EE382V: Principles in Computer Architecture
Parallelism and Locality
Fall 2008

Lecture 7 – Parallelism in SW and Parallel Patterns

Mattan Erez

The University of Texas at Austin

Outline

- Parallelism in SW
  - ILP/DLP/TLP?
- 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

ILP/DLP/TLP in Software

- Does software also have ILP, DLP, and TLP?

TLP or DLP?

Converting Between ILP, TLP, and DLP?

- HW finally determines what parallelism mechanisms were used
- Easy: DLP → TLP → ILP
- Harder/inefficient: ILP→TLP→DLP
  - Requires significant analysis
  - Often need to speculate

Converting Between ILP, TLP, and DLP

- Examples for conversion:
- SW:
- HW:

Outline

- Parallelism in SW
  - ILP/DLP/TLP?
- 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

Credits

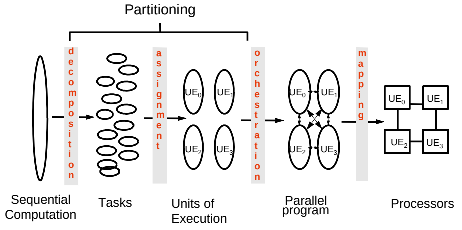
- Most of the slides courtesy Dr. Rodric Rabbah (IBM)
  - Taken from 6.189 IAP taught at MIT in 2007.

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



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

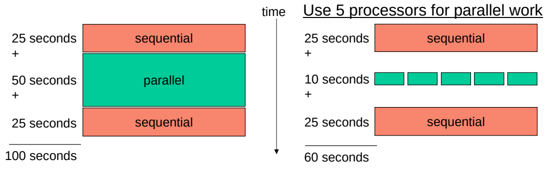
Main consideration: coverage and Amdahl's Law

Coverage

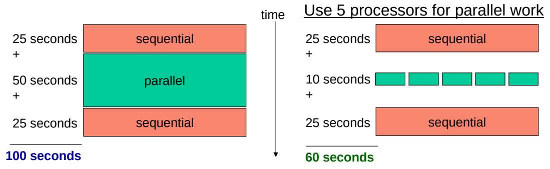
- **Amdahl's Law**: *The performance improvement to be gained from using some faster mode of execution is limited by the fraction of the time the faster mode can be used.*
  - Demonstration of the law of diminishing returns

Amdahl's Law

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



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 processor

$$speedup = \frac{\text{old running time}}{\text{new running time}}$$

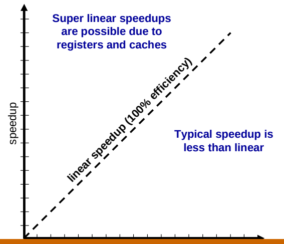
$$= \frac{1}{(1-p) + \frac{p}{n}}$$

fraction of time to complete sequential work

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

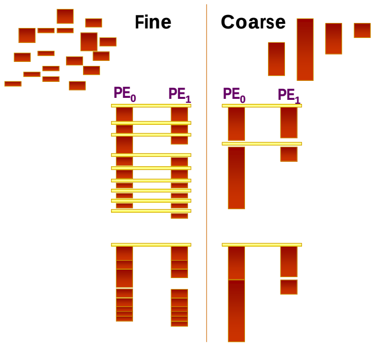
- Specify mechanism to divide work among PEs
  - Balance work and reduce communication
- Structured approaches usually work well
  - Code inspection or understanding of application
  - Well-known design patterns
- As programmers, we worry about partitioning first
  - Independent of architecture or programming model?
  - Complexity often affects decisions
  - Architectural model affects decisions

Main considerations: granularity and locality

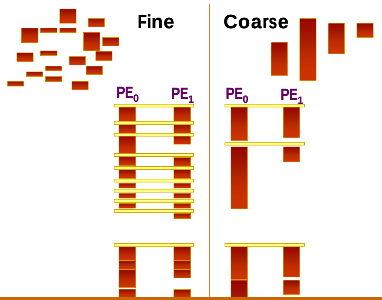
Fine vs. Coarse Granularity

- Fine-grain Parallelism
  - Low computation to communication ratio
  - Small amounts of computational work between communication stages
  - High communication overhead
    - Potential HW assist
- Coarse-grain Parallelism
  - High computation to communication ratio
  - Large amounts of computational work between communication events
  - Harder to load balance efficiently

