The Legion Programming Model

(and the Regent compiler)

ATPESC – 2017

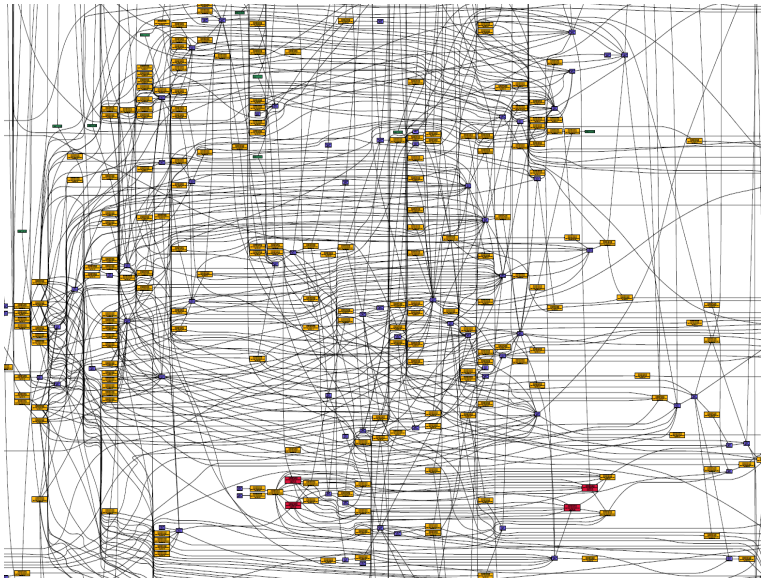

Programming HPC systems is hard today and will only get harder without new approaches

- **Aspects of programming future large-scale systems**
  - Focusing on **full-system**, ***data-awareness*** *and* ***improved productivity***
    - *Programming in the small is not the challenge, we must take a broader view*
    - *Co-designing the full tool chain with applications*
    - *End-to-end awareness is required to avoid point solutions "non-solutions"*
  - Targeting large scale dynamic computation environments
    - *Hardware dynamics: frequency scaling, dark silicon, adaptive routing, …*
    - *Software dynamics: system services, in-situ/co-resident services, …*
    - *Application dynamics: multiscale andmultiphysics*
- **Programming model goals (*What must we deliver?*)**
  - High performance – *we must be fast*
  - Performance portability – *across many kinds of machines over many generations*
  - Programmability – *sequential semantics, parallel execution*

Can we fulfill our programming model goals today?

We can, to some degree…

… but at great cost: Programmer Pain



Task graph for one time step on one node…

… of a mini-app

Do you want to schedule this graph?

(High Performance)

Do you want to re-schedule this graph for every new machine?

(Performance Portability)

Do you want to be responsible for generating this graph?

(Programmability)

