EE382N (20): Computer Architecture
Parallelism and Locality
Fall 2009

Lecture 10 – Patterns for Parallel Programming (II)

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Credits

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

Patterns for Parallelizing Programs

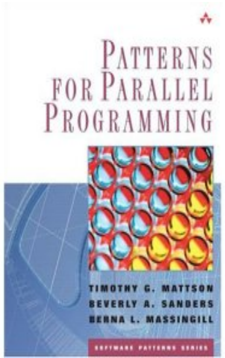
4 Design Spaces

Algorithm Expression

- Finding Concurrency
  - Expose concurrent tasks
- Algorithm Structure
  - Map tasks to processes to exploit parallel architecture

Software Construction

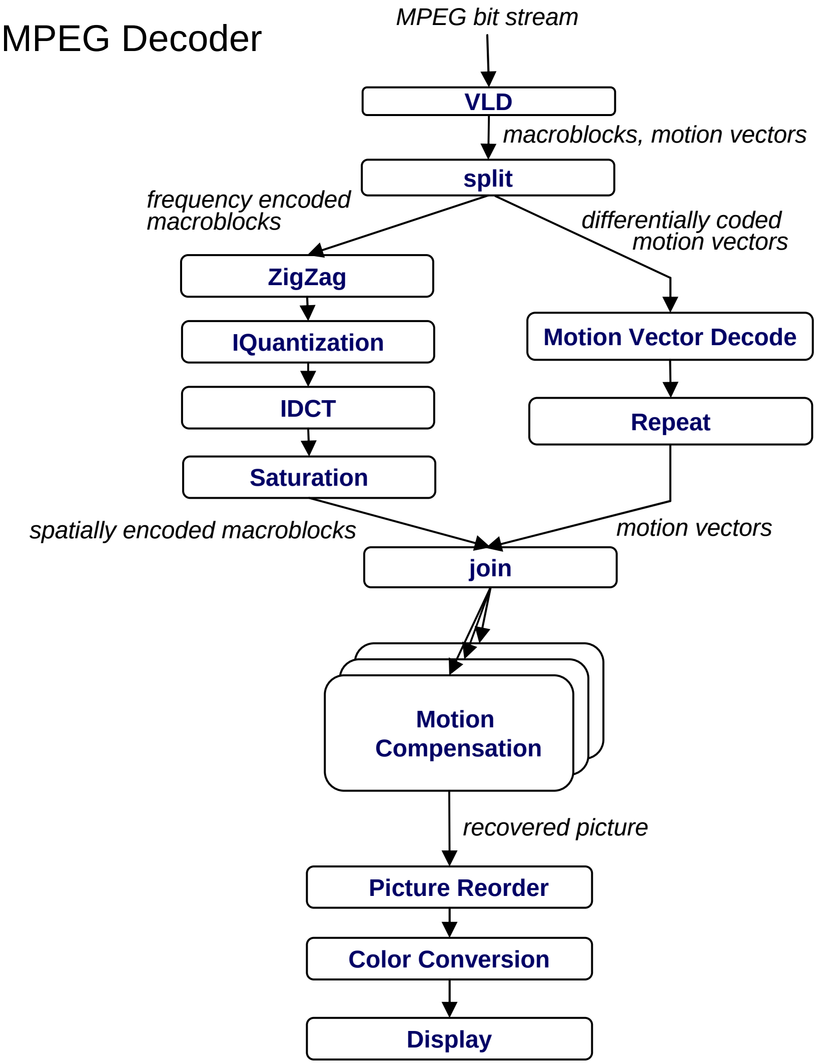
- Supporting Structures
  - Code and data structuring patterns
- Implementation Mechanisms
  - Low level mechanisms used to write parallel programs



