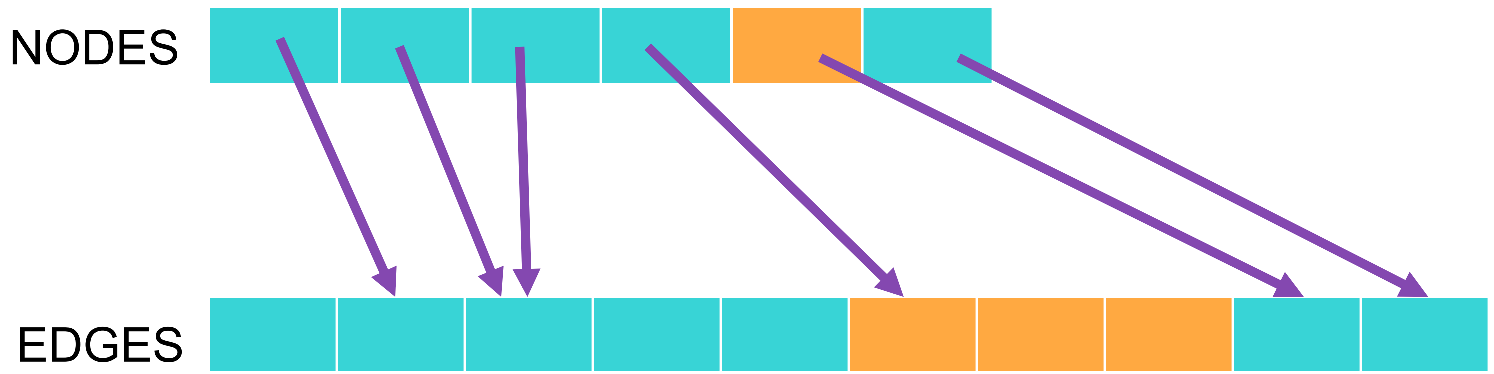
Dependent Partitioning in PageRank

- The use of dependent partitioning in PageRank is simple

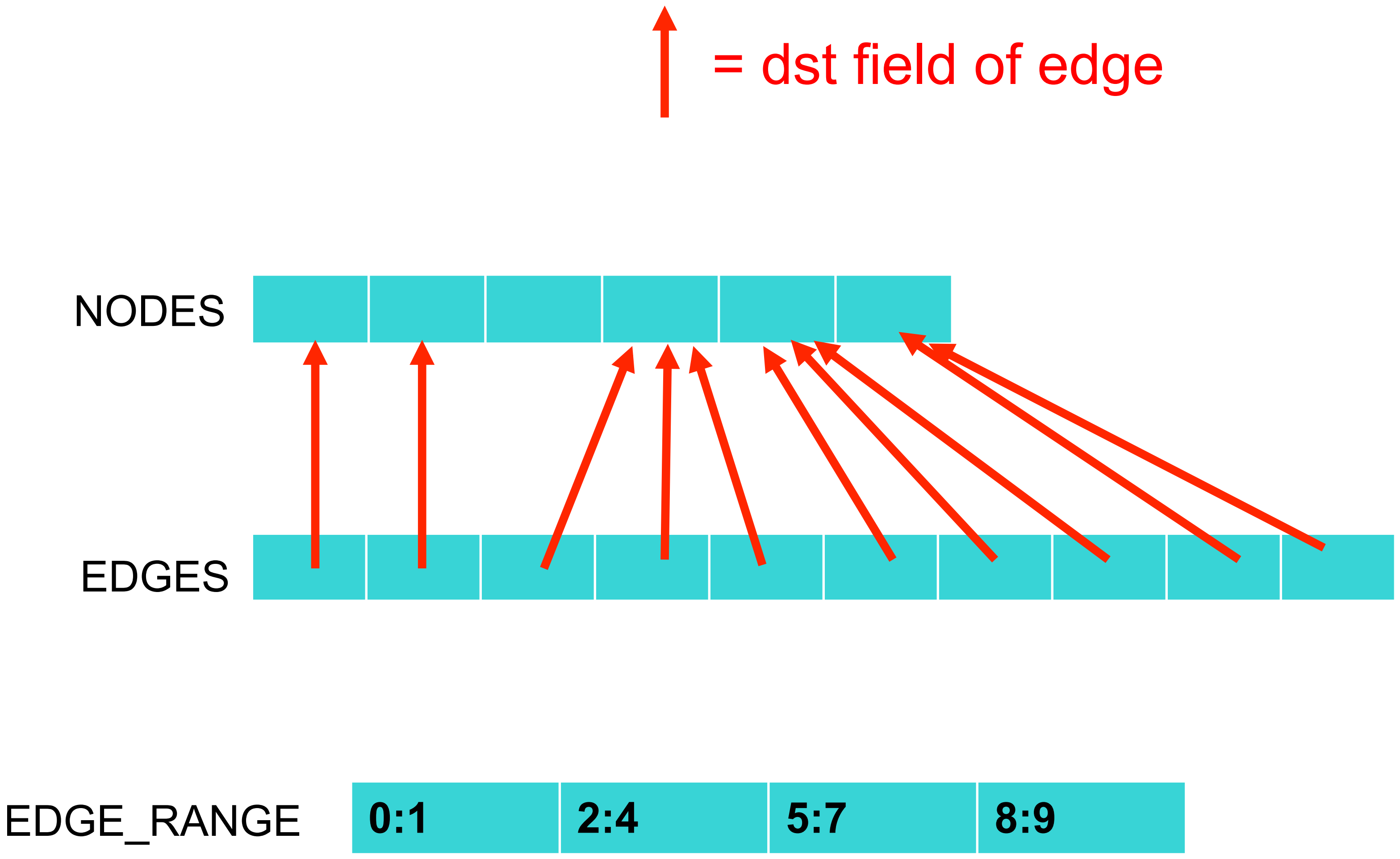
- Define a partition of the edges
  - Using the computed edge ranges