Today: programmer's responsibility

Tomorrow: programming system's responsibility

We need the right programming abstractions to achieve our goals

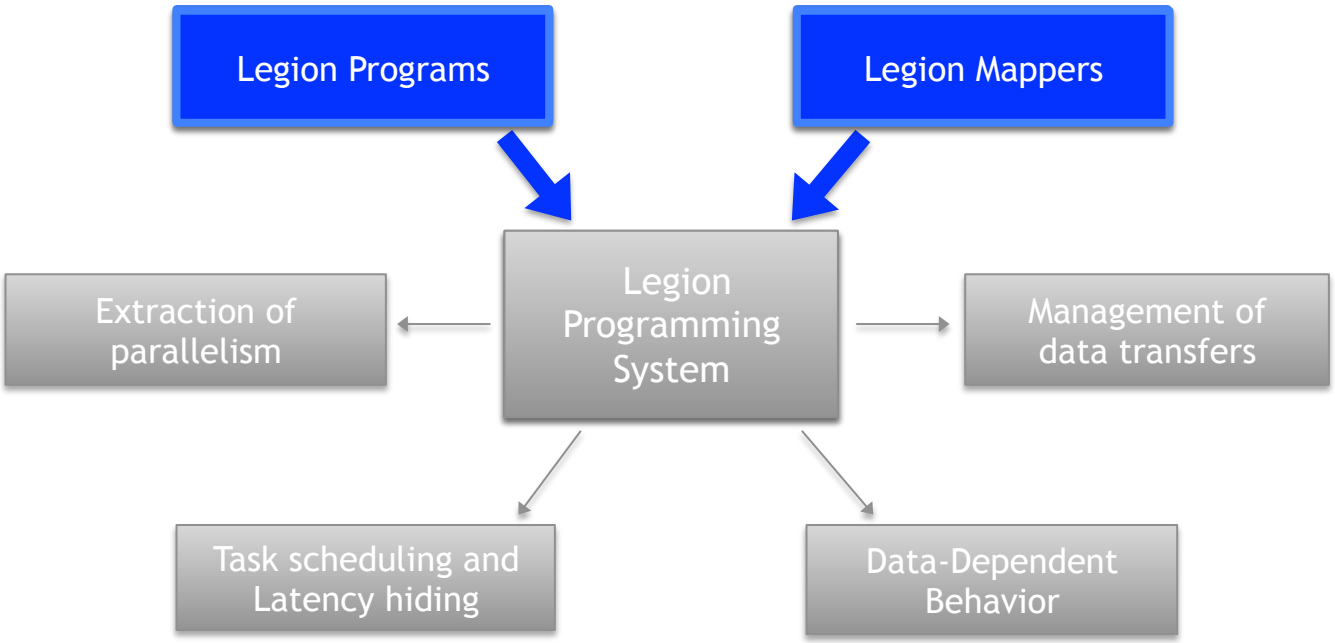
- ***Today's programming environments:***
- ***Are using the wrong abstractions…***
- ***Focus on control flow, parallelism and have low-level data abstractions (i.e. no data model)***

```
AsyncRecv(X);
DoWork(Y);
Sync();
F(X);
```

- *How much work should I do?*
- *Is this performance portable?*
- *When does forward progress **really** occur?*
- *What if I have more work and data movement happening in `DoWork`?*
- *What resources are in use? Where is the data? Who is using it and how?*
- *Is this modular?*
- *What if there is a fault?*

- Concept from: Mike Bauer's Thesis (Stanford), *Legion: Programming Distributed Heterogeneous Architectures with Logical Regions*

Our approach to meeting our programing model goals is different



Legion: Separation of Concerns

Tasks
(execution model)

Describe parallel execution elements and algorithmic operations with sequential semantics, out-of-order execution

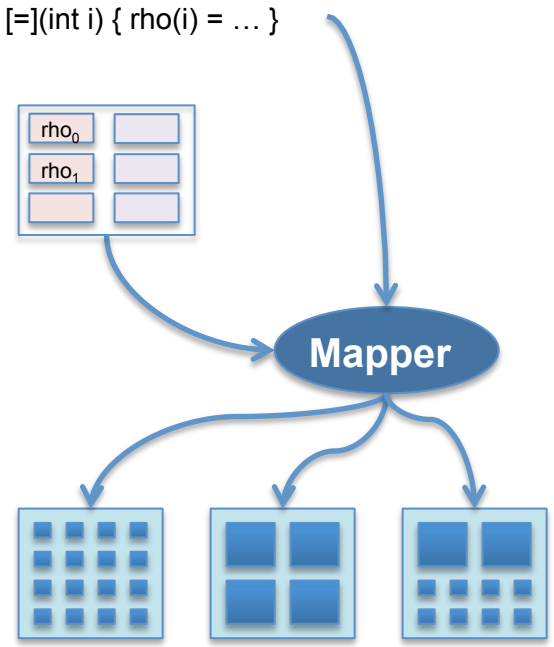
Regions
(data model)

Describe decomposition of computational domain.