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

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

MPEG Decoder



MPEG bit stream

VLD

macroblocks, motion vectors

split

frequency encoded macroblocks

differentially coded motion vectors

ZigZag

IQuantization

IDCT

Saturation

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Repeat

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recovered picture

Picture Reorder

Color Conversion

Display

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

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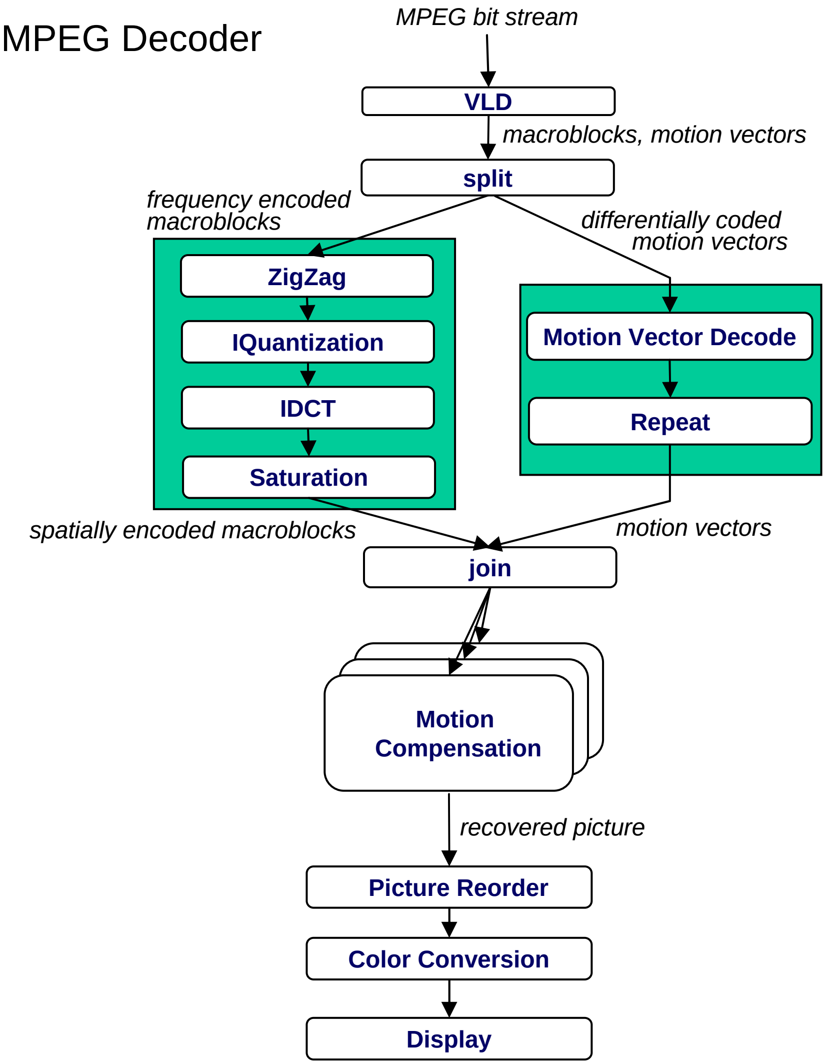
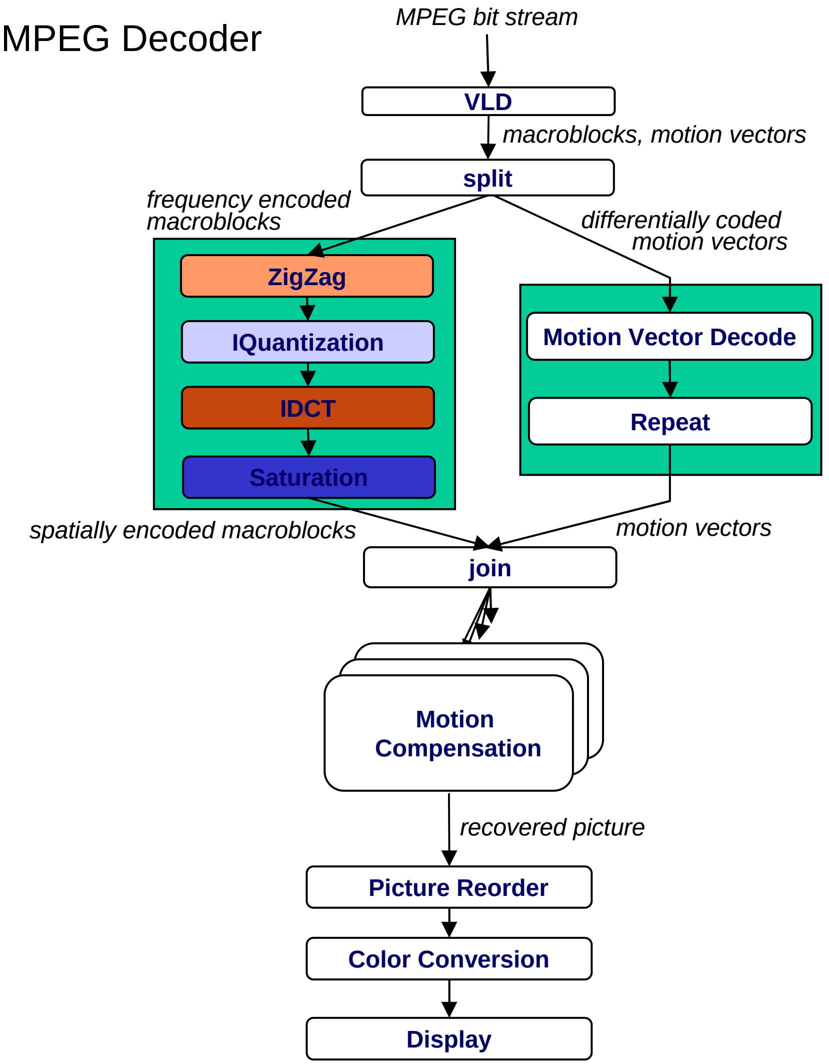
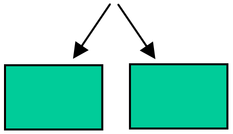