- Then define a partition of the nodes using the destination node of each edge

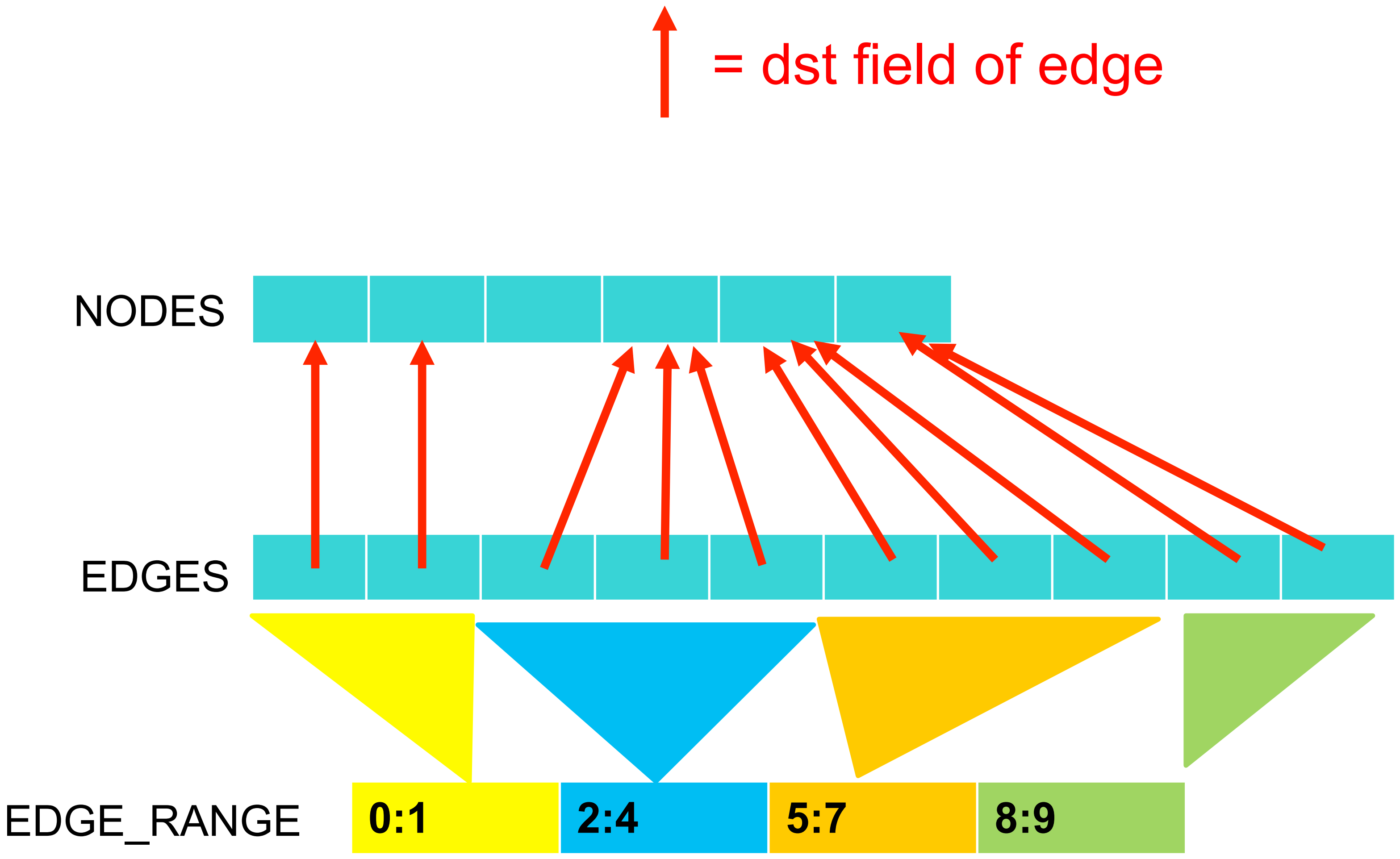
Picture (Reminder)



