StarPU

CS315B
Lecture 12

What is StarPU?

- A task-based runtime
- Similar in motivation to Legion
  - Very similar!
  - Even though the projects are independent

History

- First paper in 2008
  - First called StarPU in 2009
- Development at least through 2013?
- Application papers through today

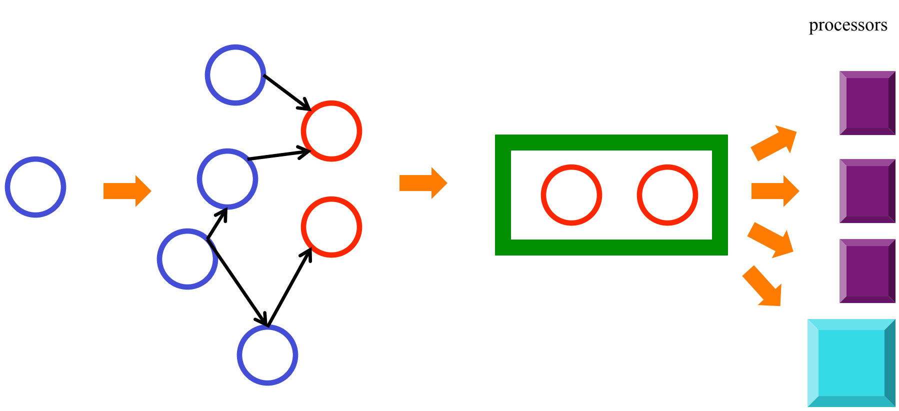
The Basics

- Task-based
  - Dependencies define execution order constraints between tasks
- Task inputs and outputs must be explicitly declared
  - Along with Read, Write, Read/Write
- Hierarchical partitioning of data
- Programmer gets
  - Automatic task scheduling
  - Automated data movement

Execution Pipeline

- The application submits *tasks* & *dependencies*
- The StarPU runtime maintains a *dependence graph* of tasks
- Tasks that are not dependent on other tasks are placed in a *work queue*
- *A scheduler* assigns tasks from the work queue to processors

Execution Model



Execution Pipeline

- The application submits tasks & dependencies
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Declaring Dependencies

The application is responsible for declaring dependencies between tasks

```
declare_deps(tagB, 1, tagA);
declare_deps(tagC, 1, tagA);
declare_deps(tagD, 2, tagB, tagC);

task1->tag_id = tagA;
task2->tag_id = tagD;
…
submit_task(task1);
submit_task(task2);
…
tag_wait(tagD);
```

Maintaining Dependencies

- Tasks also must declare privileges on data
  - Read, Write, Read/Write
- Data dependencies between tasks are discovered by the runtime
  - A dependency between A and B
  - A writes some data, B reads it
  - System will move the data if necessary to where B executes

Scheduling

- Given a set of read-to-execute tasks:
  - Which one should be executed next?
  - On which processor?
- Tasks may have variants that allow the same task to be run on different kinds of processors
  - E.g., CPUs or GPUs
  - Just like Sequoia/Legion

Scheduling Heuristic

- Estimate the time Time(t,p) to run task t on processor p
  - Estimates can be obtained from programmer-supplied models or from profiling

- $Latency(p) = \Sigma_t \; Time(t,p)$
  - Where the sum is over tasks assigned to p

- Send a new task t' to the processor p' that minimizes Time(t,p) + Latency(p)

Priorities

- The scheduling heuristic is FIFO

- Tasks can also have priorities
  - Allow important tasks to jump the queue
  - Doesn't necessarily interact well with the scheduling heuristic

- Many other scheduling policies have been explored for StarPU

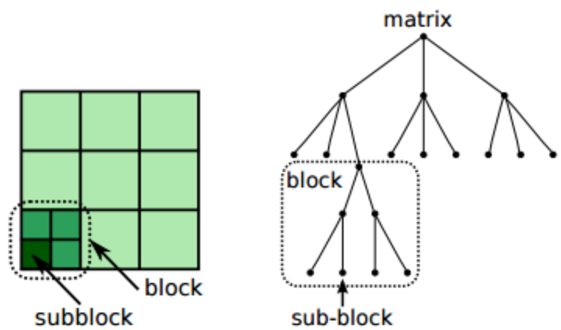
Partitioning Data

- Data can be partitioned using *filters*
  - Can express blocking of rectangular collections
- Can also be applied recursively
  - i.e., can express hierarchical partitioning
- And dynamically
  - All partitioning done at runtime

Partitioning Example

```
h = register_matrix( &matrix, ptr, n, n, …)

map_filters(matrix, 2, filter_row, 3, filter_col, 3)

block = get_sub_data(matrix, 2, 2, 0);

map_filters(block, 2, filter_row, 2, filter_col, 2);

subblock = get_sub_data(block, 2, 1, 0);
```