- Task decomposition
  - Independent coarse-grained computation
  - Inherent to algorithm
- Sequence of statements (instructions) that operate together as a group
  - Corresponds to some logical part of program
  - Usually follows from the way programmer thinks about a problem

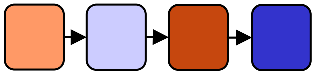
Here's my algorithm. Where's the concurrency?



- Task decomposition
  - Parallelism in the application



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



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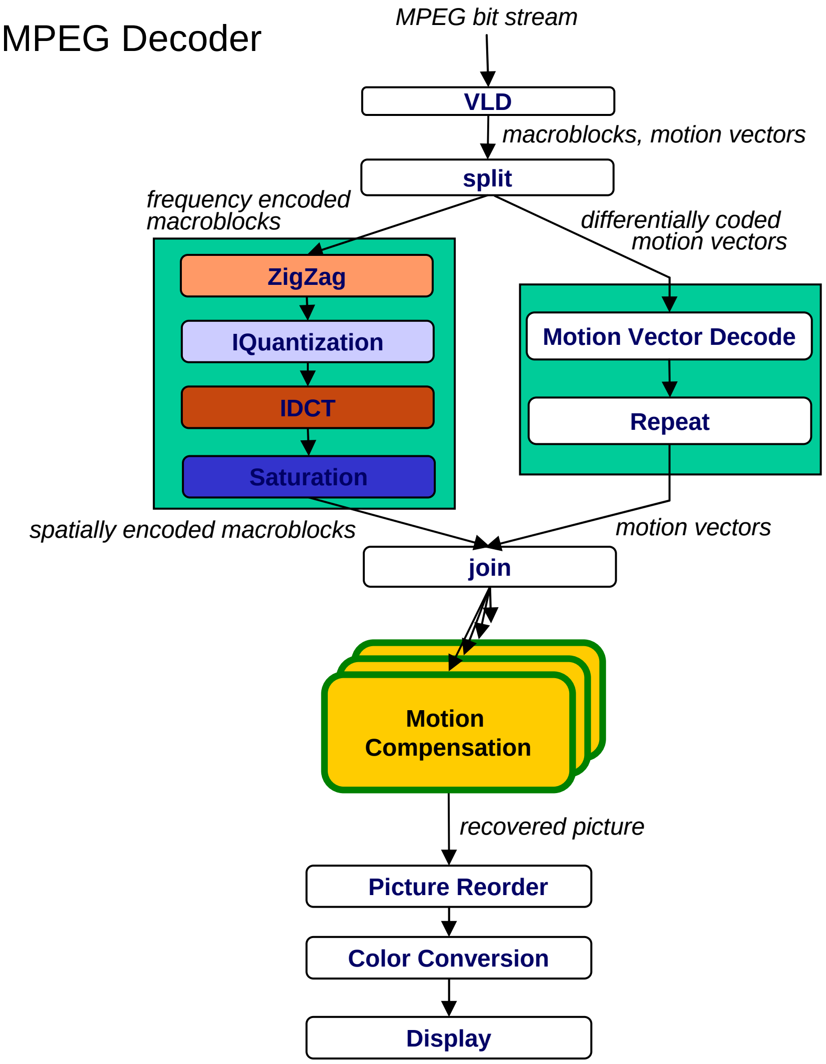