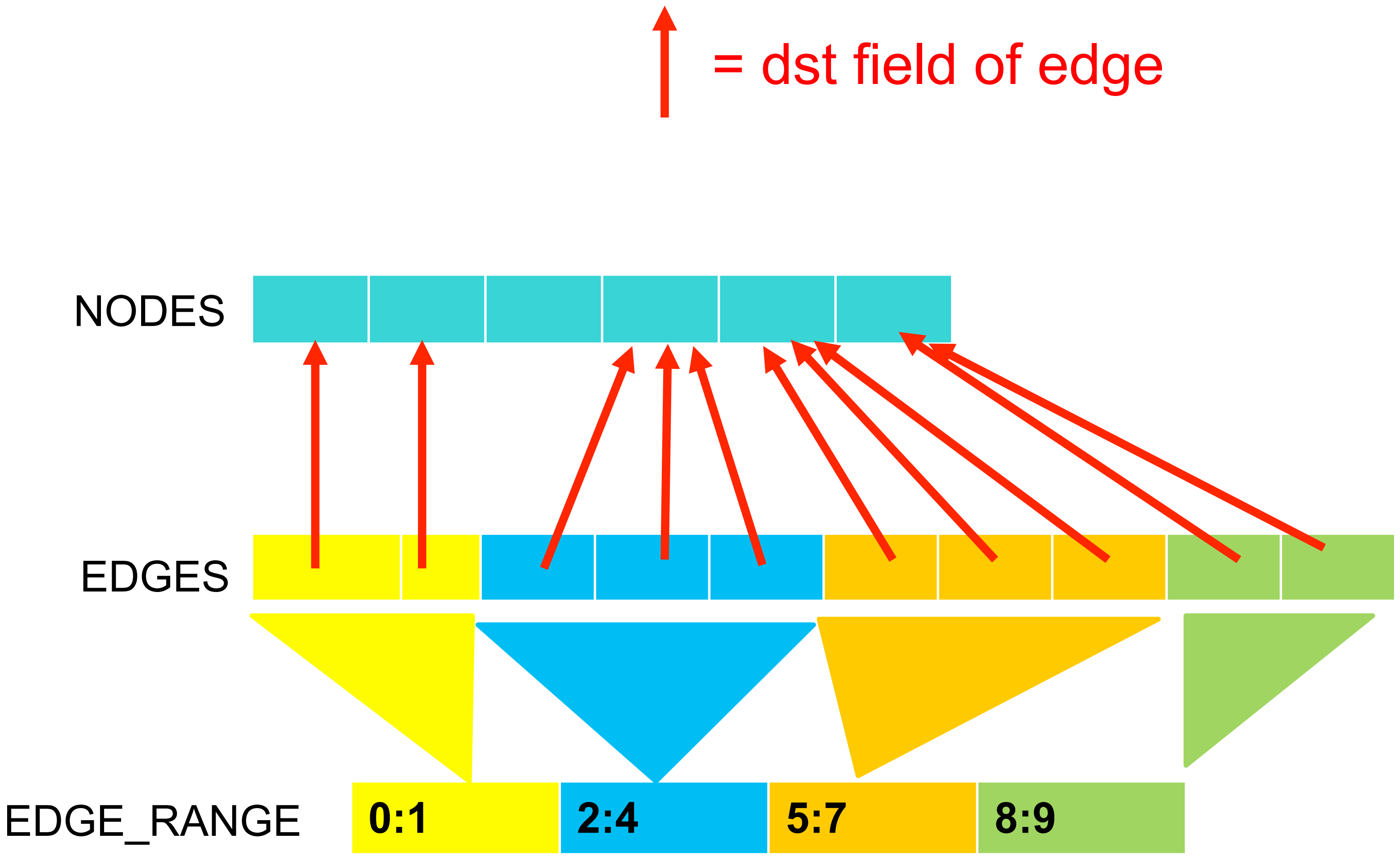
Picture



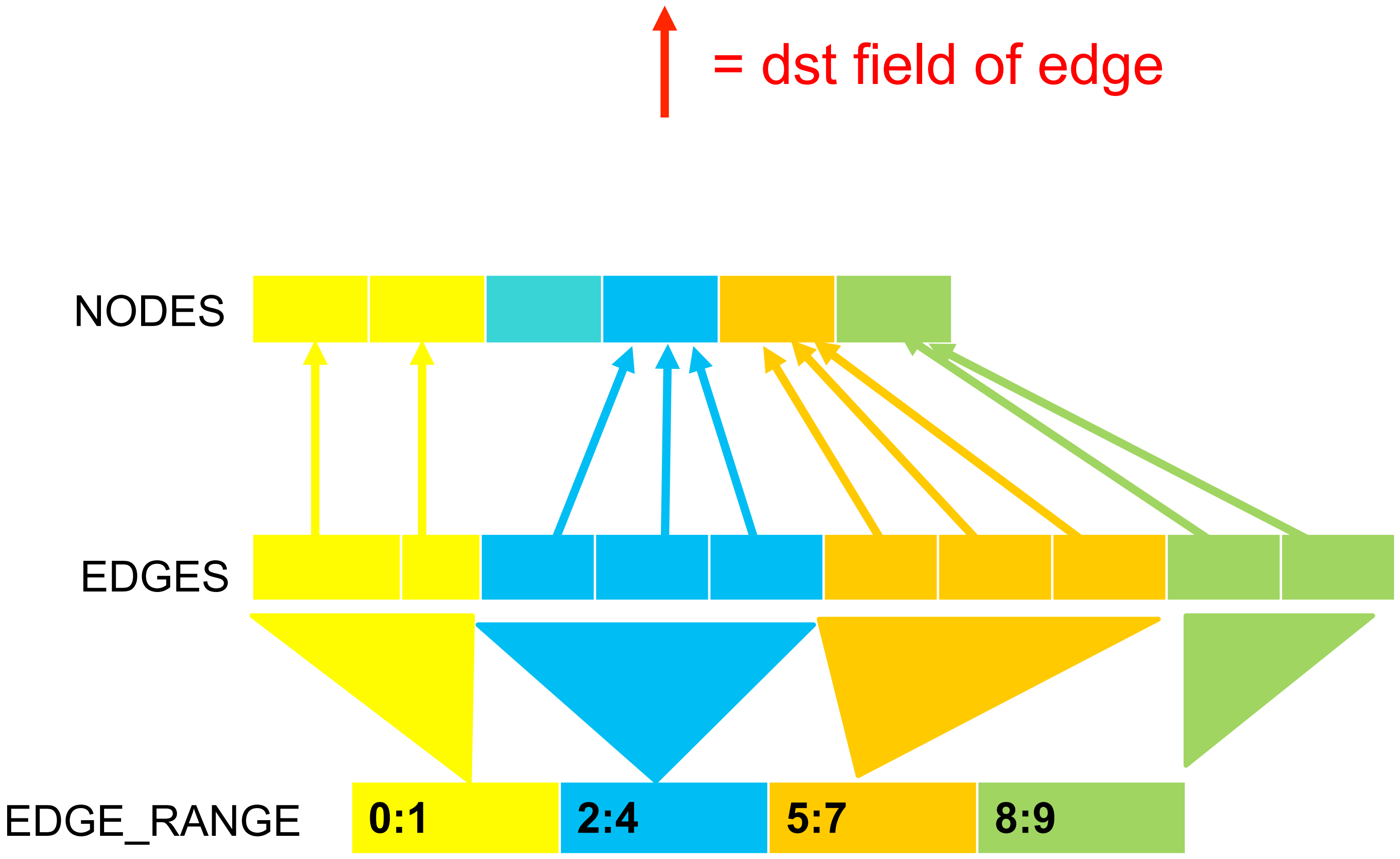
Picture



Picture



Picture



PAGERANK MAIN

PARALLELISM

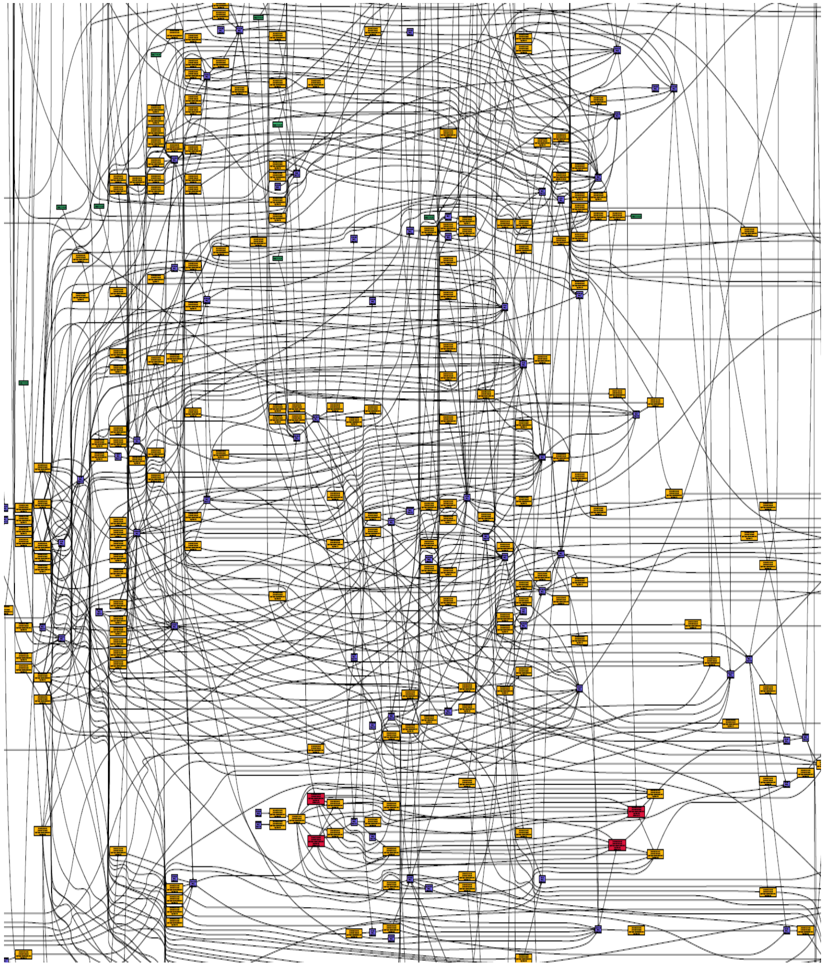
Program Semantics

- A Legion program is a sequence of task launches
- The runtime analyzes the tasks for *interference*
  - Tasks with conflicting accesses to the same data
  - Non-interfering tasks can execute in parallel
  - Interfering tasks are serialized
- Guarantees sequential semantics
  - Program result is as if it had executed sequentially
  - Very useful for debugging at scale

