CIS 631
Parallel Processing

Lecture 5: Parallel Programming

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- Portions of the lectures slides were adopted from:
Outline

- Dependency and Synchronization
- Methodological design of parallel programs
- Types of parallel programs
  - Data parallel vs. task parallel
  - Pipelining
  - Task graphs
  - Master-slave
  - Producer-consumer
  - Divide-and-conquer
  - SPMD
  - Loop scheduling
Fork-Join Parallelism

\[ x = g(a); \]
\[ \text{for( } i=0; i<100; i++ \text{ ) } a[i] = f(i); \]
\[ y = h(a); \]
\[ \text{for( } i=0; i<100; i++ \text{ ) } b[i] = x + h( a[i]); \]

- First loop is a DOALL loop
- Middle statement is sequential
- Second loop is a DOALL loop
- Execution moves between sequential and parallel phases
- Call this *fork-join* parallelism
Fork-Join and Barrier Synchronization

- `fork()` causes a number of processes to be created and to be run in parallel.
- `join()` causes all these processes to wait until all of them have executed a `join()` (barrier synchronization).

```plaintext
fork();
for( i=0; i<100; i++ ) a[i] = f(i);
join();
y = h(a);
fork();
for( i=0; i<100; i++ ) b[i] = x + h(a[i]);
join();
```
Synchronization Issues

- Synchronization is necessary to make some programs execute correctly in parallel.
- Dependences have to be “covered” by appropriate synchronization operations.
- Different synchronization constructs exist in different parallel programming models.
- However, synchronization is expensive.
- To reduce synchronization:
  - May need to limit parallelization.
  - Look for opportunities to increase parallelism granularity.
Methodological Design

- Partition:
  - Task/data decomposition

- Communication
  - Task execution coordination

- Agglomeration
  - Evaluation of the structure

- Mapping
  - Resource assignment
Partitioning

- Partitioning stage is intended to expose opportunities for parallel execution.
- Focus on defining large number of small tasks to yield a fine-grained decomposition of the problem.
- A good partition divides into small pieces both the *computation* associated with a problem and the *data* on which this computation operates.
- *Domain decomposition* focuses on computation data.
- *Functional decomposition* focuses on computation tasks.
- Mixing domain/functional decomposition is possible.
Domain and Functional Decomposition

- Domain decomposition of two / three-dimensional grid

1D

- BLOCK

2D

- BLOCK, *
- CYCLIC

- CYCLIC, *

- CYCLIC, CYCLIC

3D

- 1-D
- 2-D
- 3-D

- Functional decomposition of a climate model

Problem Instruction Set

Task 1

Task 2

Task 3

Task 4

Atmospheric Model

Hydrology Model

Ocean Model

Land Surface Model
Partitioning Checklist

- Does your partition define at least an order of magnitude more tasks than there are processors in your target computer? If not, may lose design flexibility.
- Does your partition avoid redundant computation and storage requirements? If not, may not be scalable.
- Are tasks of comparable size? If not, it may be hard to allocate each processor equal amounts of work.
- Does the number of tasks scale with problem size? If not may not be able to solve larger problems with more processors.
- Have you identified several alternative partitions?
Communication

- Tasks generated by a partition must interact to allow the computation to proceed
  - Information flow: data and control

- Types of communication
  - *Local* vs. *Global*: locality of communication
  - *Structured* vs. *Unstructured*: communication patterns
  - *Static* vs. *Dynamic*: determined by runtime conditions
  - *Synchronous* vs. *Asynchronous*: coordination degree

- Granularity and frequency of communication
  - Size of data exchange

- Communication as control
Types of Communication

- Point-to-point
- Group-based
- Hierarchical
- Collective
# Communication Design Checklist

- Is the distribution of communications equal?
  - Unbalanced communication may limit scalability

- What is the communication locality?
  - Wider communication locales are more expensive

- What is the degree of communication concurrency?
  - Communication operations may be parallelized