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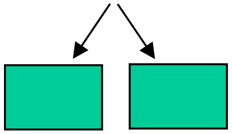

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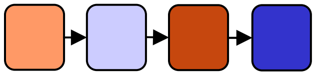
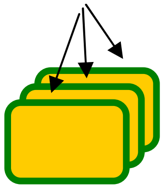


- Data decomposition
  - Same computation is applied to small data chunks derived from large data set



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

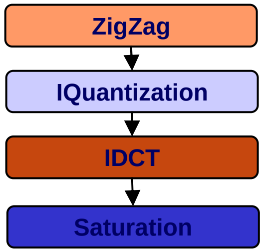
Guidelines for Task Decomposition

- 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



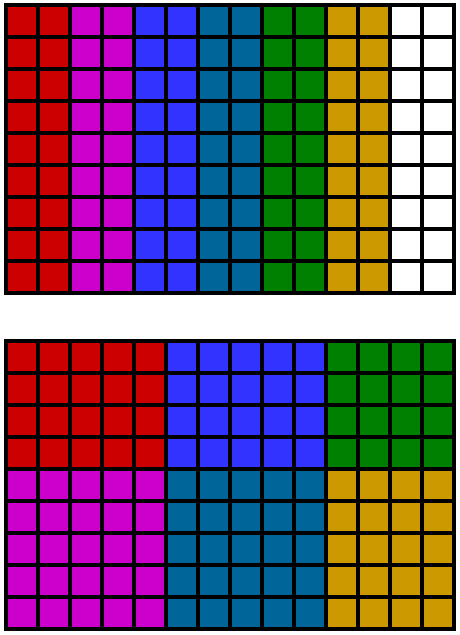
- Data is flowing through a sequence of stages
  - Assembly line is a good analogy
- What's a prime example of pipeline decomposition in computer architecture?
  - Instruction pipeline in modern CPUs
- What's an example pipeline you may use in your UNIX shell?
  - Pipes in UNIX: cat foobar.c | grep bar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