Task Graphs

- When Legion discovers interfering tasks an edge is added to the *task graph* recording the dependency

- Three wavefronts:
  - The runtime building the task graph
  - The application executing the graph
  - The runtime collecting resources from finished tasks



Parallel Loop from PageRank

```
for p in part do
  pagerank(part_nodes[p], part_edges[p],
                 pr_score0, part_score1[p],  … )
end
```

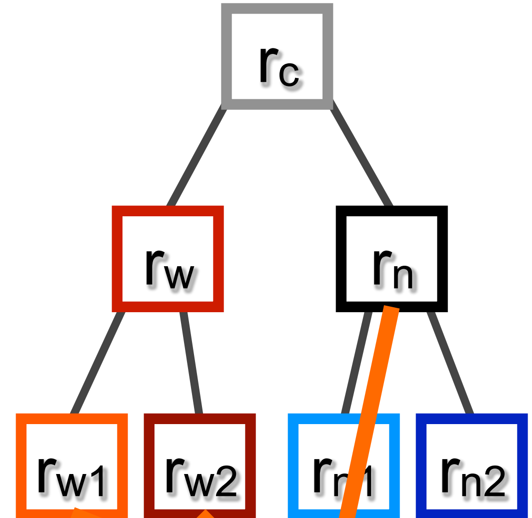
The different calls to pagerank don’t interefere.
Why? Only part_score1[] is written and it is a disjoint partition.

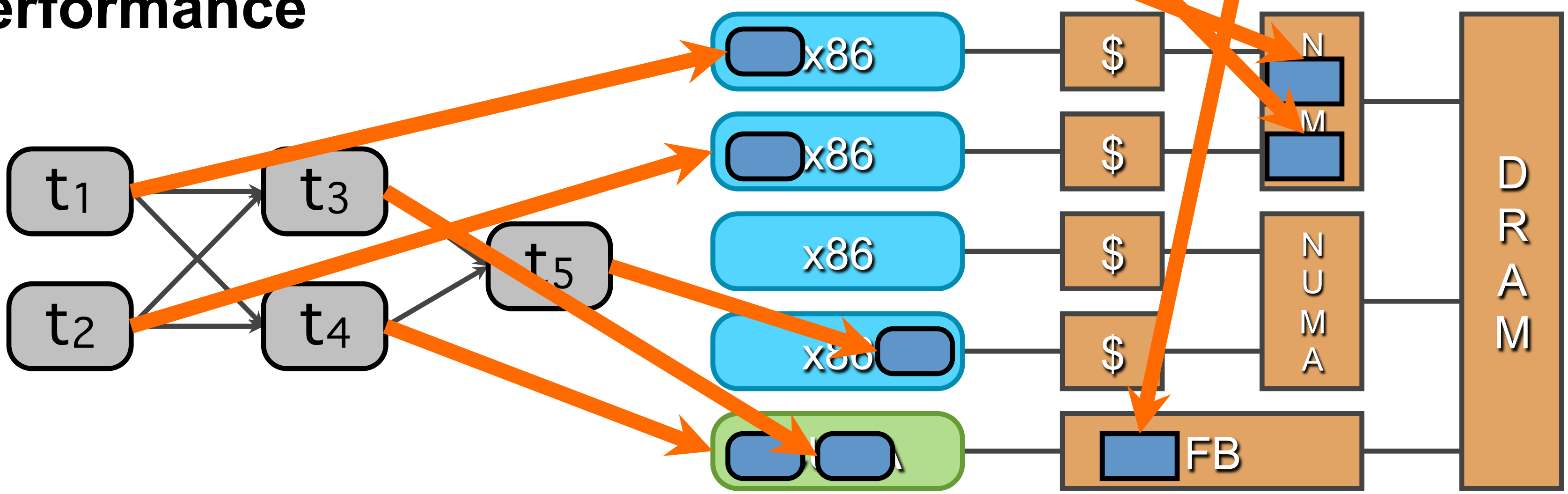
Note the use of different views on to the data. We use both the entire pr_score0[] region and subregions of part_score1[].

MAPPING

Mapping Interface

- **Application selects:**
  - **Where tasks run**
  - **Where regions are placed**
- **Mapping computed dynamically**
- **Decouple correctness from performance**





Mapping

- Mapping is the process of assigning resources to Regent/Legion programs

- Conceptually
  - Assign a processor to each task
    - The task will execute in its entirety on that processor

  - Assign a memory to each region argument

- And many other things!

- There is a default mapper with reasonable heuristics
  - Just another mapper, but a generic one

Mapping Interface

- At the Legion level, mapping is an API
  - A set of callbacks
  - Each is called at a particular point in a task's lifetime
  - To write mappers, need to know this sequence of stages
- Regent has a mapping DSL
  - Concise, easy to use
  - Compiles to the Legion mapping API
  - Currently supports only static mappings

High-Level Overview of Mapping

- An instance of the Legion runtime runs on each node

- When a task is launched on the local runtime:
  - The mapper picks a processor for the task
  - The mapper picks memories for the region arguments
  - … and other things as well …

New Concepts

- There are a number of concepts at the mapping level that don't exist in Regent

- Machine models
- Variants
- Physical Instances

Machine Model

- To pick concrete processors & memories, the runtime must know:
- How many processors/memories there are
  - And of what kinds
- And where the processors/memories are
  - At least relative to each other
- A machine model is written once for each machine

Components of a Machine Model

- Processors
  - LOC
  - TOC
  - PROC_SET
  - UTILITY
  - IO
- Memories
  - GLOBAL
  - SYSTEM
  - RDMA
  - FRAME_BUFFER
  - ZERO_COPY
  - DISK
  - HDF5

Affinities

- Processor -> Memory
  - Which memories are attached to a processor
- Memory -> Memory
  - Which memories have channels between them
- Memory -> Processor
  - All processors attached to a memory
- Affinities are provided as a list
  - *(proc,mem)* and *(mem,mem)* pairs
  - Also include bandwidth and latency information

Task Variants

- A task can have multiple *variants*
  - Different implementations of the same task
  - Multiple variants can be registered with the runtime
  - Variants can have associated *constraints*

- Examples
  - A variant for LOC
  - Another variant for TOC
  - Variants for different data layouts

Variants in Regent

- Place immediately before a task declaration
  - __demand(__cuda)
- Causes both CPU and GPU task variants to be produced
- And the default mapper always prefers to pick a GPU variant if possible

Physical Instances

- A *region* is a logical name for data

- A *physical instance* is a copy of that data
  - For some set of fields

- There can be 0, 1 or many physical instances of a specific field of a region at any time

Physical Instances

- Can be *valid* or *invalid*
  - Is the data current or not?
- Live in a specific memory
- Have a specific layout
  - Column major, row major, blocked, struct-of-arrays, array-of-structs, …
- Are allocated explicitly by the mapper
- Are deallocated by the runtime
  - Garbage collected

