Credits

• Most of the slides courtesy Dr. Rodric Rabbah (IBM)
  – Taken from 6.189 IAP taught at MIT in 2007.
Outline

• Parallel programming
  – Start from scratch
  – Reengineering for parallelism

• Parallelizing a program
  – Decomposition (finding concurrency)
  – Assignment (algorithm structure)
  – Orchestration (supporting structures)
  – Mapping (implementation mechanisms)

• Patterns for Parallel Programming
Parallel programming from scratch

• Start with an algorithm
  – Formal representation of problem solution
  – Sequence of steps

• Make sure there is parallelism
  – In each algorithm step
  – Minimize synchronization points

• Don’t forget locality
  – Communication is costly
    • Performance, Energy, System cost

• More often start with existing sequential code
4 Common Steps to Creating a Parallel Program

Sequential Computation → Tasks → Units of Execution → Parallel Program → Processors

Partitioning

Decomposition → Assignment → Orchestration → Mapping
Reengineering for Parallelism

- Parallel programs often start as sequential programs
  - Easier to write and debug
  - Legacy codes

- How to reengineer a sequential program for parallelism:
  - Survey the landscape
  - Pattern provides a list of questions to help assess existing code
  - Many are the same as in any reengineering project
  - Is program numerically well-behaved?

- Define the scope and get users acceptance
  - Required precision of results
  - Input range
  - Performance expectations
  - Feasibility (back of envelope calculations)
Reengineering for Parallelism

• Define a testing protocol

• Identify program hot spots: where is most of the time spent?
  - Look at code
  - Use profiling tools

• Parallelization
  - Start with hot spots first
  - Make sequences of small changes, each followed by testing
  - Patterns provide guidance
Decomposition

- Identify concurrency and decide at what level to exploit it

- Break up computation into tasks to be divided among processes
  - Tasks may become available dynamically
  - Number of tasks may vary with time

- Enough tasks to keep processors busy
  - Number of tasks available at a time is upper bound on achievable speedup

Main consideration: coverage and Amdahl’s Law
Coverage

- **Amdahl's Law**: The performance improvement to be gained from using some faster mode of execution is limited by the fraction of the time the faster mode can be used.
  - Demonstration of the law of diminishing returns
Amdahl’s Law

- Potential program speedup is defined by the fraction of code that can be parallelized.

**Diagram:**
- Sequential: 25 seconds + 50 seconds + 25 seconds = 100 seconds
- Parallel: 100 seconds

**Use 5 processors for parallel work:**
- 25 seconds sequential + 10 seconds parallel + 25 seconds sequential = 60 seconds
Amdahl’s Law

• Speedup = old running time / new running time

= 100 seconds / 60 seconds
= 1.67
(parallel version is 1.67 times faster)
Amdahl’s Law

- \( p \) = fraction of work that can be parallelized
- \( n \) = the number of processors

\[
speedup = \frac{\text{old running time}}{\text{new running time}} = \frac{1}{(1 - p) + \frac{p}{n}}
\]

- \((1 - p)\) = fraction of time to complete sequential work
- \(\frac{p}{n}\) = fraction of time to complete parallel work
Implications of Amdahl’s Law

- Speedup tends to $\frac{1}{1-p}$ as number of processors tends to infinity.

Super linear speedups are possible due to registers and caches.

Typical speedup is less than linear.

Parallelism only worthwhile when it dominates execution.
Assignment

• Specify mechanism to divide work among PEs
  – Balance work and reduce communication

• Structured approaches usually work well
  – Code inspection or understanding of application
  – Well-known design patterns

• As programmers, we worry about partitioning first
  – Independent of architecture or programming model?
  – Complexity often affects decisions
  – Architectural model affects decisions

Main considerations: granularity and locality
Fine vs. Coarse Granularity

- **Fine-grained Parallelism**
  - Low computation to communication ratio
  - Small amounts of computational work between communication stages
  - High communication overhead
    - Potential HW assist

- **Coarse-grained Parallelism**
  - High computation to communication ratio
  - Large amounts of computational work between communication events
  - Harder to load balance efficiently
Load Balancing vs. Synchronization

Fine

Coarse

PE₀ PE₁

PE₀ PE₁
Load Balancing vs. Synchronization

Fine

Coarse

Expensive sync $\rightarrow$ coarse granularity

Few units of exec + time disparity $\rightarrow$ fine granularity
Orchestration and Mapping

- Computation and communication concurrency
- Preserve locality of data
- Schedule tasks to satisfy dependences early
- Survey available mechanisms on target system