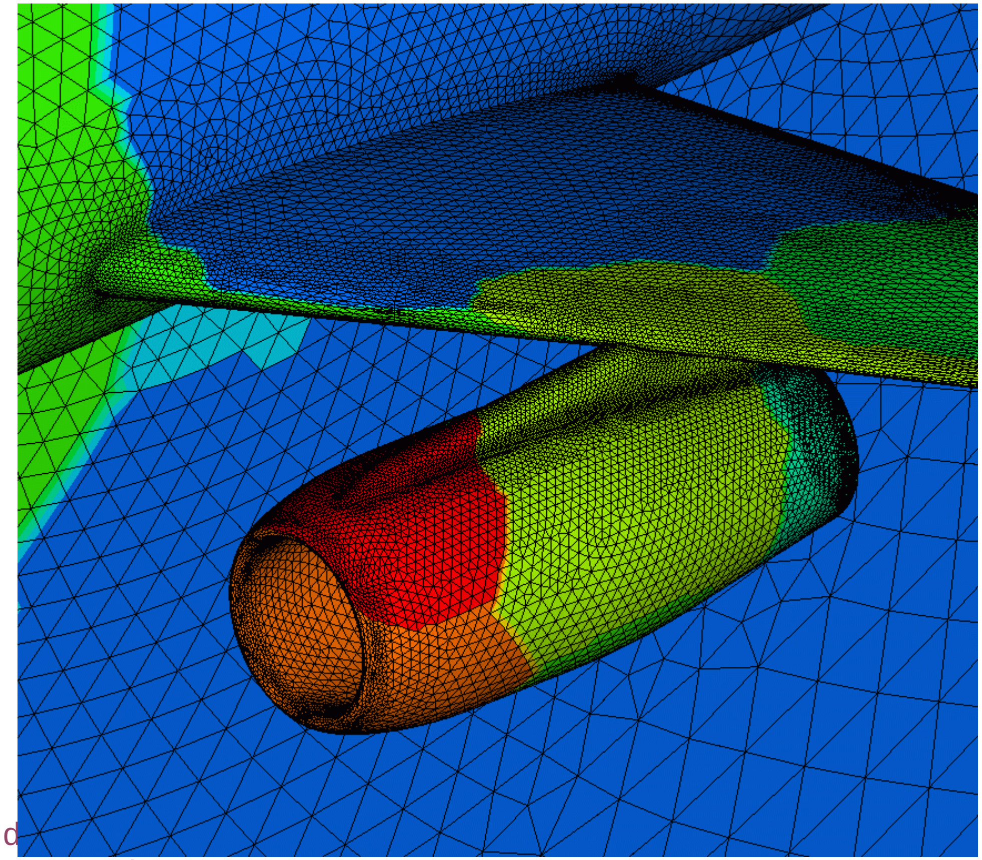
Guidelines for Data Decomposition

- 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





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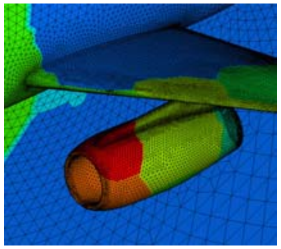
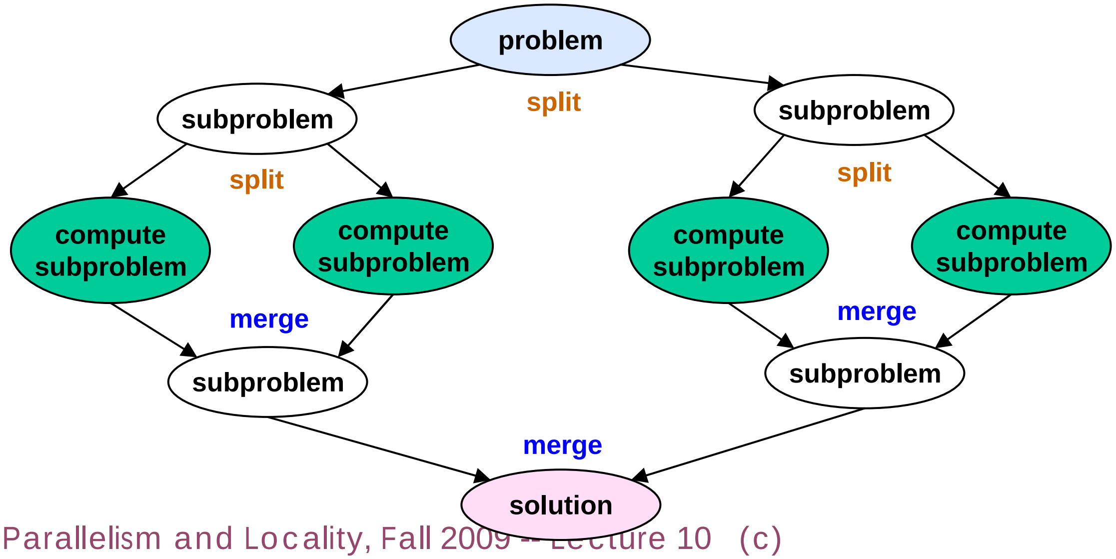