- **Privileges (read-write, read-only, reduce)**
- **Coherence (exclusive, atomic)**

Mapper

Describes how tasks and regions should be mapped to the target architecture



Mapper allows architecture-specific optimization without effecting the correctness of the task or domain descriptions

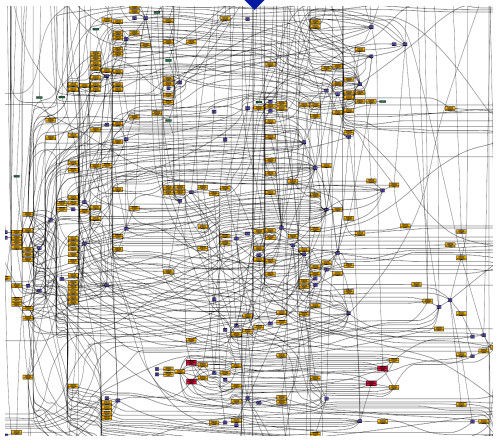
The Legion programming model: enabling the runtime to manage the complexity of a dynamic environment

Machine-Independent Specification

Defines application correctness

Sequential semantics

Analysis!



Programmatic interface for performing machine-specific and app-specific mapping

Only impacts performance

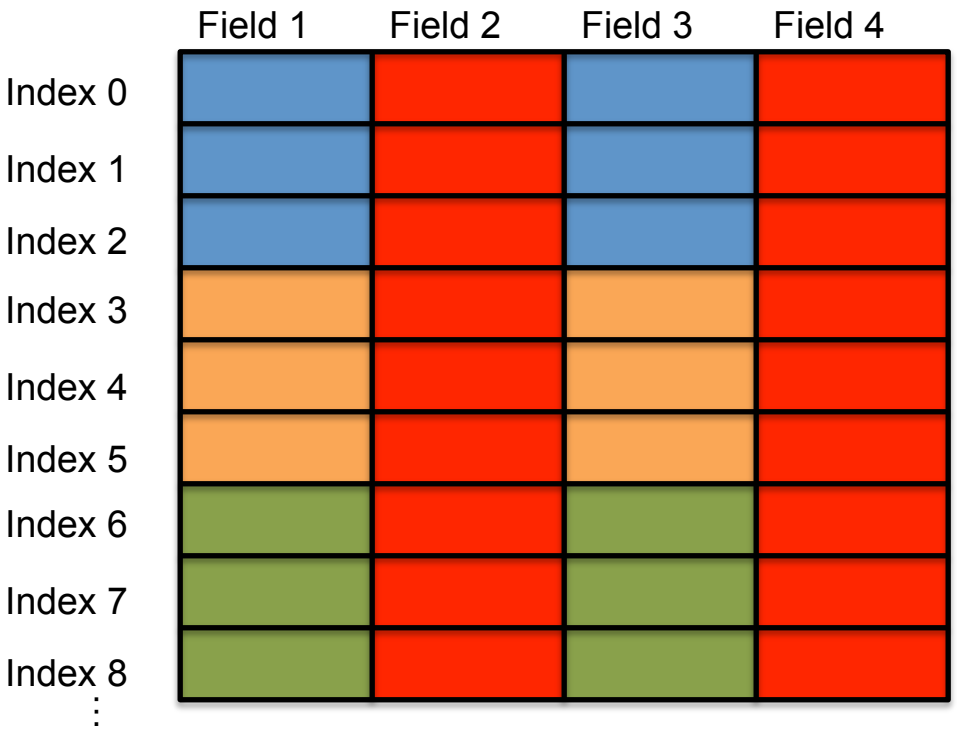
Yesterday: manual mapping

Today: programmatic mapping

Tomorrow: generated mappers

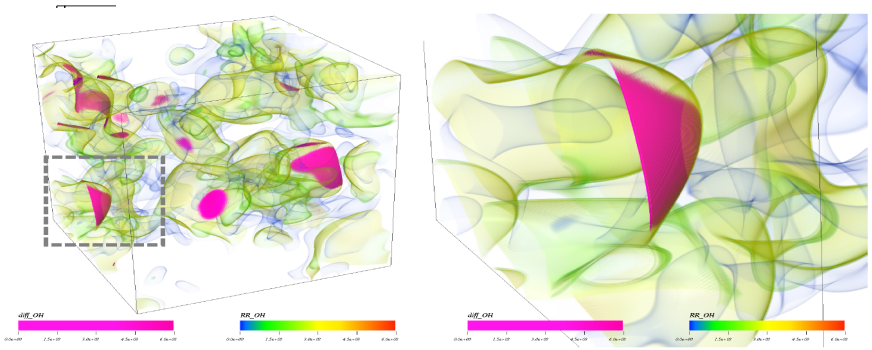
Data Model – Logical Regions

- Unbounded set of rows (index space)
- Bounded set of columns (fields)
- Can be partitioned (disjoint or aliased)
- **Tasks operate on regions**
  - Must specify which fields and how they "use" them (fields and privileges: read, write, read+write, exclusive, etc.)
  - Allows fields to be "sliced"
- Tasks launched in program order (execution order relaxed based on dependencies)
  - "out of order" software processor