Main considerations: locality, parallelism, mechanisms (efficiency and dangers)
Parallel Programming by Pattern

• Provides a cookbook to systematically guide programmers
  – Decompose, Assign, Orchestrate, Map
  – Can lead to high quality solutions in some domains

• Provide common vocabulary to the programming community
  – Each pattern has a name, providing a vocabulary for discussing solutions

• Helps with software reusability, malleability, and modularity
  – Written in prescribed format to allow the reader to quickly understand the solution and its context

• Otherwise, too difficult for programmers, and software will not fully exploit parallel hardware
History

- Berkeley architecture professor Christopher Alexander

- In 1977, patterns for city planning, landscaping, and architecture in an attempt to capture principles for “living” design
Example 167 (p. 783): 6ft Balcony

Therefore:

Whenever you build a balcony, a porch, a gallery, or a terrace always make it at least six feet deep. If possible, recess at least a part of it into the building so that it is not cantilevered out and separated from the building by a simple line, and enclose it partially.
Patterns in Object-Oriented Programming

• Design Patterns: Elements of Reusable Object-Oriented Software (1995)
  - Gang of Four (GOF): Gamma, Helm, Johnson, Vlissides
  - Catalogue of patterns
  - Creation, structural, behavioral
Patterns for Parallelizing Programs

4 Design Spaces

Algorithm Expression

- Finding Concurrency
  - Expose concurrent tasks

- Algorithm Structure
  - Map tasks to processes to exploit parallel architecture

Software Construction

- Supporting Structures
  - Code and data structuring patterns

- Implementation Mechanisms
  - Low level mechanisms used to write parallel programs

Here’s my algorithm. Where’s the concurrency?

MPEG Decoder

MPEG bit stream

VLD
macroblocks, motion vectors

split

ZigZag
frequency encoded macroblocks

IQuantization

IDCT

differentially coded motion vectors

Motion Vector Decode

Repeat

Saturation
spatially encoded macroblocks

Motion Compensation

recovered picture

Picture Reorder

Color Conversion

Display

Here’s my algorithm.

Where’s the concurrency?
Here’s my algorithm.
Where’s the concurrency?

- **Task decomposition**
  - Independent coarse-grained computation
  - Inherent to algorithm

- **Sequence of statements (instructions) that operate together as a group**
  - Corresponds to some logical part of program
  - Usually follows from the way programmer thinks about a problem
Here’s my algorithm.
Where’s the concurrency?

- **Task decomposition**
  - Parallelism in the application

- **Pipeline task decomposition**
  - Data assembly lines
  - Producer-consumer chains

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Dr. Rodric Rabbah, IBM
EE382V: Principles of Computer Architecture, Fall 2007 -- Lecture 7
Here’s my algorithm. Where’s the concurrency?

• **Task decomposition**
  – Parallelism in the application

• **Pipeline task decomposition**
  – Data assembly lines
  – Producer-consumer chains

• **Data decomposition**
  – Same computation is applied to small data chunks derived from large data set
Guidelines for Task Decomposition

• Algorithms start with a good understanding of the problem being solved

• Programs often naturally decompose into tasks
  – Two common decompositions are
    • Function calls and
    • Distinct loop iterations

• Easier to start with many tasks and later fuse them, rather than too few tasks and later try to split them
Guidelines for Task Decomposition

• Flexibility
  – Program design should afford flexibility in the number and size of tasks generated
    - Tasks should not be tied to a specific architecture
    - Fixed tasks vs. Parameterized tasks

• Efficiency
  – Tasks should have enough work to amortize the cost of creating and managing them
  – Tasks should be sufficiently independent so that managing dependencies doesn’t become the bottleneck

• Simplicity
  – The code has to remain readable and easy to understand, and debug
Case for Pipeline Decomposition

- Data is flowing through a sequence of stages
  - Assembly line is a good analogy

- What’s a prime example of pipeline decomposition in computer architecture?
  - Instruction pipeline in modern CPUs

- What’s an example pipeline you may use in your UNIX shell?
  - Pipes in UNIX: `cat foobar.c | grep bar | wc`

- Other examples
  - Signal processing
  - Graphics
Guidelines for Data Decomposition

• Data decomposition is often implied by task decomposition

• Programmers need to address task and data decomposition to create a parallel program
  - Which decomposition to start with?