- Recursive data structures
  - Example: decomposition of trees into sub-trees

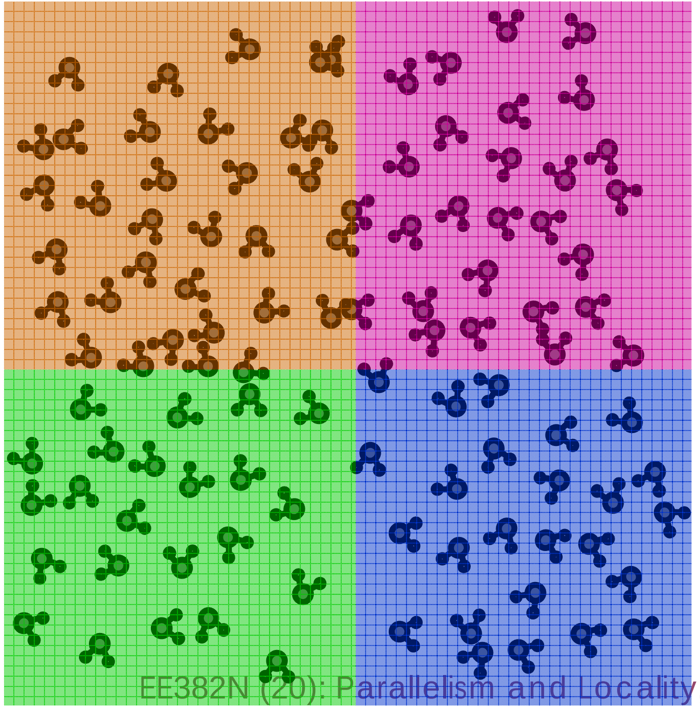


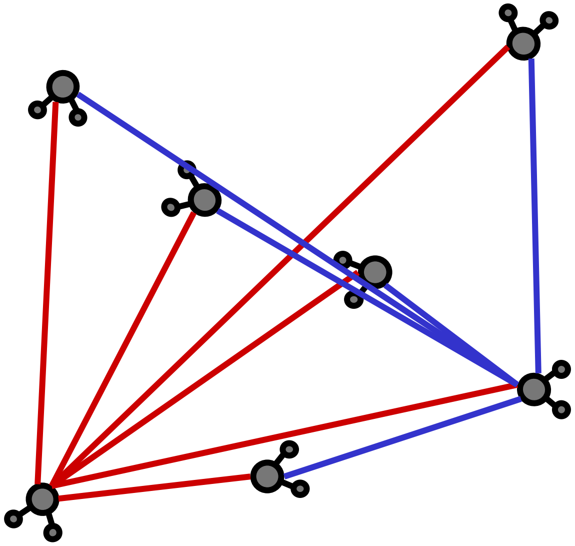
Guidelines for Data Decomposition

- 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

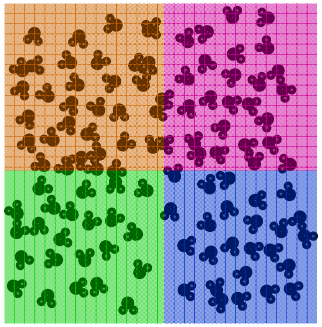
- Molecular dynamics
  - Compute forces
  - Update accelerations and velocities
  - Update positions



