Bulk Synchronous and SPMD Programming

CS315B

Lecture 2

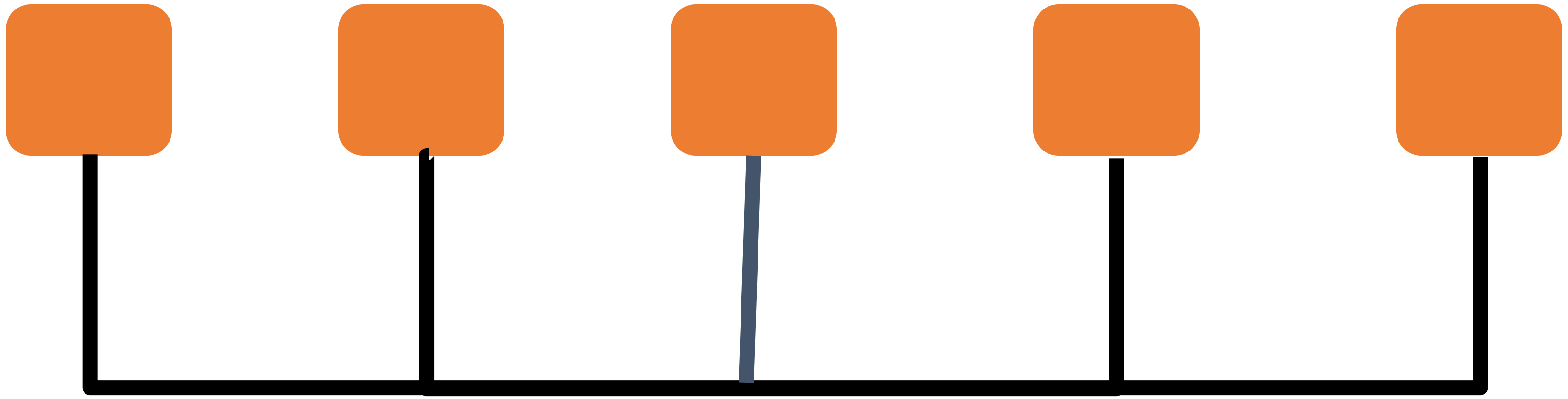
The Bulk Synchronous Model

Bulk Synchronous Model

- A model
  - An idealized machine

- Originally proposed for analyzing parallel algorithms
  - Leslie Valiant
  - “A Bridging Model for Parallel Computatation”, 1990

The Machine



What are some properties of this machine model?

Computations

- A sequence of *supersteps:*

- Repeat:
- *All processors do local computation*
- *Barrier*
- *All processors communicate*
- *Barrier*

What are properties of this computational model?

Basic Properties

- Uniform
    - compute nodes
    - communication costs
- Separate communication and computation
- Synchronization is global

The Idea

- Programs are
  - written for v virtual processors
  - run on p physical processors

- If $v >= p \log p$ then
  - Managing memory, communication and synchronization can be done automatically within a constant factor of optimal

How Does This Work?

- Roughly
  - Memory addresses are hashed to a random location in the machine
  - Guarantees that on average, memory accesses have the same cost
  - The extra log p factor of threads are multiplexed onto the p processors to hide the latency of memory requests
  - The processors are kept busy and do no more compute than necessary

SPMD

Terminology

- SIMD
  - Single Instruction, Multiple Data
- SPMD
  - Single Program, Multiple Data

SIMD = Vector Processing

```
if (factor == 0)
   factor = 1.0
A[1..N] = B[1..N] * factor;
j += factor;
```

Picture

```
if (factor == 0)
  factor = 1.0
```

```
A[1] = B[1] * factor
```

```
A[2] = B[2] * factor
```

```
A[3] = B[3] * factor
```

. . .

```
j += factor
```

Comments

- Single thread of control
  - Global synchronization at each program instruction
- Can exploit fine-grain parallelism
  - Assumption of hardware support