A Word About Physical Instances

- Many physical instances of a region can exist simultaneously
  - Including different versions of the same data

- A task writing version 0 to disk
- A task reading version 5
- A task writing version 6
  - The current version!
- A task scheduled to read version 6
- A task scheduled to write version 7
- A (meta)task scheduled to deallocate version 6
- …

Layout Constraints

- Tasks can have layout constraints on physical instances
  - “This task requires data in row major order”
- Constraints are just that
  - Don’t specify an exact layout
  - Multiple instances may satisfy the constraints

Summary

- Mapping
  - Selects processors for tasks
  - Selects memories for physical instances
    - Satisfying region requirements of tasks
- Many options
  - Default mapper does reasonable things
  - But any sufficiently complex program will need some customization

PAGERANK MAPPER

PROFILING

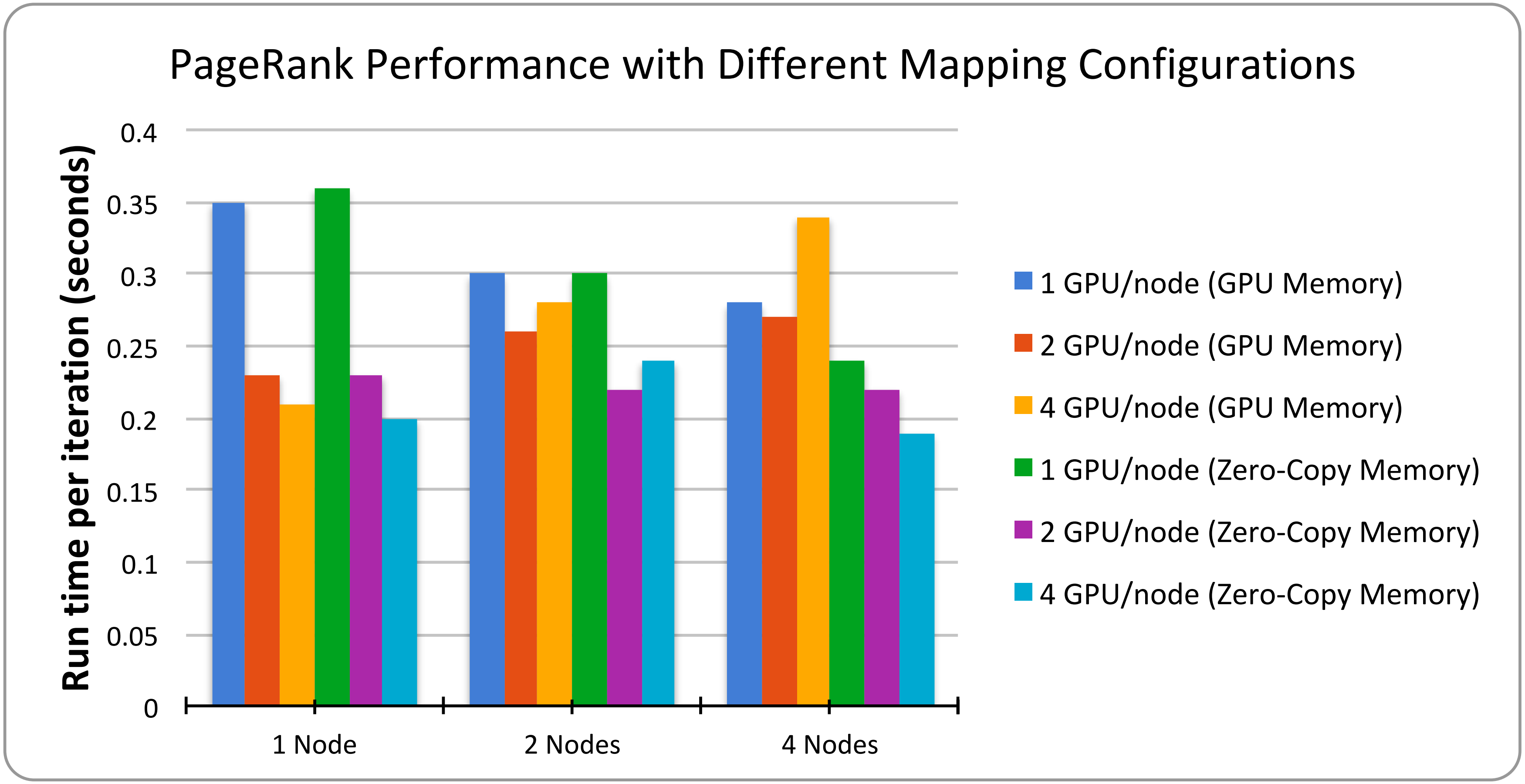
Legion Prof

- A tool for showing performance timeline
  - Each processor is a timeline
  - Each operation is a time interval
  - Different kinds of operations have different colors
- White space = idle time
  - Want to understand why there is white space

Example Profiles from PageRank

- [1 node, 8 cpus]()
  - pagerank/run_pr.sh --program baseline --cpus 8 --nodes 1 --gpus 0
- [1 node, 1 GPU]()
  - pagerank/run_pr.sh --program baseline --cpus 4 --nodes 1 --gpus 1
- [1 node, 2 GPUs]()
  - pagerank/run_pr.sh --program baseline --cpus 4 --nodes 1 --gpus 2
- [1 node, 4 GPUS]()
  - pagerank/run_pr.sh --program baseline --cpus 4 --nodes 1 --gpus 4