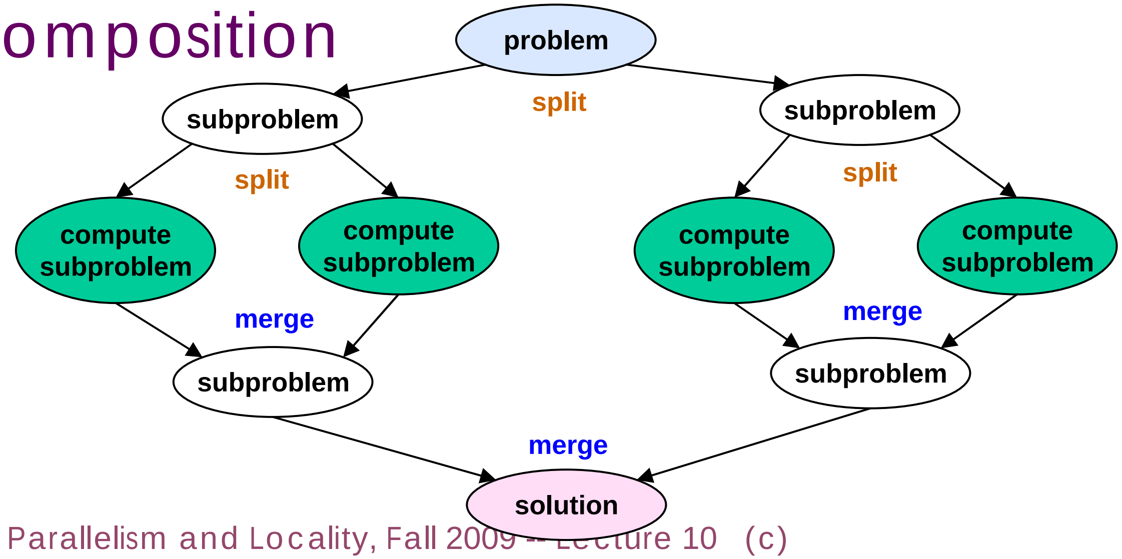


Data Decomposition Examples

- Molecular dynamics
  - Geometric decomposition



- Merge sort
  - Recursive decomposition



Dependence Analysis

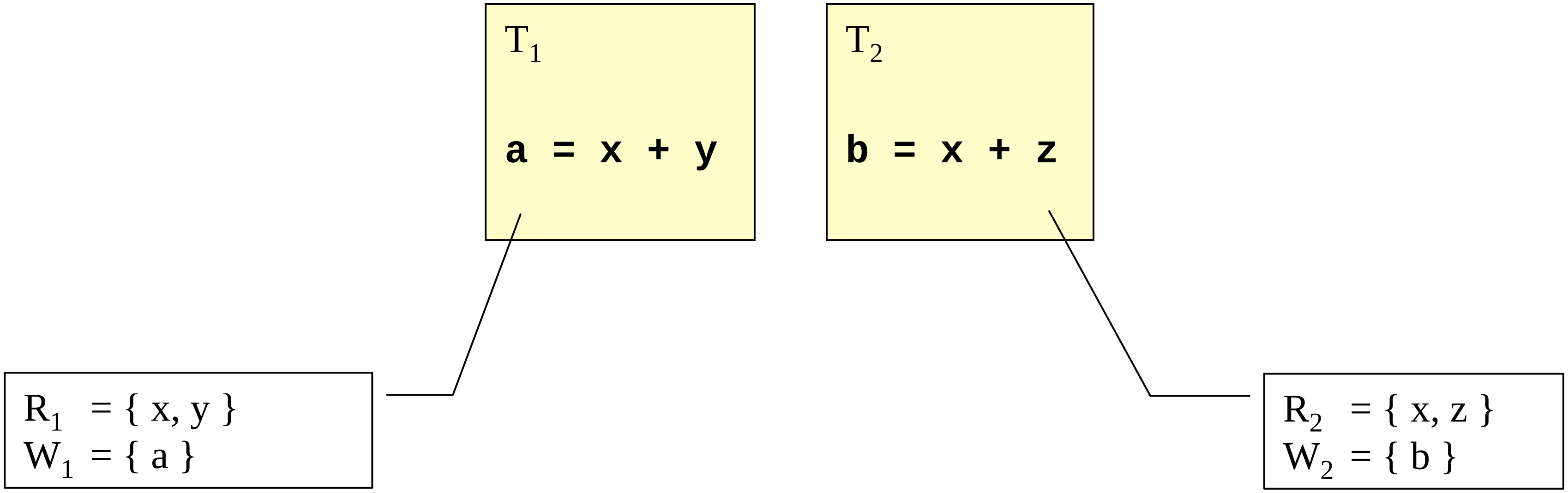
- Given two tasks how to determine if they can safely run in parallel?

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 }

$$R_1 \cap W_2 = \phi$$

$$R_2 \cap W_1 = \phi$$

$$W_1 \cap W_2 = \phi$$

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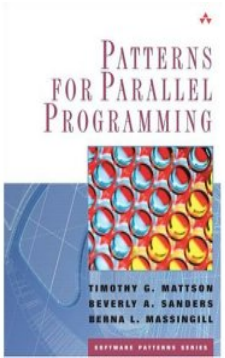


Patterns for Parallel Programming. Mattson, Sanders, and Massingill (2005).

Algorithm Structure Design Space

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

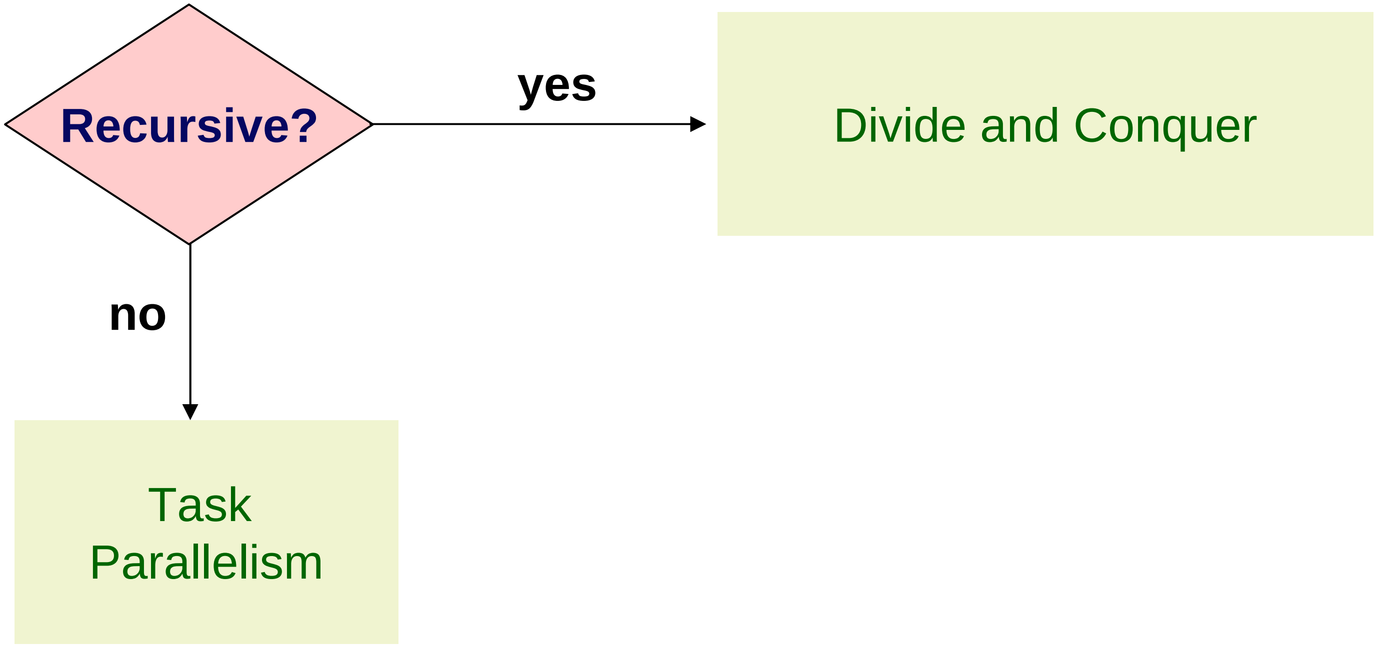
- Important considerations
  - Magnitude of number of execution units platform will support
  - Cost of sharing information among execution units
  - Avoid tendency to over constrain the implementation
    - Work well on the intended platform
    - Flexible enough to easily adapt to different architectures