- Is computation associated with different tasks able to proceed concurrently? Can communication be overlapped with computation?
  - Try to reorder computation and communication to expose opportunities for parallelism
Agglomeration

- Move from parallel abstractions to real implementation
- Revisit partitioning and communication
  - View to efficient algorithm execution
- Is it useful to agglomerate (combine) tasks?
- Is it useful to replicate data and/or computation?
- Changes important algorithm and performance ratios
  - Surface-to-volume: reduction in communication at the expense of decreasing parallelism
  - Communication/computation: which cost dominates
- Replication may allow reduction in communication
- Maintain flexibility to allow overlap
Types of Agglomeration

- Element to column
- Element to block
  - Better surface to volume
- Task merging
- Task reduction
  - Reduces communication
Agglomeration Design Checklist

- Has increased locality reduced communication costs?
- Is replicated computation worth it?
- Does data replication compromise scalability?
- Is the computation still balanced?
- Is scalability in problem size still possible?
- Is there still sufficient concurrency?
- Is there room for more agglomeration?
- Fine-grained vs. coarse-grained?
Mapping

- Specify where each task is to execute
  - Less concern on shared-memory computers
- Attempt to minimize execution time
  - Place concurrent tasks on different processors to enhance physical concurrency
  - Place communicating tasks on same processor, or on processors close to each other, to increase locality
  - Strategies can conflict!
- Mapping problem is \textit{NP-complete}
  - Use problem classifications and heuristics
- Static and dynamic load balancing
Mapping Algorithms

- Load balancing (partitioning) algorithms
- Data-based algorithms
  - Think of computational load with respect to amount of data being operated on
  - Assign data (i.e., work) in some known manner to balance
  - Take into account data interactions
- Task-based (task scheduling) algorithms
  - Used when functional decomposition yields many tasks with weak locality requirements
  - Use task assignment to keep processors busy computing
  - Consider centralized and decentralize schemes
Mapping Design Checklist

☐ Is static mapping too restrictive and non-responsive?
☐ Is dynamic mapping too costly in overhead?
☐ Does centralized scheduling lead to bottlenecks?
☐ Do dynamic load-balancing schemes require too much coordination to re-balance the load?
☐ What is the tradeoff of dynamic scheduling complexity versus performance improvement?
☐ Are there enough tasks to achieve high levels of concurrency? If not, processors may idle.
Types of Parallel Programs

- Flavors of parallelism
  - Data parallelism
    - All processors do the same thing on different data
  - Task parallelism
    - Processors are assigned tasks that do different things

- Parallel execution models
  - Data parallel
  - Pipelining (Producer-Consumer)
  - Task graph
  - Work pool
  - Master-Worker
Data Parallel

- Data is decomposed (mapped) onto processors
- Processors performance similar (identical) tasks on data
- Tasks are applied concurrently
- Load balance is obtained through data partitioning
  - Equal amounts of work assigned
- Certainly may have interactions between processors
- Data parallelism scalability
  - Degree of parallelism tends to increase with problem size
  - Makes data parallel algorithms more efficient
- Single Program Multiple Data (SPMD)
  - Convenient way to implement data parallel computation
Matrix - Vector Multiplication

- $A \times b = y$
- Allocate tasks to rows of $A$
  \[ y[i] = \sum_{j} A[i,j] * b[j] \]
- Dependencies?
- Speedup?
- Computing each element of $y$ can be done independently
Matrix-Vector Multiplication with Limited Tasks

- Suppose we only have 4 tasks
- Dependencies?
- Speedup?