Performance Results

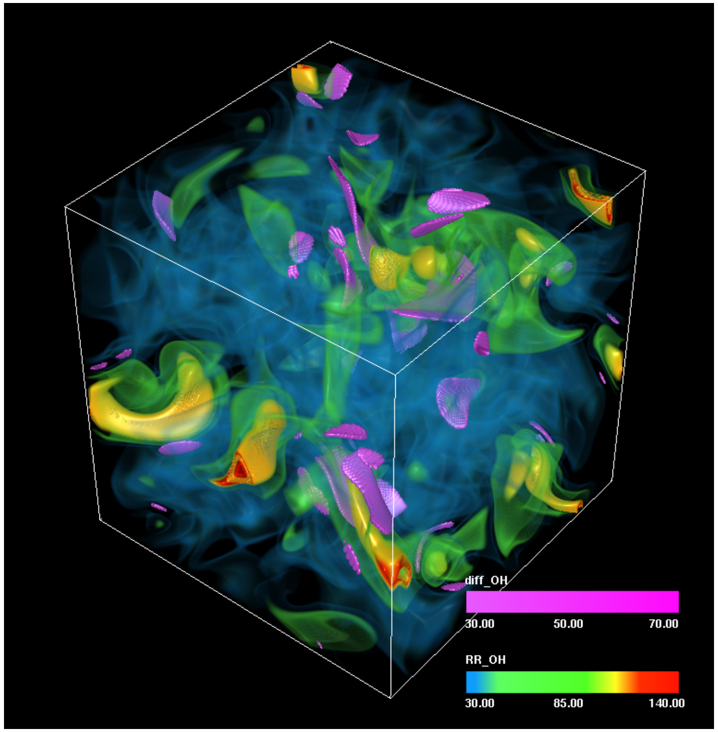


OTHER APPLICATIONS

S3D: Combustion Simulation

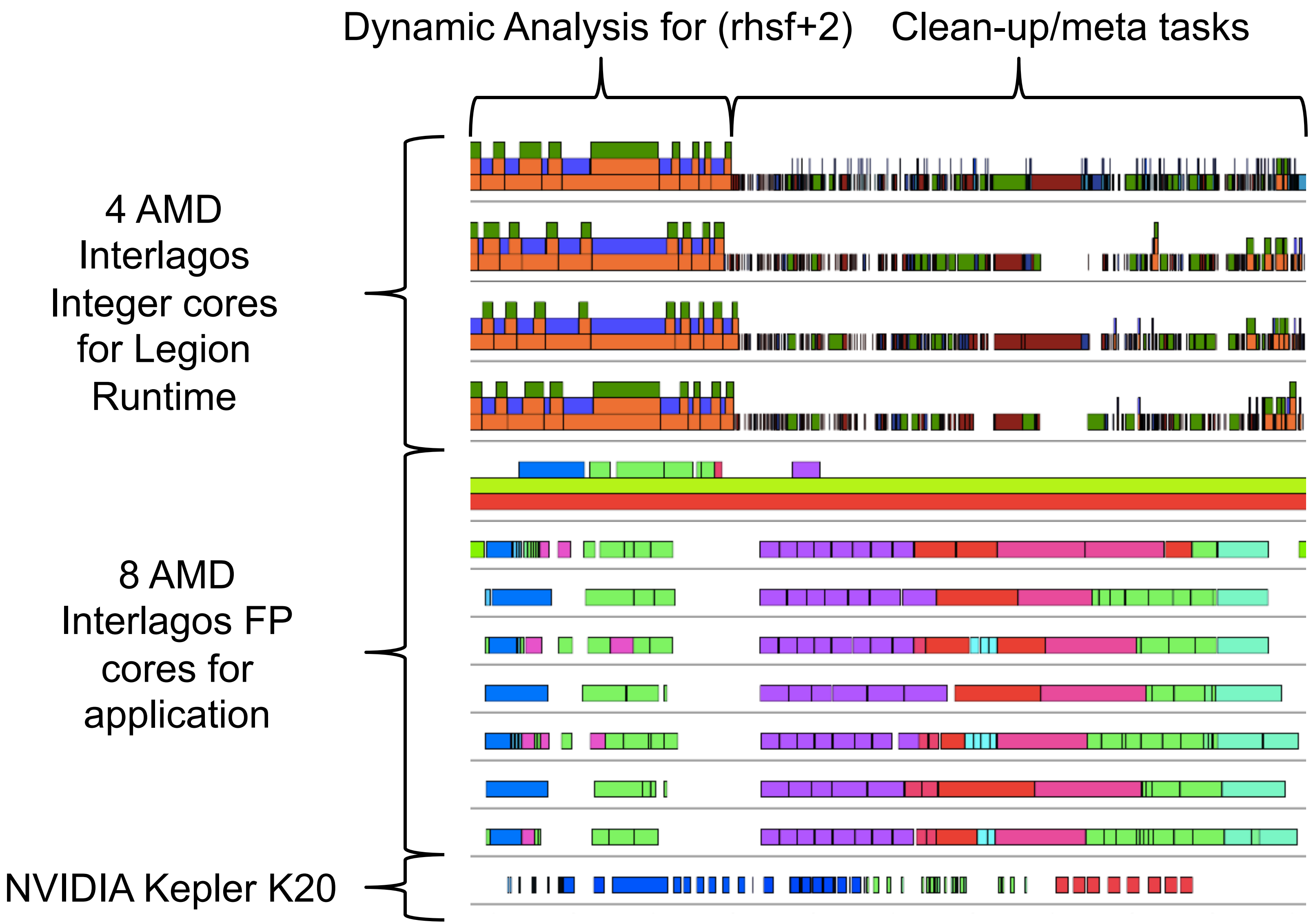
- **Simulates chemical reactions**
  - **DME (30 species)**
  - **Heptane (52 species)**
  - **PRF (116 species)**

- **Two parts**
  - **Physics**
    - **Nearest neighbor communication**
    - **Data parallel**
  - **Chemistry**
    - **Local**
    - **Complex task parallelism**
  - **Large working sets/task**



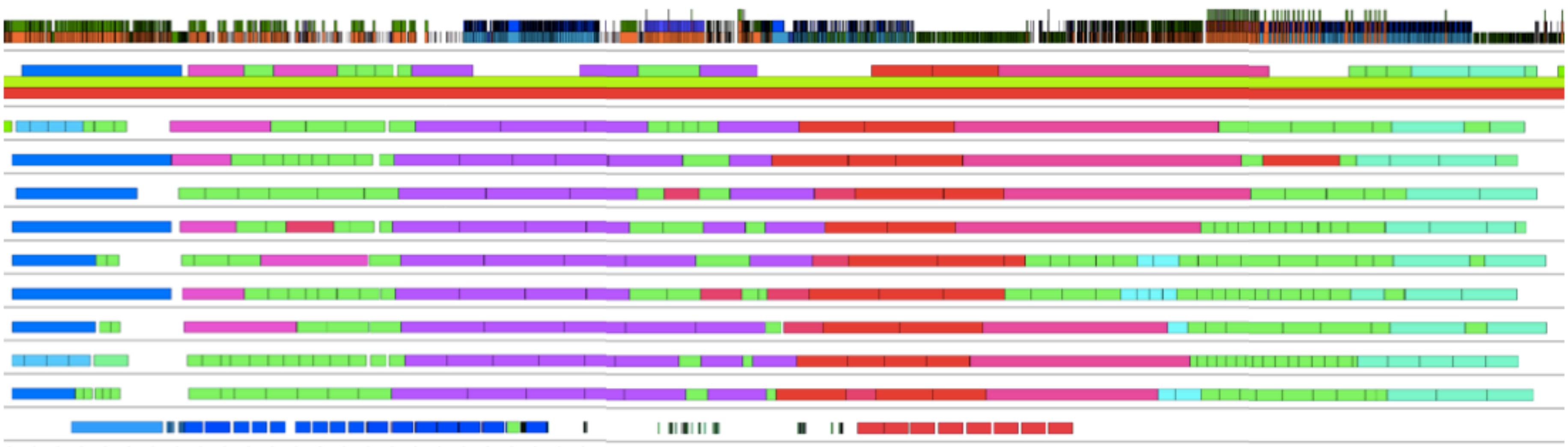
Recent 3D DNS of auto-ignition with 30-species DME chemistry (Bansal *et al*. 2011)