SPMD = Single Program, Multiple Data

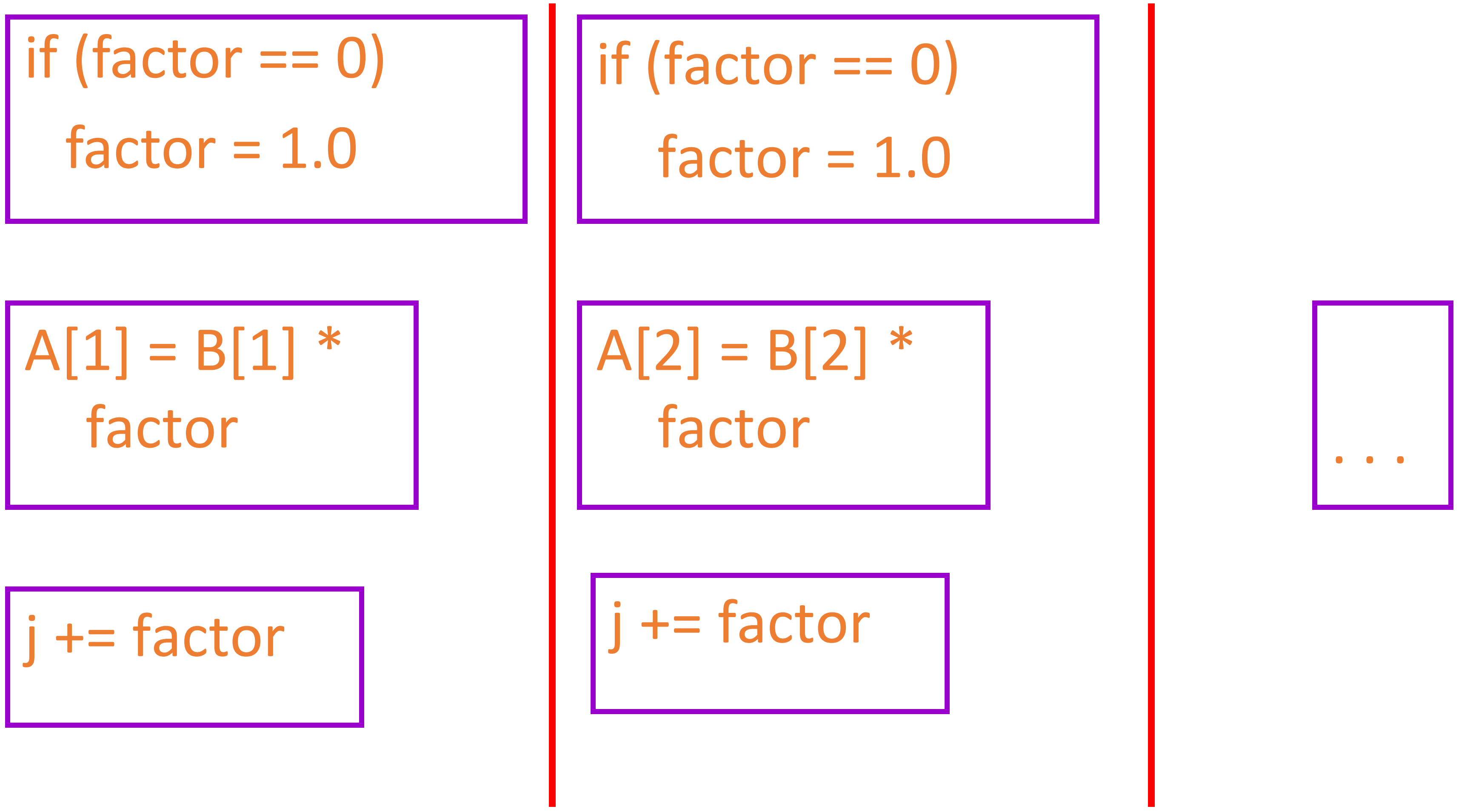
SIMD

```
if (factor == 0)
  factor = 1.0
A[1..N] = B[1..N] * factor;
j += factor;
…
```

SPMD

```
if (factor == 0)
  factor = 1.0
A[myid] = B[myid] * factor;
j += factor;
…
```

Picture



if (factor == 0)
factor = 1.0
A[1] = B[1] * factor
j += factor
if (factor == 0)
factor = 1.0
A[2] = B[2] * factor
j += factor
. . .