• Data decomposition is a good starting point when
  - Main computation is organized around manipulation of a large data structure
  - Similar operations are applied to different parts of the data structure
Common Data Decompositions

- Geometric data structures
  - Decomposition of arrays along rows, columns, blocks
  - Decomposition of meshes into domains
Common Data Decompositions

- **Geometric data structures**
  - Decomposition of arrays along rows, columns, blocks
  - Decomposition of meshes into domains

- **Recursive data structures**
  - Example: decomposition of trees into sub-trees
Guidelines for Data Decomposition

- **Flexibility**
  - Size and number of data chunks should support a wide range of executions

- **Efficiency**
  - Data chunks should generate comparable amounts of work (for load balancing)

- **Simplicity**
  - Complex data compositions can get difficult to manage and debug
Data Decomposition Examples

- Molecular dynamics
  - Compute forces
  - Update accelerations and velocities
  - Update positions
Data Decomposition Examples

• Molecular dynamics
  - Geometric decomposition

• Merge sort
  - Recursive decomposition
Dependence Analysis

- Given two tasks how to determine if they can safely run in parallel?
Bernstein’s Condition

- **$R_i$**: set of memory locations read (input) by task $T_i$
- **$W_j$**: set of memory locations written (output) by task $T_j$

- Two tasks $T_1$ and $T_2$ are parallel if
  - input to $T_1$ is not part of output from $T_2$
  - input to $T_2$ is not part of output from $T_1$
  - outputs from $T_1$ and $T_2$ do not overlap
Example

\[ T_1 \]
\[ a = x + y \]

\[ T_2 \]
\[ b = x + z \]

\[ R_1 = \{ x, y \} \]
\[ W_1 = \{ a \} \]

\[ R_2 = \{ x, z \} \]
\[ W_2 = \{ b \} \]

\[ R_1 \cap W_2 = \phi \]
\[ R_2 \cap W_1 = \phi \]
\[ W_1 \cap W_2 = \phi \]
Patterns for Parallelizing Programs

4 Design Spaces

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Algorithm Structure Design Space

• Given a collection of concurrent tasks, what’s the next step?
• Map tasks to units of execution (e.g., threads)

• Important considerations
  – Magnitude of number of execution units platform will support
  – Cost of sharing information among execution units
  – Avoid tendency to over constrain the implementation
    • Work well on the intended platform
    • Flexible enough to easily adapt to different architectures
Major Organizing Principle

• How to determine the algorithm structure that represents the mapping of tasks to units of execution?

• Concurrency usually implies major organizing principle
  - Organize by tasks
  - Organize by data decomposition
  - Organize by flow of data
Organize by Tasks?

Recursive?

- yes: Divide and Conquer
- no: Task Parallelism
Task Parallelism

- Molecular dynamics
  - Non-bonded force calculations, some dependencies

- Common factors
  - Tasks are associated with iterations of a loop
  - Tasks largely known at the start of the computation
  - All tasks may not need to complete to arrive at a solution
Divide and Conquer

- For recursive programs: divide and conquer
  - Subproblems may not be uniform
  - May require dynamic load balancing
Organize by Data?

- Operations on a central data structure
  - Arrays and linear data structures
  - Recursive data structures
Recursive Data

• Computation on a list, tree, or graph
  – Often appears the only way to solve a problem is to sequentially move through the data structure

• There are however opportunities to reshape the operations in a way that exposes concurrency
Recursive Data Example: Find the Root

- Given a forest of rooted directed trees, for each node, find the root of the tree containing the node.
  - Parallel approach: for each node, find its successor’s successor, repeat until no changes
    - $O(\log n)$ vs. $O(n)$
Work vs. Concurrency Tradeoff

• Parallel restructuring of find the root algorithm leads to $O(n \log n)$ work vs. $O(n)$ with sequential approach

• Most strategies based on this pattern similarly trade off increase in total work for decrease in execution time due to concurrency
Organize by Flow of Data?

- In some application domains, the flow of data imposes ordering on the tasks
  - Regular, one-way, mostly stable data flow
  - Irregular, dynamic, or unpredictable data flow
Pipeline Throughput vs. Latency

- Amount of concurrency in a pipeline is limited by the number of stages.

- Works best if the time to fill and drain the pipeline is small compared to overall running time.

- Performance metric is usually the throughput:
  - Rate at which data appear at the end of the pipeline per time unit (e.g., frames per second).

- Pipeline latency is important for real-time applications:
  - Time interval from data input to pipeline, to data output.
Event-Based Coordination

- In this pattern, interaction of tasks to process data can vary over unpredictable intervals

- Deadlocks are a danger for applications that use this pattern
  - Dynamic scheduling has overhead and may be inefficient
    - Granularity a major concern