Mapping for Heptane 48^3

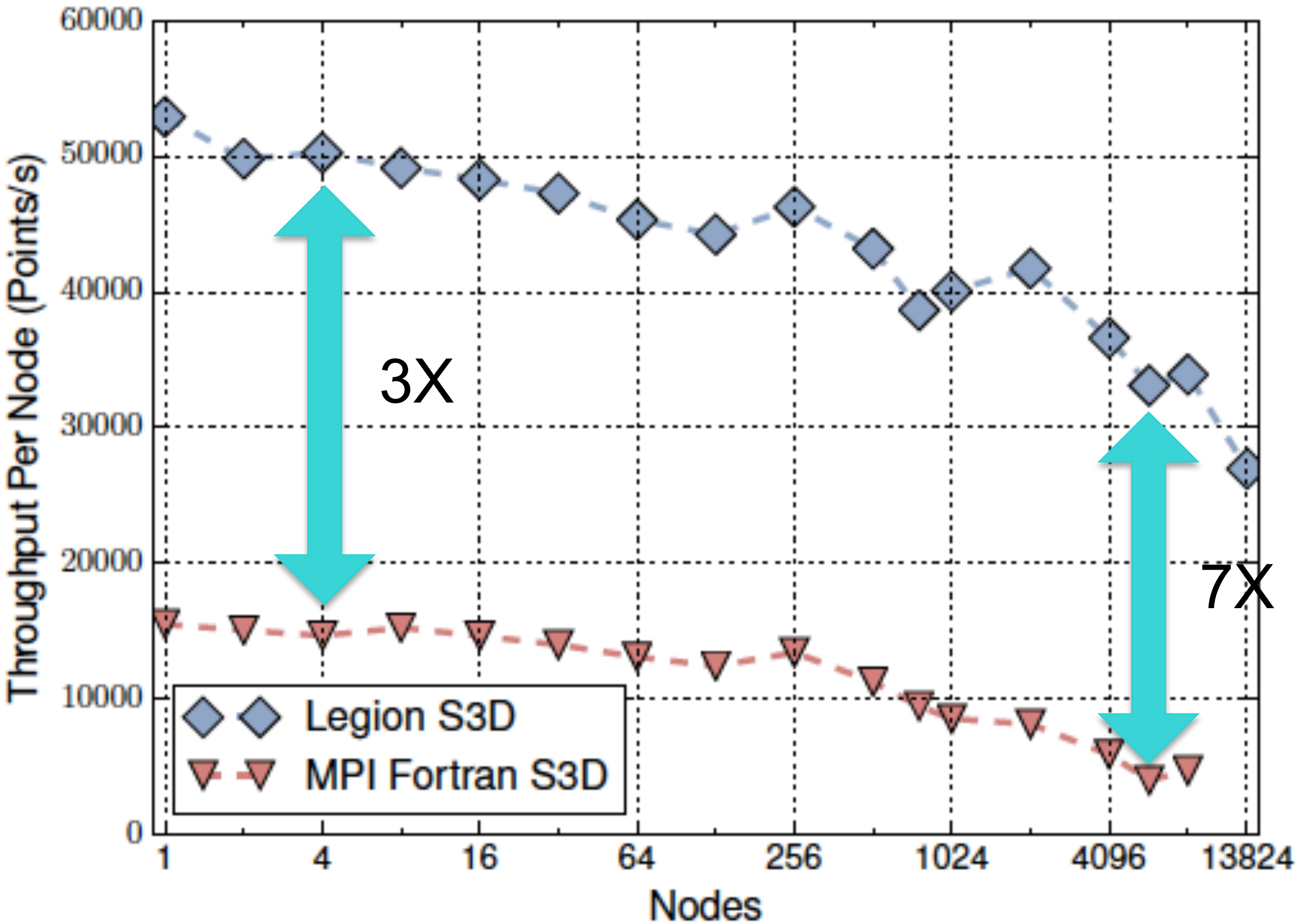


Mapping for Heptane 96^3

- Handle larger problem sizes per node
  - Higher computation-to-communication ratios
  - More power efficient
- Different mapping
  - Limited by size of GPU framebuffer
- Legion analysis is independent of problem size
  - Larger tasks -> fewer runtime cores