Comments

- Multiple threads of control
  - One (or more) per processor
- Asynchronous
  - All synchronization is programmer-specified
- Threads are distinguished by myid
- Choice: Are variables local or global?

Comparison

- SIMD
  - Designed for tightly-coupled, synchronous hardware
  - i.e., vector units

- SPMD
  - Designed for clusters
  - Too expensive to synchronize every statement
  - Need a model that allows asynchrony

MPI

- Message Passing Interface
  - A widely used standard
  - Runs on everything

- A runtime system

- Most popular way to write SPMD programs

MPI Programs

- Standard sequential programs
  - All variables are local to a thread

- Augmented with calls to the MPI interface
  - SPMD model
  - Every thread has a unique identifier
  - Threads can send/receive messages
  - Synchronization primitives

MPI Point-to-Point Routines

- MPI_Send(buffer, count, type, dest, …)
- MPI_Recv(buffer, count, type, source, …)

Example

```
 for (….)  {
// p = number of chunks of 1D grid, id = process id, h[] = local chunk of the grid
// boundary elements of h[] are copies of neighbors boundary elements

  .... Local computation ...

// exchange with neighbors on a 1-D grid
 if ( 0 < id )
     MPI_Send ( &h[1], 1, MPI_DOUBLE, id-1, 1, MPI_COMM_WORLD );
if ( id < p-1 )
     MPI_Recv ( &h[n+1], 1,  MPI_DOUBLE, id+1, 1, MPI_COMM_WORLD, &status );
if ( id < p-1 )
     MPI_Send ( &h[n], 1, MPI_DOUBLE, id+1, 2, MPI_COMM_WORLD );
if ( 0 < id )
     MPI_Recv ( &h[0], 1, MPI_DOUBLE, id-1, 2, MPI_COMM_WORLD, &status );

… More local computation ...

}
```

MPI Point-to-Point Routines, Non-Blocking

- MPI_ISend(…)
- MPI_Irecv(…)

- MPI_Wait(…)

Example

```
 for (….)  {
// p = number of chunks of 1D grid, id = process id, h[] = local chunk of the grid
// boundary elements of h[] are copies of neighbors boundary elements

  .... Local computation ...

// exchange with neighbors on a 1-D grid
 if ( 0 < id )
     MPI_ISend ( &h[1], 1, MPI_DOUBLE, id-1, 1, MPI_COMM_WORLD );
if ( id < p-1 )
     MPI_IRecv ( &h[n+1], 1,  MPI_DOUBLE, id+1, 1, MPI_COMM_WORLD, &status );
if ( id < p-1 )
     MPI_ISend ( &h[n], 1, MPI_DOUBLE, id+1, 2, MPI_COMM_WORLD );
if ( 0 < id )
     MPI_IRecv ( &h[0], 1, MPI_DOUBLE, id-1, 2, MPI_COMM_WORLD, &status );
MPI_Wait(…1...)
MPI_Wait(...2...)

… More local computation ...
}
```

MPI Collective Communication Routines

- MPI_Barrier(…)
- MPI_Bcast(…)
- MPI_Scatter(…)
- MPI_Gather(…)
- MPI_Reduce(…)

Typical Structure

```
communicate_get_work_to_do();
barrier;                    // not always needed
do_local_work();
barrier;
communicate_write_results();
```

What does this remind you of?

