Lecture 3
Patterns for Parallel Programming I

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Overview

- Parallelizing a sequential program
- Design Patterns for Parallel Programs
  - Finding Concurrency
  - Algorithmic Structure
  - Supporting Structures
  - Implementation Mechanisms
Parallelizing a Program

1. Study sequential program
   - Compile and profile
   - What are the “hot” spots?
2. Look for parallelism opportunities
   - Decompose the data or code
   - Decomposing data implicitly decomposes code
3. Orchestrate and map tasks
Parallelization Common Steps

1. Study problem or code
2. Look for parallelism opportunities
3. Try to keep all cores busy doing useful work
1. Study problem or code

2. Look for parallelism opportunities

3. Try to keep all cores busy doing useful work

Slide Source: Dr. Rabbah, IBM, MIT Course 6.189 IAP 2007
1. Study problem or code

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Parallelization Common Steps

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Decomposition

- Identify Concurrency
  - Decide level to exploit
  - Understand algorithm and data structures!
  - May require restructuring algorithm or an entirely new algorithm
Decomposition (cont’d)

- Break computation into tasks
  - Divided among processes
  - Tasks may become available dynamically
  - Number of tasks can vary with time

Want enough tasks to keep processors busy.
Tasks to Processes

- Specify mechanism to divide work
- Balance of computation
- Reduce communication and synchronization
- Structured approaches work well
  - Code inspection and understanding algorithm
  - Using design patterns (next lecture)
Granularity

- Ratio of computation and communication

**Fine-grain parallelism**
- Tasks execute little comp. between comm.
- Easy to load balance
- If *too fine*, communication may take longer than computation

**Coarse-grain parallelism**
- Long computations between communication
- Harder to load balance
- More opportunity for performance increase

Which should we use?
• Computation and communication concurrency
• Schedule task to satisfy dependences
• Preserve locality of data
Lecture 5: Overview

• Parallelizing a sequential Program
• Design Patterns for Parallelization
  • Finding Concurrency
  • Algorithmic Structure
  • Supporting Structures
  • Implementation Mechanisms
Patterns for Parallelization

- Parallelization is a difficult problem
  - Hard to get everything to work correctly!
  - Hard to fully exploit parallel hardware
- One Solution: Design Patterns
Design Patterns

- Cookbook for parallel programmers
  - Can lead to high quality solutions
- Provides a common vocabulary
- Software reusability and modularity
• Christopher Alexander
  • Berkeley architecture professor
• Developed patterns for architecture
  • City planning
  • Layout of windows in a room
• Attempt to capture principles for “living” designs
Patterns for OOP

- Brought patterns to computer science
- Design Patterns: Elements of Reusable Object-Oriented Software (1994)
  - Gamma et al. (Gang of Four)
- Catalogue of “patterns”
- Not a finished solution!
• Patterns for Parallel Programming.
  • Mattson et al. (2005)
• Four Design Spaces
  • Finding Concurrency
  • Algorithm Structure
    • Map tasks to processes
  • Supporting Structures
    • Code and data structuring patterns
• Implementation Mechanisms
  • Low-level mechanisms for writing programs
Finding Concurrency

- Expose concurrent task or data
- Decomposition
  - Task, Data, Pipeline
- Dependency Analysis
  - Control dependences
  - Data dependences
- Design Evaluation
  - Suitability for target platform
  - Design quality
Decomposition

- Data (domain) decomposition
  - Break data up independent units
- Task (functional) decomposition
  - Break problem into parallel tasks
- Pipeline decomposition
Data Decomposition

- Also known as Domain Decomposition
- Implied by Task Decomposition

*Which decomposition more natural to start with, data or tasks?*

1) Decide how data is divided
2) Decide how tasks should be performed
Data Decomposition

Data decomposition is good when:

- Main computation manipulating a large data structure
- Similar operations applied to different parts of data structure (e.g., SIMD)
Common Data Decompositions

- Array-based computations
  - Decompose in a variety of ways, including rows, columns, blocks (tiles)
- Linked list data structures
  - Break up into sub-lists
- Recursive-data structures
  - Example: Parallel updates of large tree, by decomposing into small trees
Find the largest element of an array
Find the largest element of an array
Find the largest element of an array