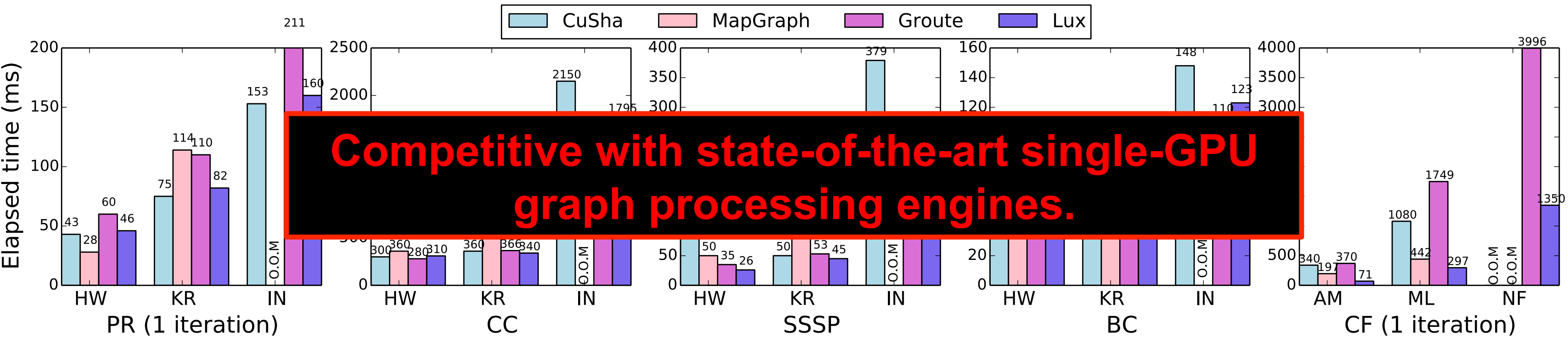
Weak Scaling: PRF on Titan



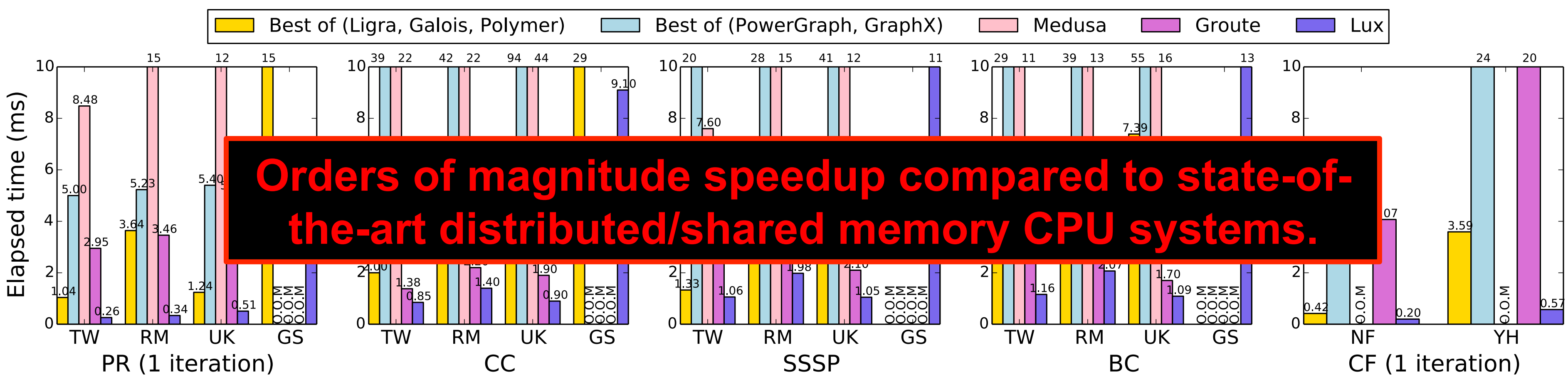
Fast Graph Analytics

- Conventional wisdom:
  - Graph processing has trouble taking advantage of distributed memory
- High performance graph processing systems are dominated by shared-memory CPU-based systems
- Observation
  - GPUs provide higher memory bandwidth than CPUs
  - Can avoid communication by careful placement of data in the memory hierarchy

Fast Graph Processing [VLDB'18]



Competitive with state-of-the-art single-GPU graph processing engines.



Orders of magnitude speedup compared to state-of-the-art distributed/shared memory CPU systems.

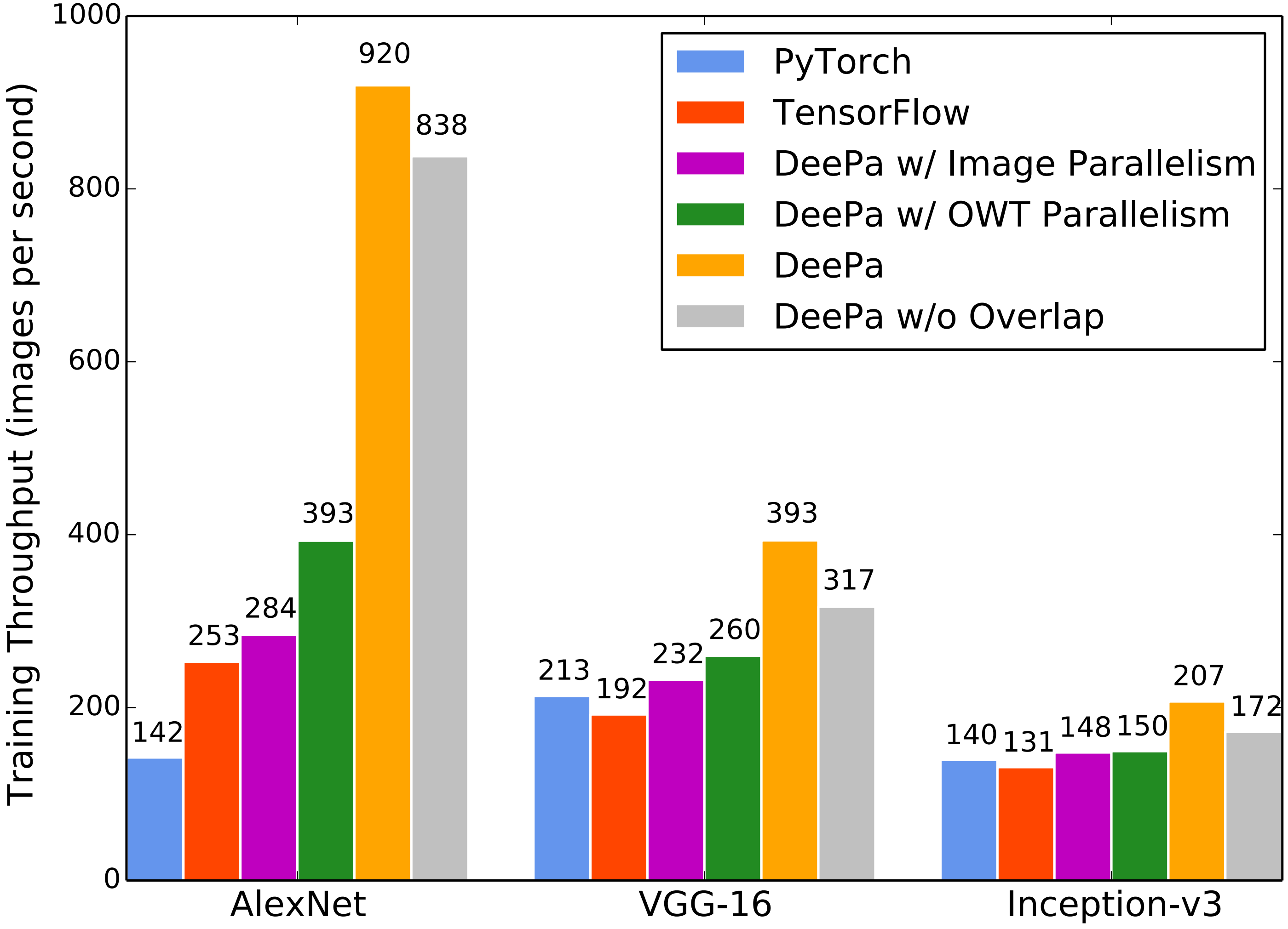
Convolutional Neural Networks [ICML18]

- **In CNNs, data is commonly organized as 4D tensors.**
  - **tensor = [image, height, width, channel]**

- **Existing tools parallelize the *image* dimension.**

- **Motivation**
  - **Explore other parallelizable dimensions**
  - **Allow each layer to be parallelized differently**

Results



Training Throughput (images per second)
1000
800
600
400
200
0
PyTorch
TensorFlow
DeePa w/ Image Parallelism
DeePa w/ OWT Parallelism
DeePa
DeePa w/o Overlap
142
253
284
393
920
838
213
192
232
260
393
317
140
131
148
150
207
172
AlexNet
VGG-16
Inception-v3

Perspectives

Separating Concerns

- Current practice entangles functionality, scheduling, and mapping
  - Consider a code written in MPI + OpenMP + CUDA

- Alternative
  - Specify functionality and dependencies first
  - Then focus on mapping and scheduling for a machine
  - A lot of the benefits of Legion flow from this design

Programmer Productivity

- In the end, it's all about productivity
- How much work is needed to achieve a desired level of performance?
- Legion philosophy
  - More expressive data model
  - Requires more initial work from the programmer
  - But makes later stages easier & more flexible
    - Easy to try different partitioning strategies
    - Easy to explore alternative mappings

Legion

Legion website: http://legion.stanford.edu