Our approach shows compelling results with a full application

- Ported production combustion application (S3D)
  - Sufficient complexity to validate our approach – **beyond the "Proxy"**



- High-level application constructs remain in MPI form… - essentially all the initial setup was kept
- Full right hand side function implemented in Legion including all communication (the full stencil computation and all chemistry calculations)
  - **~2-3X faster than MPI+OpenACC**
  - **~7X faster than MPI only**
  - **Enabling new science that is not possible with current approaches**

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 will focus on Regent

Regent/Legion Design Goals

- Sequential semantics
  - The better to understand what you write
  - Parallelism is extracted automatically
- Throughput-oriented
  - The latency of a single thread/process is (mostly) irrelevant
  - The overall time is what matters
- Runtime decision making
  - Because machines are unpredictable/dynamic

Throughput-Oriented

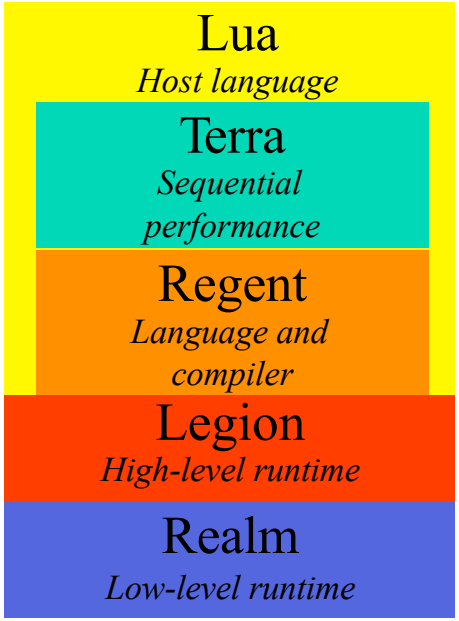
- Keep the machine busy

- How? Ideally,
  - Every core has a queue of independent work to do
  - Every memory unit has a queue of transfers to do
  - At all times

Consequences

- Highly asynchronous
  - Minimize synchronization
  - Esp. global synchronization
- Sequential semantics but support for parallelism
- Emphasis on describing the structure of data
  - Later

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

- Examples Overview/1.rg & 2.rg

- To run:
  - ssh –l USER bootcamp.regent-lang.org
  - cd Bootcamp/Overview
  - qsub r1.sh

Tasks

Tasks

- Tasks are Regent's unit of parallel execution
  - Distinguished functions that can be executed asynchronously

- No preemption
  - Tasks run until they block or terminate
  - And ideally they don't block …

Blocking

- Blocking means a task cannot continue
  - So the task stops running
- Blocking does not prevent independent work from being done
  - If the processor has something else to do
  - Does prevent the task from continuing and launching more tasks
- Avoid blocking.

Subtasks

- Tasks can call subtasks
  - Nested parallelism
- Terminology: parent and child tasks

Example

```
task tester(sum: int64)
...
end

task main()
    var sum: int64 = summer(10)
    sum = tester(sum)
    c.printf("The answer is: %d\n",sum)
end
```

If a parent task inspects the result of a child task, the parent task blocks pending completion of the child task.