CPU 0  CPU 1  CPU 2  CPU 3

Slide Source: Intel Software College, Intel Corp.
CISC 879 : Advanced Parallel Programming
Find the largest element of an array

CPU 0  CPU 1  CPU 2  CPU 3
Find the largest element of a 2D array
Find the largest element of an array
Find the largest element of an array
Find the largest element of an array
Find the largest element of an array

CPU 0
CPU 1
CPU 2
CPU 3
Find the largest element of an array

CPU 0  CPU 1  CPU 2  CPU 3

Slide Source: Intel Software College, Intel Corp.
Find the largest element of an array
Find the largest element of an array
Data Decomposition Forces

- Flexibility
  - Size of data chunks should support a range of systems

- Efficiency
  - Data chunks should have comparable (balanced) computation

- Simplicity
  - Complex decomposition hard to debug
Task Decomposition

- Also known as functional decomposition
- Some programs naturally decompose
- Divide tasks among cores
- Decide data accessed by each core
- Example: Event-handler for a GUI
Task Decomposition

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Slide Source: Intel Software College, Intel Corp.
Task Decomposition

CPU 1

- g()
- h()

CPU 0

- f()
- r()
- s()

CPU 2

- q()

Slide Source: Intel Software College, Intel Corp.

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Task Decomposition

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Task Decomposition

CPU 0

CPU 1

CPU 2

Slide Source: Intel Software College, Intel Corp.

CISC 879 : Advanced Parallel Programming
Task Decomposition

CPU 1

CPU 2

CPU 0

f()
g()
s()
Task Decomposition Forces

- Flexibility in number and size of tasks
  - Not architecture-specific
- Efficiency
  - Tasks large enough and as independent as possible
- Simplicity
  - Easy to understand and debug
Pipeline Decomposition

- Special kind of task decomposition
  - Data flows through a sequence of tasks
- “Assembly line” parallelism
- Example: compression

Read Block → Compress → Write Block
• Processing read uncompressed block (Step 1)
Pipeline Decomposition

- Compress block (Step 2)
• Write compressed block (Step 3)
Pipeline Decomposition

- Processing five data set (Step 1)

Slide Source: Intel Software College, Intel Corp.
Pipeline Decomposition

- Processing five data set (Step 2)

CPU 0 → CPU 1 → CPU 2

Data set 0
Data set 1
Data set 2
Data set 3
Data set 4
• Processing five data set (Step 3)
• Processing five data set (Step 4)
Pipeline Decomposition

- Processing five data set (Step 5)

Slide Source: Intel Software College, Intel Corp.
Pipeline Decomposition

- Processing five data set (Step 6)
Pipeline Decomposition

- Processing five data set (Step 7)

Slide Source: Intel Software College, Intel Corp.
Pipeline Decomposition Forces

- Flexibility
  - Deeper pipelines are better
- Efficiency
  - Stages of pipeline should not cause bottleneck
- Simplicity
  - Manageable chunks of code
• Control and Data Dependences
• Dependence Graph
  • Graph = (nodes, edges)
  • Data dependency graph (nodes = variables)
  • Control flow (nodes = basic blocks)
  • Call graph (nodes = functions)
• Edge indicates possible control or data dependency
for (i = 0; i < 3; i++)
    a[i] = b[i] / 2.0;
for (i = 0; i < 3; i++)
a[i] = b[i] / 2.0;

Domain decomposition possible
for (i = 1; i < 4; i++)
    a[i] = a[i-1] * b[i];
for (i = 1; i < 4; i++)
    a[i] = a[i-1] * b[i];

No domain decomposition
a = f(x, y, z);
b = g(w, x);
t = a + b;
c = h(z);
s = t / c;
a = f(x, y, z);
b = g(w, x);
t = a + b;
c = h(z);
s = t / c;

Task decomposition with 3 CPUs.
Evaluate Design

- Is the design good enough?
  - YES - move to next phase
  - NO - re-evaluate previous patterns

- Forces
  - Suitability to target platform
    - Should not depend on underlying architecture
  - Design quality
    - Trade-offs between simplicity, flexibility, and efficiency
  - Preparation for next phase
    - Algorithm Structure
Read for Next Time

- Reengineering for Parallelism: An Entry Point for PLPP (Pattern Language for Parallel Programming) for Legacy Applications  
  http://www.cise.ufl.edu/research/ParallelPatterns/plop2005.pdf