Load Balancing vs. Synchronization



Load Balancing vs. Synchronization



Expensive sync → coarse granularity
Few units of exec + time disparity → 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

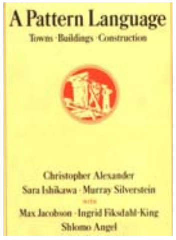
Main considerations: locality, parallelism, mechanisms (efficiency and dangers)

Parallel Programming by Pattern

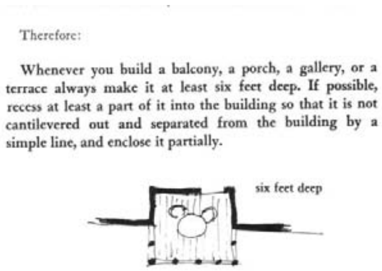
- Provides a cookbook to systematically guide programmers
  - Decompose, Assign, Orchestrate, Map
  - Can lead to high quality solutions in some domains
- Provide common vocabulary to the programming community
  - Each pattern has a name, providing a vocabulary for discussing solutions
- Helps with software 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

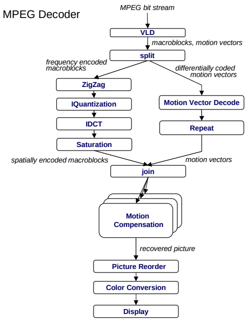
Patterns for Parallel Programming. Mattson, Sanders, and Massingill (2005).

Outline

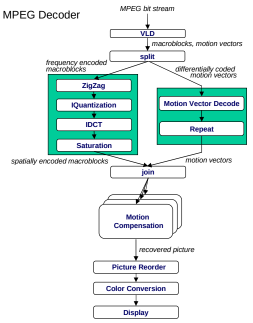
- Parallelism in SW
  - ILP/DLP/TLP?
- Parallel programming
  - Start from scratch
  - Reengineering for parallelism
- Parallelizing a program
  - Decomposition (finding concurrency)
  - Assignment (algorithm structure)
  - Orchestration (supporting structures)
  - Mapping (implementation mechanisms)
- Patterns for Parallel Programming

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

MPEG Decoder



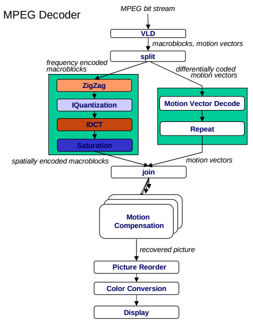
Here’s my algorithm. Where’s the concurrency?



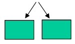
- Task decomposition
  - Independent coarse-grained computation
  - Inherent to algorithm
- Sequence of statements (instructions) that operate together as a group
  - Corresponds to some logical part of program
  - Usually follows from the way programmer thinks about a problem

---

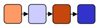
Here’s my algorithm. Where’s the concurrency?



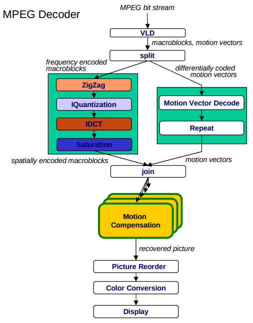
- Task decomposition
  - Parallelism in the application



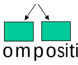
- Pipeline task decomposition
  - Data assembly lines
  - Producer-consumer chains



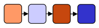
Here’s my algorithm. Where’s the concurrency?



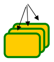
- Task decomposition
  - Parallelism in the application



- 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

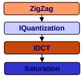
---

Guidelines for Task Decomposition

- Flexibility
  - Program design should afford flexibility in the number and size of tasks generated
    - Tasks should not 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



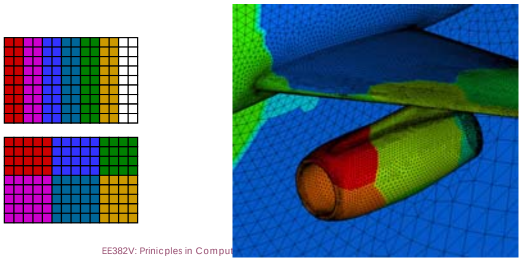
- Data is flowing through a sequence of stages
  - Assembly line is a good analogy
- What’s a prime example of pipeline decomposition in computer architecture?
  - Instruction pipeline in modern CPUs
- What’s an example pipeline you may use in your UNIX shell?
  - Pipes in UNIX: cat foobar.c | grep bar | 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