![Diagram of matrix multiplication with limited tasks](image)
Matrix Multiplication

- \( A \times B = C \)
- \( A[i,:] \cdot B[:,j] = C[i,j] \)

- **Row partitioning**
  - \( N \) tasks

- **Block partitioning**
  - \( N \times N/B \) tasks

- Shading shows data sharing in B matrix
Granularity of Task and Data Decompositions

- Granularity can be with respect to tasks and data
- Task granularity
  - Equivalent to choosing the number of tasks
  - Fine-grained decomposition results in large # tasks
  - Large-grained decomposition has smaller # tasks
  - Translates to data granularity after # tasks chosen
    - consider matrix multiplication
- Data granularity
  - Think of in terms of amount of data needed in operation
  - Relative to data as a whole
  - Decomposition decisions based on input, output, input-output, or intermediate data
Mesh Allocation to Processors

- Mesh model of Lake Superior
- How to assign mesh elements to processors
- Distribute onto 8 processors
  - randomly
  - graph partitioning for minimum edge cut
Pipeline Model

- Stream of data operated on by succession of tasks
  - Tasks are assigned to processors
- Consider $N$ data units
- Sequential
- Parallel (each task assigned to a processor)

4-way parallel

4-way parallel, but for longer time
Pipeline Performance

- \( N \) data and \( T \) tasks
- Each task takes unit time \( t \)
- Sequential time = \( N \times T \times t \)
- Parallel pipeline time = \( \text{start} + \text{finish} + \frac{(N-2T)}{T} \times t \)
  \( = O(\frac{N}{T}) \) (for \( N >> T \))

- Try to find a lot of data to pipeline
- Try to divide computation in a lot of pipeline tasks
  - More tasks to do (longer pipelines)
  - Shorter tasks to do

- Pipeline computation special form of producer-consumer
  - Producer tasks output data input by consumer tasks
**Tasks Graphs**

- Computations in any parallel algorithms can be viewed as a task dependency graph
- Task dependency graphs may be simple or non-trivial
  - Pipeline
  - Arbitrary (represents the algorithm dependencies)

Numbers are time taken to perform task
Task Graph Performance

- Determined by the *critical path*
  - Sequence of dependent tasks that takes the longest time

![Task Graph](image)

- Critical path length bounds parallel execution time

Min time = 27

Min time = 34
Task Assignment (Mapping) to Processors

- Given a set of tasks and number of processors
- How to assign tasks to processors?
- Should take dependencies into account
- Task mapping will determine execution time

(a) Task 4
   Task 3
   Task 2
   Task 1

   Task 6
   Task 5
   Task 7

   Total time = ?

(b) Task 4
   Task 3
   Task 2
   Task 1

   Task 5
   Task 6
   Task 7

   Total time = ?
Bag o’ Tasks Model and Worker Pool

- Set of tasks to be performed
- Find independent tasks
- Assign tasks to available processors
  - Worker pool of processor

- Dynamic approach
- Useful for achieving load balance
- Asynchronous Dynamic Load Balancing (ADLB, ANL)
Master-Worker Parallelism

- One or more master processes generate work
- Masters allocate work to worker processes
- Workers idle if have nothing to do
- Workers are mostly stupid and must be told what to do
  - Execute independently
  - May need to synchronize, but most be told to do so
- Master may become the bottleneck if not careful
  - Consider task granularity and asynchrony
Master-Worker Execution Model (Li Li)

master

- init.
- setup
- send
- recv.
- final.

worker1

- init.
- recv.
- compute
- send
- final.

worker2

- init.
- recv.
- compute
- send
- final.
M-W Execution Trace (Li Li)
Search-Based (Exploratory) Decomposition

- 15-puzzle problem
- 15 tiles numbered 1 through 15 placed in 4x4 grid
  - Blank tile located somewhere in grid
  - Initial configuration is out of order
  - Find shortest sequence of moves to put in order

- Sequential search across space of solutions
  - May involve some heuristics
Parallelizing the 15-Puzzle Problem

- Enumerate move choices at each stage
- Assign to processors
- May do pruning
- Wasted work
Divide-and-Conquer Parallelism

- Break problem up in orderly manner into smaller, more manageable chunks and solve
- Quicksort example
Next Class

- Programming models
- Standard parallel programming techniques
  - shared memory (Pthreads)
  - message passing (MPI)
  - data parallelism (Fortran 90, CUDA)
  - shared memory + data parallelism (OpenMP)
  - object-oriented parallelism (?)