- Examples Tasks/1.rg & 2.rg
- Reminder:

  cd Bootcamp/Tasks

  qsub r1.sh

Legion Prof

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

Example 1: Legion Prof

cd Bootcamp/Tasks qsub rp1.sh
make prof

http://bootcamp.regent-lang.org/~USER/prof1

Example 2: Legion Prof

cd Bootcamp/Tasks qsub rp2.sh
make prof

http://bootcamp.regent-lang.org/~USER/prof2

Mapping

- How does Regent/Legion decide on which processor to run tasks?
- This decision is under the mapper's control
- Here we are using the default mapper
  - Passes out tasks to which CPU on a node is not busy
  - Programmers can write their own mappers

Parallelism

Example Tasks/3.rg

- "for all" style parallelism
- Note the order of completion of the tasks
  - main() finishes first (or almost first)!
  - All subtasks managed by the runtime system
  - Subtasks execute in non-deterministic order
- How?
  - Regent notices that the tasks are independent
  - No task depends on another task for its inputs

Runtime Dependence Analysis

- Example Tasks/4.rg is more involved
  - Positive tasks (print a positive integer)
  - Negative tasks (print a negative integer)

- Some tasks are dependent
  - The task for -5 depends on the task for 5
  - Note loop in main() does not block on the value of j!

- Some are independent
  - Positive tasks are independent of each other
  - Negative tasks are independent of each other

Legion Spy

Legion Spy

- A tool for showing ordering dependencies
- Very useful for figuring out why things are not running in parallel

Example Tasks/4.rg: Legion Spy

cd Bootcamp/Tasks qsub

rs4.sh

make spy

http://bootcamp.regent-lang.org/~USER/spy4.pdf

Workflow

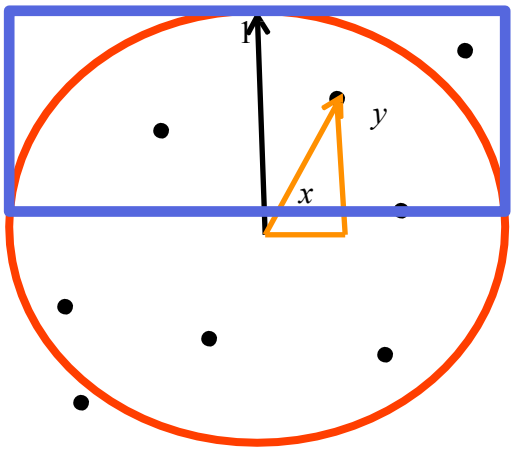
- Use Legion Prof to find idle time
  - white space
- Use Legion Spy to examine tasks that are delayed
  - What are they waiting for?!

Exercise 1

Computing the Area of a Unit Circle

- A Monte Carlo simulation to compute the area of a unit circle inscribed in a square

- Throw darts
  - Fraction of darts landing in the circle = ratio of circle's area to square's area



Computing the Area of a Unit Circle

- Example Pi/1.rg
  - Slow!
  - Why?

Exercise 1

- Compare Pi/1.rg and Pi/x1.rg
  - Identify use of multiple trials per subtask
- Modify Pi/x1.rg (change "terra hits" to "task hits")
- Uses
  - 4 subtasks
  - 2500 trials per subtask
- Which is faster? Why?
  - Hint: Use Legion Prof and Legion Spy

Terra

Leaf Tasks

- Leaf tasks call no other tasks
  - The "leaves" of the task tree
- Leaf tasks are sequential programs
  - And generally where the heavy compute will be
- Thus, leaf tasks should be optimized for latency, not throughput
  - Want them to finish as fast as possible!

Terra

- Terra is a low-level, typed language embedded in Lua
- Designed to be like C
  - And to compile to similarly efficient code
- Also supports vector intrinsics
  - Not illustrated today

Terra Example

- Terra/1.rg converts the hits task in Terra/ x1.rg to a Terra function

- Trivial in this example
  - Just change ”task” to “terra”
  - Marginally faster
    - On average …

Considerations in Writing Regent Programs

- The granularity of tasks must be sufficient
  - Don't write very short running tasks
- Don't block in tasks that launch many subtasks
- Terra is an option for heavy sequential computations