PGAS Model

- PGAS = *Partitioned Global Address Space*

- There is one global address space

- But each thread owns a partition of the address space that is more efficient to access
  - i.e., the local memory of a processor

- Equivalent in functionality to MPI
  - But typically presented as a programming language
  - Examples: Split-C, UPC, Titanium

PGAS Languages

- No library calls for communication

- Instead, variables can name memory locations on other machines

```
// Assume y points to a remote location
// The following is equivalent to a send/receive
x = *y
```

PGAS Languages

- Also provide collective communication
- Barrier
- Broadcast/Reduce
  - 1-many
- Exchange
  - All-to-all

PGAS vs. MPI

- Programming model very similar
  - Both provide SPMD
- From a pragmatic point of view, MPI rules
  - Easy to add MPI to an existing sequential language
- For productivity, PGAS is better
  - Programs filled with low-level details of MPI calls
  - PGAS programs easier to modify
  - PGAS compilers can know more/do better job

Summary

- SPMD is well-matched to cluster programming
  - Also works well on shared memory machines

- One thread per core
  - No need for compiler to discover parallelism
  - No danger of overwhelming # of threads

- Model exposes memory architecture
  - Local vs. Global variables
  - Local computation vs. sends/receives

Analysis

Control

SIMD

```
if (factor == 0)
  factor = 1.0
forall (i = 1..N)
  A[i] = B[i] * factor;
j += factor;
…
```

SPMD

```
if (factor == 0)
  factor = 1.0
A[myid] = B[myid] * factor;
j += factor;
…
```

Control, Cont.

- SPMD replicates the sequential part of the SIMD computation
  - Across all threads!

- Why?
  - Often cheaper to replicate computation in parallel than compute in one place and broadcast
  - A general principle . . .

Global Synchronization Revisited

- In the presence of non-blocking global memory operations, we also need memory fence operations

- Two choices
  - Have a separate classes of memory and control synchronization operations
    - E.g., barrier and memory_fence
  - Have a single set of operations
    - E.g., barrier implies memory and control synchronization

Message Passing Implementations

- Idea: A memory fence is a special message sent on the network; when it arrives, all the memory operations are complete
- To work, underlying message system must deliver messages in order
- This is one of the key properties of MPI
    - And most message systems

Bulk Synchronous/SPMD Model

- Easy to understand
- Phase structure guarantees no data races
  - Barrier synchronization also easy to understand
- Fits many problems well

But …

- Assumes 2-level memory hierarchy
  - Local/global, a flat collection of homogenous sequential processors
- No overlap of communication and computation
- Barriers scale poorly with machine size
  - (# of operations lost) * (# of processors)

Hierarchy

- Current & future machines are more hierarchical
  - 3-4 levels, not 2
- Leads to programs written in a mix of
  - MPI (network level)
  - OpenMP (node level) + vectorization
  - CUDA (GPU level)
- Each is a different programming model

No Overlap of Computation/Communication

- Leaves major portion of the machine idle in each phase

- And this potential is lost at many scales
  - Hierarchical machines again

- Increasingly, communication is key
  - Data movement is what matters
  - Most of the execution time, most of the energy

Global Operations

- Global operations (such as barriers) are bad
  - Require synchronization across the machine
  - Especially bad when there is performance variation among participating threads

- Need a model that favors asynchrony
  - Couple as few things together as possible

Global Operations Continued

- MPI has evolved to include more asynchronous and point-to-point primitives

- But these do not always mix well with the collective/global operations

I/O

- How do programs get initial data? Produce output?

- In many models answer is clear
  - Passed in and out from root function
    - Map-Reduce

  - Multithreaded shared memory applications just use the normal file system interface

I/O, Cont.

- Not clear in SPMD

- Program begins running and
  - Each thread is running in its own address space
  - No thread is special
    - No obvious distinguished thread to do I/O

I/O, Cont.

- Option 1
  - Make thread 0 special
  - Thread 0 does all I/O on behalf of the program
  - Issue: Awkward to read/write large data sets
    - Limited by thread 0's memory size

- Option 2
  - Parallel I/O
  - Each thread has access to its own file system
  - Containing distributed files
    - Each file "f" a portion of a collective file "f"

I/O Summary

- Option 2 is clearly more SPMD-ish

- Creating/deallocating files requires a barrier

- In general, parallel programming languages have not paid much attention to I/O

Next Week

- Intro to cuNumeric
- First assignment