Overview

- Basic concepts
- Programming models
- Multiprogramming
- Shared address space model
  - UMA versus NUMA
  - Distributed shared memory
  - Task parallel
  - Data parallel, vector and SIMD
- Message passing model
- Hybrid systems
- BSP model
Parallel Programming: Basic Concepts

- Control
  - How is parallelism created, implicitly (hardwired) or explicitly?
  - What orderings exist between operations?
  - How do different threads of control synchronize?

- Naming
  - What data is private and what is shared?
  - How is logically shared data accessed or communicated?

- Operations
  - What are the basic operations on shared data?
  - Which operations are considered atomic?

- Cost
  - How do we account for the cost of each of the above to achieve parallelism (man hours spent, software/hardware cost)
Parallel Programming Models

- **Programming model** = conceptualization of the machine that a programmer uses for developing applications

- **Multiprogramming model**
  - Independence tasks, no communication or synchronization at program level, e.g. web server sending pages to browsers

- **Shared address space (shared memory) programming**
  - Tasks operate and communicate via shared data, like bulletin boards

- **Message passing programming**
  - Explicit point-to-point communication, like phone calls (connection oriented) or email (connectionless, mailbox posts)
Task versus Data Parallel

- Task parallel (maps to high-level MIMD machine model)
  - Task differentiation, like restaurant cook, waiter, and receptionist
  - Communication via shared address space or message passing
  - Synchronization is explicit (via locks and barriers)
  - Underscores operations on private data, explicit constructs for communication of shared data and synchronization

- Data parallel (maps to high-level SIMD machine model)
  - Global actions on data by tasks that execute the same code
  - Communication via shared memory or logically shared address space with underlying message passing
  - Synchronization is implicit (lock-step execution)
  - Underscores operations on shared data, private data must be defined explicitly or is simply mapped onto shared data space
Example: 

\[ A = \sum_{i=1}^{N} f(a_i) \]

- Parallel decomposition
  - Assign \( N/P \) elements to each processor
  - Each processor computes the partial sum
  - One processor collects the partial sums

- Determine the data placement:
  - Logically shared: array \( a \), global sum \( A \)
  - Logically private: the function evaluations
  - Either logically shared or private: partial sums \( A_j \)
Programming Model 1

- **Shared address space (shared memory) programming**
- Task parallel, thread-based MIMD
  - Program is a collection of threads of control
- Collectively operate on a set of *shared data* items
  - Global static variables, Fortran common blocks, shared heap
- Each thread has *private variables*
  - Thread state data, local variables on the runtime stack
- Threads coordinate explicitly by synchronization operations on shared variables, which involves
  - Thread creation and join
  - Reading and writing flags
  - Using locks and semaphores (e.g. to enforce mutual exclusion)
Programming Model 1

- **Uniform memory access (UMA) shared memory machine**
  - Each processor has uniform access to memory
  - Symmetric multiprocessors (SMP)
- No local/private memory, private variables are put in shared memory
- Cache makes access to private variables seem “local”

**Programming model**

**Machine model**
Programming Model 1

- **Nonuniform memory access (NUMA) shared memory machine**
  - Memory access time depends on location of data relative to processor
  - Local access is faster
- No local/private memory, private variables are put in shared memory

**Programming model**

**Machine model**
Programming Model 1

- Distributed shared memory machine (DSM)
- Logically shared address space
  - Remote memory access is more expensive (NUMA)
  - Remote memory access requires communication, automatic either done in hardware or via software layer

![Diagram of shared and private memory]

Programming model

Machine model
Programming Model 1

Thread 1

shared A
shared A[1..2]
private i

A[1] := 0
for i = 1..N/2

Thread 2

shared A
shared A[1..2]
private i

for i = N/2+1..N

What could go wrong?
Programming Model 1

Thread 1

\[ A_1 := A_1 + f(a[0]) \]
\[ A_1 := A_1 + f(a[1]) \]
\[ A_1 := A_1 + f(a[2]) \]
\[ \ldots \]
\[ A_1 := A_1 + f(a[9]) \]
\[ A := A_1 + A_2 \]

Thread 2

\[ \ldots \]
\[ A_2 := A_2 + f(a[10]) \]
\[ A_2 := A_2 + f(a[11]) \]
\[ A_2 := A_2 + f(a[12]) \]
\[ \ldots \]

Thread 2 has not completed in time
Programming Model 1

Thread 1

shared A
shared A[1..2]
private i

A := 0
A[1] := 0
for i = 1..N/2
A := A + A[1]

Thread 2

shared A
shared A[1..2]
private i

A := 0
for i = N/2+1..N

What could go wrong?
Programming Model 1

Thread 1

\[ \ldots \]
\[ A := A + A[1] \]