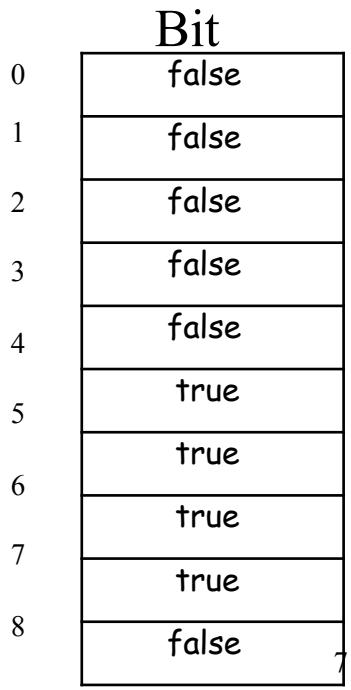
Structured Regions

Regions

- A region is a (typed) collection

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

StructuredRegions/1.rg



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 1D, 2D and 3D index spaces

Privileges

- A task that takes region arguments must
  - Declare its privileges on the region
  - Reads, Writes, Reduces

- The task may only perform operations for which it has privileges
  - Including any subtasks it calls

- Example StructuredRegions/2.rg
- Example StructuredRegions/3.rg

Reduction Privileges

- StructuredRegions/4.rg
  - A sequence of tasks that increment elements of a region
  - With Read/Write privileges
- StructuredRegions/5.rg
  - 4.rg but with Reduction privileges
- Note: Reductions can create additional copies
  - To get more parallelism
  - Under mapper control
  - Not always preferred to Read/Write privileges

Partitioning

Partitioning

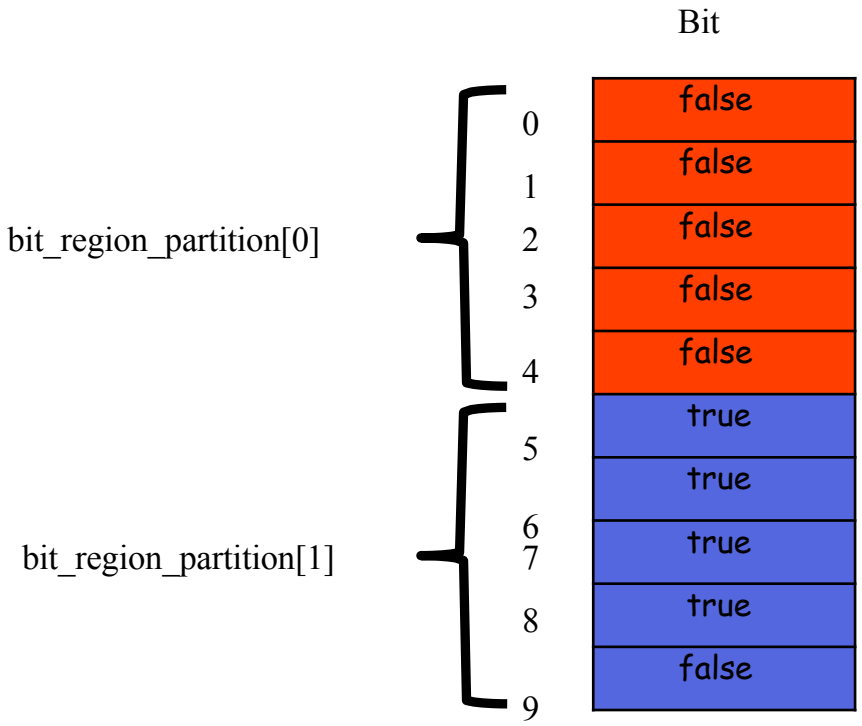
- To enable parallelism on a region, partition it into smaller pieces
  - And then run a task on each piece

- Legion/Regent have a rich set of partitioning primitives

Partitioning Example

	Bit
0	false
1	false
2	false
3	false
4	false
5	true
6	true
7	true
8	true
9	false

Partitioning Example



Equal Partitions

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

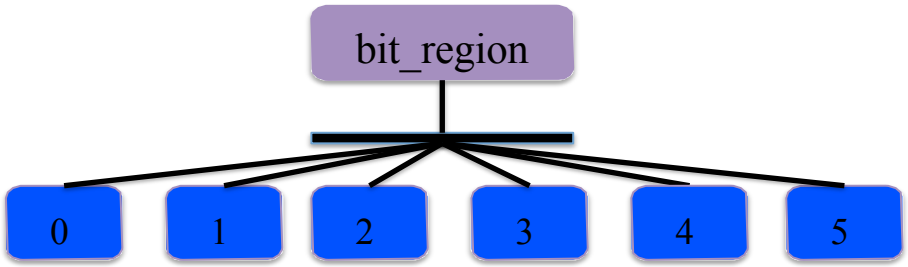
- Partitioning/1.rg

- Partitioning/2.rg

Discussion

- Partitioning does not create copies
  - It names subsets of the data
- Partitioning does not remove the parent region
  - It still exists and can be used
- Regions and partitions are first-class values
  - Can be created, destroyed, stored in data structures, passed to and returned from tasks