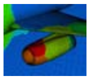
Common Data Decompositions

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

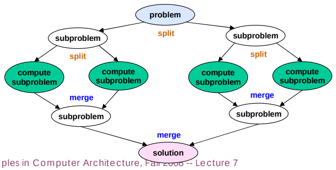


Common Data Decompositions

- 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

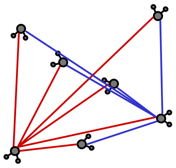


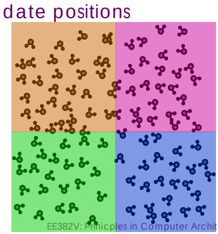
Guidelines for Data Decomposition

- 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

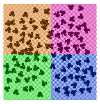
- Molecular dynamics
  - Compute forces
  - Update accelerations and velocities
  - Update positions



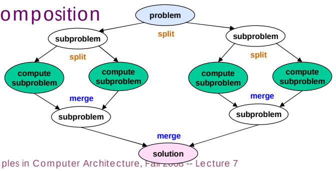


Data Decomposition Examples

- Molecular dynamics
  - Geometric decomposition



- Merge sort
  - Recursive decomposition



Dependence Analysis

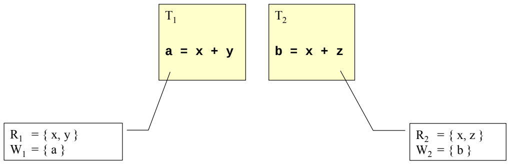
- Given two tasks how to determine if they can safely run in parallel?

Bernstein's Condition

- $\mathbf{R_i}$: set of memory locations read (input) by task $\mathbf{T_i}$
- $\mathbf{W_j}$: set of memory locations written (output) by task $\mathbf{T_j}$

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

Example



$$R_1 \cap W_2 = \phi$$
$$R_2 \cap W_1 = \phi$$
$$W_1 \cap W_2 = \phi$$

Patterns for Parallelizing Programs

4 Design Spaces

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

Patterns for Parallel Programming. Mattson, Sanders, and Massingill (2005).

Algorithm Structure Design Space

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

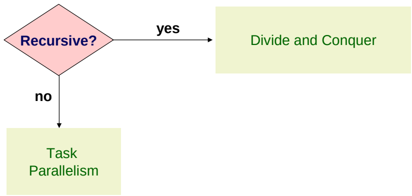
- Important considerations
  - Magnitude of number of execution units platform will support
  - Cost of sharing information among execution units
  - Avoid tendency to over constrain the implementation
    - Work well on the intended platform
    - Flexible enough to easily adapt to different architectures

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

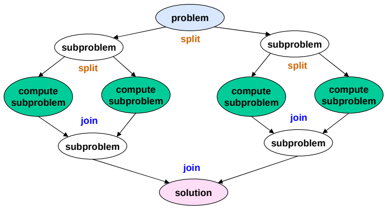
Task Parallelism

- 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

---

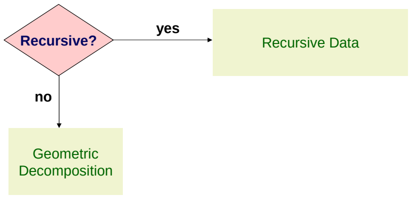
Divide and Conquer

- 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?

yes

Recursive Data

no

Geometric Decomposition

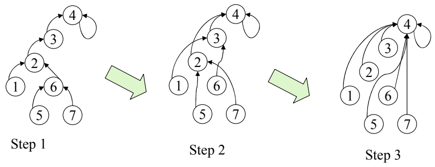
Recursive Data

- 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)

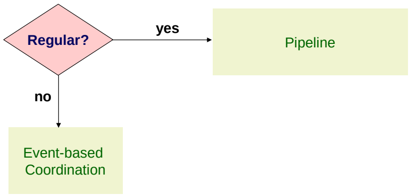


Work vs. Concurrency Tradeoff

- 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