Thread 2

\[ \ldots \]

Race condition

\[ \text{reg1} = A \]
\[ \text{reg2} = A[1] \]
\[ \text{reg1} = \text{reg1} + \text{reg2} \]
\[ A = \text{reg1} \]

\[ \text{reg1} = A \]
\[ \text{reg2} = A[2] \]
\[ \text{reg1} = \text{reg1} + \text{reg2} \]
\[ A = \text{reg1} \]

Instructions from different threads can be interleaved arbitrarily:
Programming Model 1

Thread 1

shared A
shared A[1..2]
private i

A[1] := 0
for i = 1..N/2
atomic A := A + A[1]

Thread 2

shared A
shared A[1..2]
private i

for i = N/2+1..N

Solution with atomic operations to prevent race condition
Programming Model 1

Thread 1

shared A
shared A[1..2]
private i

A[1] := 0
for i = 1..N/2

Critical section

lock
A := A + A[1]
unlock

Thread 2

shared A
shared A[1..2]
private i

for i = N/2+1..N

Critical section

lock
unlock

Solution with locks to ensure mutual exclusion
Programming Model 1

Thread 1

\[ A_j = \sum_{i=(j-1)k+1}^{jk} f(a_i) \]
\[ A = \sum_{i=1}^{P} A_i \]

shared A
private Aj
private i

\[ A_j := 0 \]
for \( i = 1..N/2 \)
\[ A_j := A_j + f(a[i]) \]
lock
A := A + A_j
unlock

Note that the \( A[1] \) and \( A[2] \) are just local, so make them private

Thread 2

shared A
private Aj
private i

\[ A_j := 0 \]
for \( i = N/2+1..N \)
\[ A_j := A_j + f(a[i]) \]
lock
A := A + A_j
unlock
Programming Model 1

Thread 1

shared A
private Aj
private i

Aj := 0
for i = 1..N/2
    Aj := Aj + f(a[i])
lock
A := A + Aj
unlock
... := A

Thread 2

shared A
private Aj
private i

Aj := 0
for i = N/2+1..N
    Aj := Aj + f(a[i])
lock
A := A + Aj
unlock
... := A

What could go wrong?
Programming Model 1

Thread 1

shared A
private Aj
private i

Aj := 0
for i = 1..N/2
   Aj := Aj + f(a[i])
lock
A := A + Aj
unlock
barrier
... := A

Thread 2

shared A
private Aj
private i

Aj := 0
for i = N/2+1..N
   Aj := Aj + f(a[i])
lock
A := A + Aj
unlock
barrier
... := A

With locks, private $A_j$, and barrier synchronization
Programming Model 2

- **Shared address space** (shared memory) programming
- **Data parallel programming**
  - Single thread of control consisting of parallel operations
  - Parallel operations are applied to (a specific segment of) a data structure, such as an array
- Communication is implicit
- Synchronization is implicit

```plaintext
shared array a, x
shared A
a := array of input data
x := f(a)
A := sum(x)
```
Programming Model 2

- E.g. data parallel programming with a vector machine
- One instruction executes across multiple data elements, typically in a pipelined fashion

```plaintext
shared array a, x
shared A
a := array of input data
x := f(a)
A := sum(x)
```

Programming model

Machine model
Programming Model 2

- Data parallel programming with a SIMD machine
- Large number of (relatively) simple processors
  - Like multimedia extensions (MMX/SSE/AltiVec) on uniprocessors, but with scalable processor grids
- A control processor issues instructions to simple processors
  - Each processor executes the same instruction (in lock-step)
  - Processors are selectively turned off for control flow in program

```
REAL, DIMENSION(6) :: a,b
...
WHERE b /= 0.0
  a = a/b
ENDWHERE
```

Fortran 90 / HPF
(High-Performance Fortran)

Lock-step execution by an array of processors with some processors temporarily turned off
Programming Model 3

- **Message passing programming**
- Program is a set of *named* processes
  - Process has thread of control and local memory with local address space
- Processes communicate via explicit data transfers
  - Messages between source and destination, where source and destination are named processors P0…Pn (or compute nodes)
  - Logically shared data is explicitly partitioned over local memories
  - Communication with send/recv via standard message passing libraries, such as MPI and PVM
Programming Model 3

- Message passing programming
- Each node has a network interface
  - Communication and synchronization via network
  - Message latency and bandwidth is dependent on network topology and routing algorithms

![Programming model](image1)
![Machine model](image2)
Programming Model 3

- Message passing programming
- Each node has a network interface
  - Communication and synchronization via network
  - Message latency and bandwidth is dependent on network topology and routing algorithms