Picture



Automated Data Movement

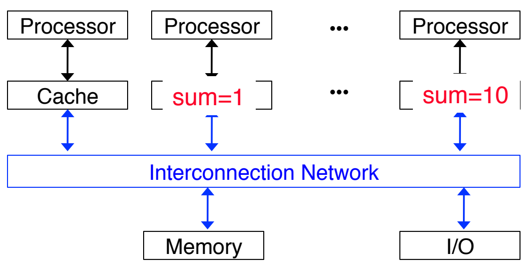
- Multiple tasks may access the same data
- And in different ways
  - Reading, writing, reading and writing
- Need to solve two problems
  - Be lazy – don't move data unless necessary
    - E.g., to have multiple copies if everyone is reading
  - But need to ensure tasks have most recent version
    - If a task writes, future reads must come from that version of the data

Cache Coherence

- Managing data coherence is not a new problem
- The original and best known version occurs in cache coherent multiprocessors

Cache Coherence Problem

- Want to cache shared data to reduce access time
- Problem
  - Two caches with inconsistent values



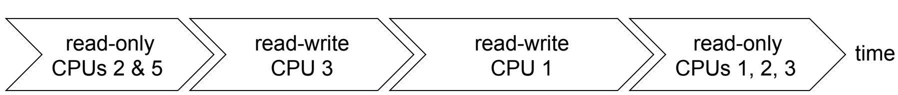
Cache Coherence

1. Single-Writer, Multiple-Read (SWMR) Invariant

   For any memory location *A*, in any given *epoch*, there is
   - one processor that may write (and read) *A*, or
   - some number of processors that may only read *A*

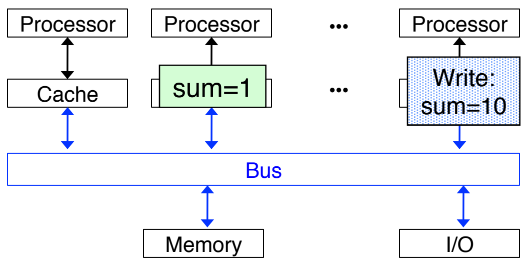
2. Data-Value Invariant

   The value of the memory location at the start of an epoch is the same as the value of the memory location at the end of its last read-write epoch



Snoopy Cache Coherence

- Solution
  - Have caches "snoop" on other caches' reads and writes
  - Writes: Invalidate other cached copies (READ EXCLUSIVE)
  - Reads: Get latest version from other cache, if it has a "dirty" copy (READ SHARED)
  - Coherence at granularity of cache lines



Snoopy Cache Coherence 2

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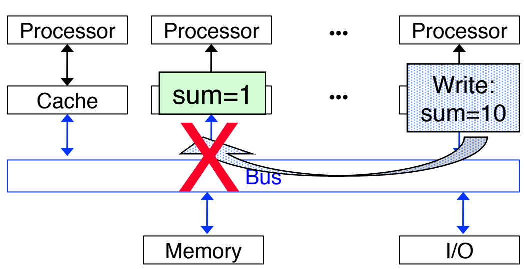

Snoopy Cache Coherence 3

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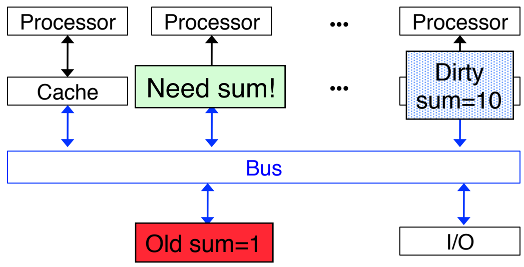

Snoopy Cache Coherence 4

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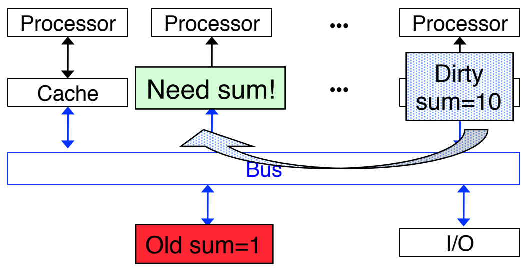
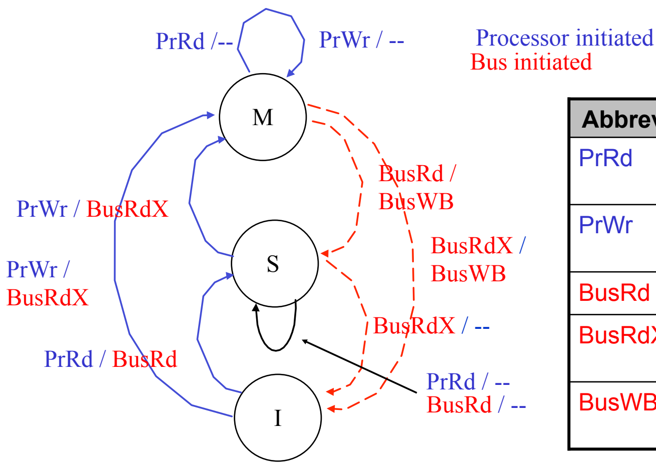