Region Trees



More Discussion

- The same data can be partitioned multiple ways
  - Again, these are just names for subsets
- Subregions can themselves be partitioned

Dependence Analysis

- Regent uses tasks' region arguments to compute which tasks can run in parallel
  - What region is being accessed
    - Does it overlap with another region that is in use?
  - What field is being accessed
    - If a task is using an overlapping region, is it using the same field?
  - What are the privileges?
    - If two tasks are accessing the same field, are they both reading or both reducing?

A Crucial Fact

- Regent analyzes sibling tasks
  - Tasks launched directly by the same parent task

- Theorem: Analyzing dependencies between sibling tasks is sufficient to guarantee sequential semantics

  - Question: Why does this hold? (Intuitively)

- Never check for dependencies otherwise
  - Crucial to the overall design of Regent

Consequences

- Dependence analysis is a source of runtime overhead
- Can be reduced by reducing the number of sibling tasks
  - Group some tasks into subtasks
- But beware!
  - This may also reduce the available parallelism
- Partitioning/3.rg

Partitioning/3.rg

- Note that passing a region to a task does not mean the data is copied to where that task runs
  - C.f., launcher task must name the parent region for type checking reasons

- If the task doesn't touch a region/field, that data doesn't need to move

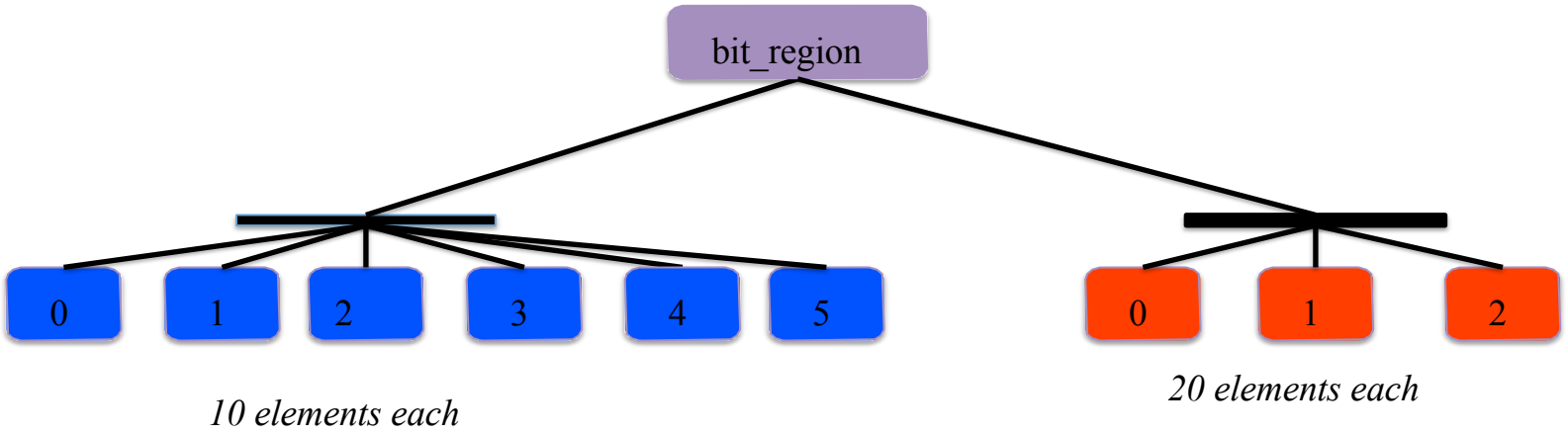
Fills

- A better way to initialize regions is to use fill operations

```
fill(region.field, value)
```

- Partitioning/4.rg

Multiple Partitions



Discussion

- Different views onto the same data
- Again, can have multiple views in use at the same time
- Regent will figure out the data dependencies