Programming model

Machine model
Programming Model 3

- Message passing programming
- Each node has a network interface
  - Communication and synchronization via network
  - Message latency and bandwidth is dependent on network topology and routing algorithms
Programming Model 3

- Message passing programming
- On shared memory machine
  - Communication and synchronization via shared memory
  - Message passing library copies data (messages) in memory, less efficient (MPI call overhead) but portable

![Diagram of programming model and machine model]

Message passing on a shared memory machine

Programming model

Machine model
Programming Model 3

Solution with message passing, where global \( a[1..N] \) is distributed such that each processor has a local array \( a1[1..N/2] \)
Programming Model 3

Processor 1

A1 := 0
for i = 1..N/2
   A1 := A1 + f(al[i])
send A1 to P2
receive A2 from P2
A := A1 + A2

Processor 2

A2 := 0
for i = 1..N/2
   A2 := A2 + f(al[i])
send A2 to P1
receive A1 from P1
A := A1 + A2

Alternative solution with message passing, where global a[1..N] is distributed such that each processor has a local array al[1..N/2]

What could go wrong?
Programming Model 3

Processor 1

\[ A_1 := 0 \]
\[
\text{for } i = 1..N/2 \\
A_1 := A_1 + f(a_1[i]) \\
\text{send } A_1 \text{ to } P_2 \\
\text{receive } A_2 \text{ from } P_2 \\
A := A_1 + A_2
\]

Processor 2

\[ A_2 := 0 \]
\[
\text{for } i = 1..N/2 \\
A_2 := A_2 + f(a_2[i]) \\
\text{send } A_2 \text{ to } P_1 \\
\text{receive } A_1 \text{ from } P_1 \\
A := A_1 + A_2
\]

Deadlock with synchronous blocking send operations: both processors wait for data to be sent to a receiver that is not ready to accept the message.

Blocking and non-blocking versions of send/recv operations are available in message passing libraries: compare connection-oriented with rendezvous (telephone) to connectionless (mailbox).
Programming Model 4

- Hybrid systems: clusters of SMPs
- Shared memory within SMP, message passing outside
- Programming model with three choices:
  - Treat as “flat” system: always use message passing, even within an SMP
    - Advantage: ease of programming and portability
    - Disadvantage: ignores SMP memory hierarchy and advantage of UMA shared address space
  - Program in two layers: shared memory programming and message passing
    - Advantage: better performance (use UMA/NUMA intelligently)
    - Disadvantage: harder (and ugly!) to program
  - Program in three layers: SIMD (e.g. SSE instructions) per core, shared memory programming between cores on an SMP node, and message passing between nodes
Programming Model 4

shared a[1..N/numnodes]  \(\{\text{Shared part}\}\)
private n = N/numnodes/numprocs
private x[1..n]
private lo = (pid-1)*n
private hi = lo+n
\(x_{[1..n]} = f(a_{[lo..hi]})\)
A[pid] := sum(x[1..n])
send A[pid] to node1

A := 0
if node=1 and pid=1
  for j = 1..numnodes
    receive Aj from node(j)
    A := A + Aj
Extra code for node 1 proc 1
Programming Model 5

- **Bulk synchronous processing** (BSP)
- A BSP **superstep** consists of three **phases**
  1. Compute phase: processes operate on local data (also read access to shared memory on SMP)
  2. Communication phase: all processes cooperate in exchange of data or reduction of global data
  3. Barrier synchronization
- A parallel program is composed of supersteps
  - Ensures that computation and communication phases are completed before the next superstep
- Simplicity of data parallel programming, without the restrictions
The cost of a BSP superstep $s$ is composed of three parts:

- $w_s$ local computation cost of $s$
- $h_s$ is the number of messages send in superstep $s$
- $l$ is the barrier cost

The total cost of a program with $S$ supersteps is

$$W + Hg + Sl = \sum_{s=1}^{S} w_s + g \sum_{s=1}^{S} h_s + Sl$$

where $g$ is the communication cost such that it takes $gh$ time to send $h$ messages.
Summary

- Goal is to distinguish the programming model from underlying hardware
- Message passing, data parallel, BSP
  - Objective is portable *correct* code
- Hybrid
  - Tuning for the architecture
  - Objective is portable *fast* code
  - Algorithm design challenge (less uniformity)
  - Implementation challenge at all levels (fine to coarse grain)
    - Blocking at loop and data level (compiler and programmer)
    - SIMD vectorization at loop level (compiler and programmer)
    - Shared memory programming for each node (OpenMP)
    - Message passing between nodes (MPI)