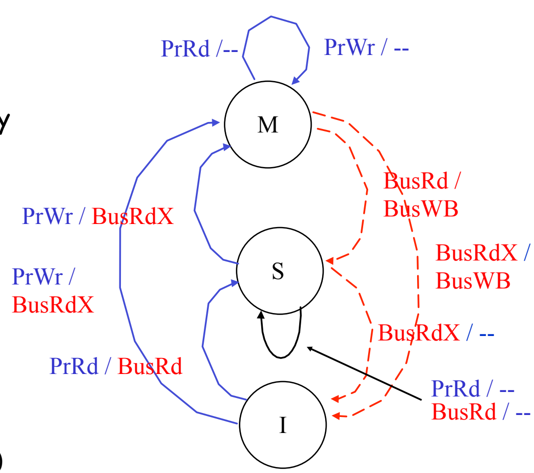
Cache Coherence Protocol: MSI State Diagram



Abbreviation	Action
PrRd	Processor Read
PrWr	Processor Write
BusRd	Bus Read
BusRdX	Bus Read Exclusive
BusWB	Bus Writeback

MSI Invalidate Protocol

- Read obtains block in "shared"
  - even if only cached copy
- Obtain exclusive ownership before writing
  - BusRdX causes others to invalidate
  - If M in another cache, will cause writeback
  - BusRdX even if hit in S
    - promote to M (upgrade)



A Cache Coherence Example

Proc Action	P1 State	P2 state	P3 state	Bus Act	Data from
1. P1 read u	S	--	--	BusRd	Memory
2. P3 read u	S	--	S	BusRd	Memory
3. P3 write u	I	--	M	BusRdX	Memory, P3
4. P1 read u	S	--	S	BusRd	P3's cache
5. P2 read u	S	S	S	BusRd	Memory
6. P2 write u	I	M	I	BusRdX	P2's cache

- Single writer, multiple reader protocol

Back to the Story ...

StarPU Implements a MSI Protocol

- Each task has it's own local "cache"
  - The copies of the data it is using
- When a task finishes, the data remains
  - Not immediately reclaimed
  - Either in modified or shared state
- Thus, new tasks may have choices
  - Of which of several versions in shared state to use
  - If a task writes, invalidates other copies

What About Hierarchy?

- But StarPU's data model also has hierarchy
  - May be working on a subset of a larger collection
- How is partitioning/hierarchy incorporated?

What About Hierarchy?

- Answer:
  - Tasks can only use the finest partition available
  - When done with a partition, an explicit *release* writes modified subsets back to the containing collection
- Thus, tasks work on the leaves of the partitioning hierarchy
  - Creating a new level of partition will cause copies from the coarser to finer level when tasks run
  - A release flushes changes back to coarser level
- Allows MSI protocol to be used more or less unchanged

Legion/Region

- Legion and Regent have the same issues
  - But allow multiple partitions of the same data
  - And parent/child regions can be used simultaneously
- Add *open* and *close* operations to MSI
  - And more states
  - Open: A subtree is *opened* by a task using a subregion
  - Close: A subtree is *closed* by copying dirty data back to the root of the subtree

Comparison StarPU & Regent

- StarPU
  - Relatively small, lightweight system
- Regent
  - Much bigger system
  - Why?

What Does StarPU Not Do?

- Two smaller things:
- Less automatic management
  - Of dependencies
    - Programmer responsible for declaring dependencies
  - Of data coherence
    - Programmer responsible for open/close operations
- Not as aggressive about scheduling ahead
  - Data movement dependencies handled separately
  - Overlaps communication/computation, but task launch not tied to data necessarily being ready

Big Ticket Item #4

- Data model is dense arrays
  - And all examples are dense linear algebra
- No distinct support for unstructured or sparse data

Big Ticket Item #3

- No support for multiple views of data
- One partitioning of the data can exist at at time
- The language of expressible partitions is also limited
  - To things that are very efficient to compute
  - Seems necessary given previous point

Big Ticket Item #2

- No support for launching large numbers of long-running tasks
- E.g.,
  - Regent's SPMD transformation
  - Legion's explicitly parallel features
- Needed to run on large node counts

Big Ticket Item #1

- Not distributed
- Designed to be a great scheduler for 1 node with attached accelerators
- A common decision in parallel programming systems!
  - Distribution is very hard.

Summary

- StarPU is a close cousin of Legion/Regent
- Well designed!
- Different decisions due to focus on
  - Single node
  - Simpler data model