Exercise 2

- Modify Partitioning/4.rg to

- Have two partitions of bit_region
  - One with 3 subregions of size 20
  - One with 6 subregions of size 10

- In a loop, alternately launch subtasks on one partition and then the other
- Edit x2.rg

Aliased Partitions

- So far all of our examples have been disjoint partitions
- It is also possible for partitions to be aliased
  - The subregions overlap
- Partitioning/5.rg

Partitioning Summary

- Significant Regent applications have interesting region trees
  - Multiple views
  - Aliased partitions
  - Multiple levels of nesting
- And complex task dependencies
  - Subregions, fields, privileges, coherence
- Regions express locality
  - Data that will be used together
  - An example of a "local address space" design
    - Tasks can only access their region arguments

Regions Review

- A region is a (typed) collection
- Regions are the cross product of
  - An index space
  - A field space
- A structured region has a structured index space
  - E.g., int1d, int2d, int3d

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

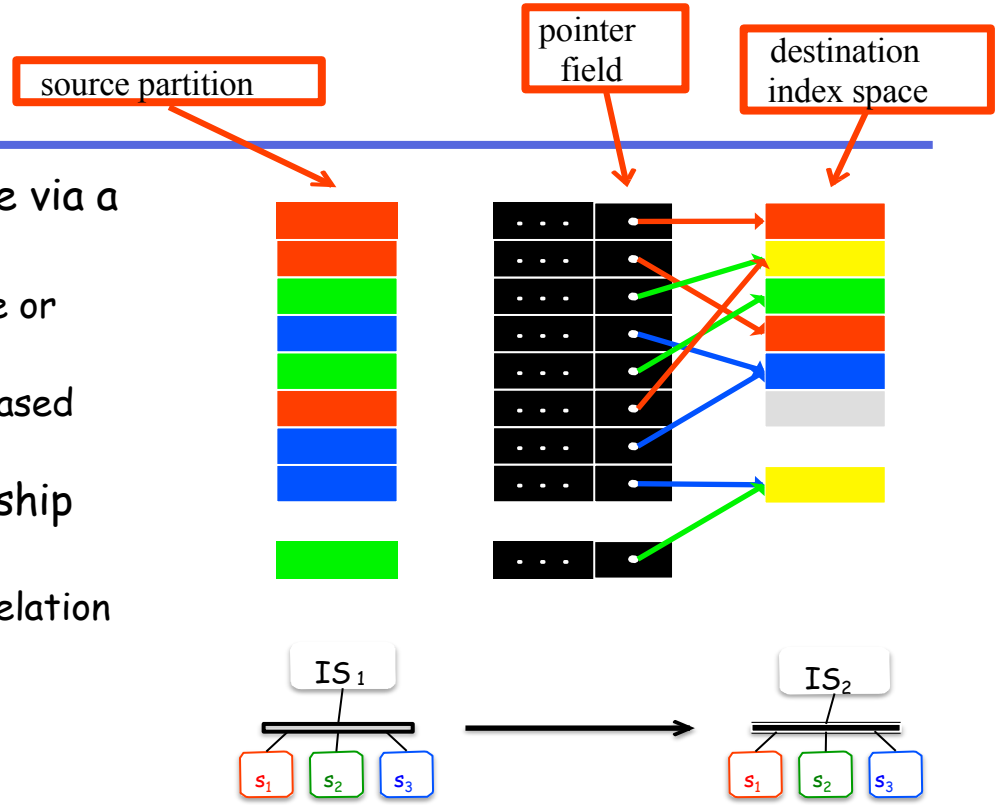
- Distinguish two kinds of partitions
- Independent partitions
  - Computed from the parent region, using, e.g.,
    - partition(equals, …)
- Dependent partitions
  - Computed using another partition

Dependent Partitioning Operations

- Image
  - Use the image of a field in a partition to define a new partition
- 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

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
- Regent understands relationship between partitions
  - Can check safety of region relation assertions at compile time



Preimage

- Inverse of image
  - Computes elements that reach a given subspace
  - Preserves disjointness
- Multiple images/preimages can be combined
  - Can capture complex task access patterns