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?



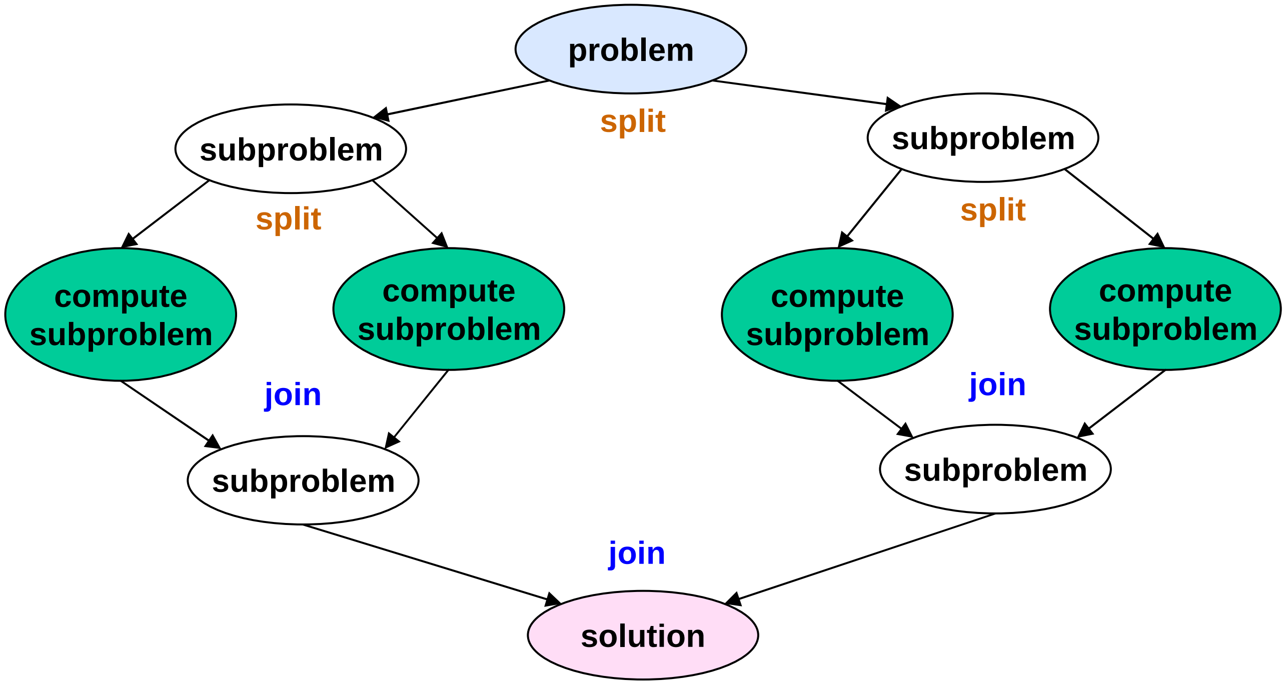
Task Parallelism

- 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

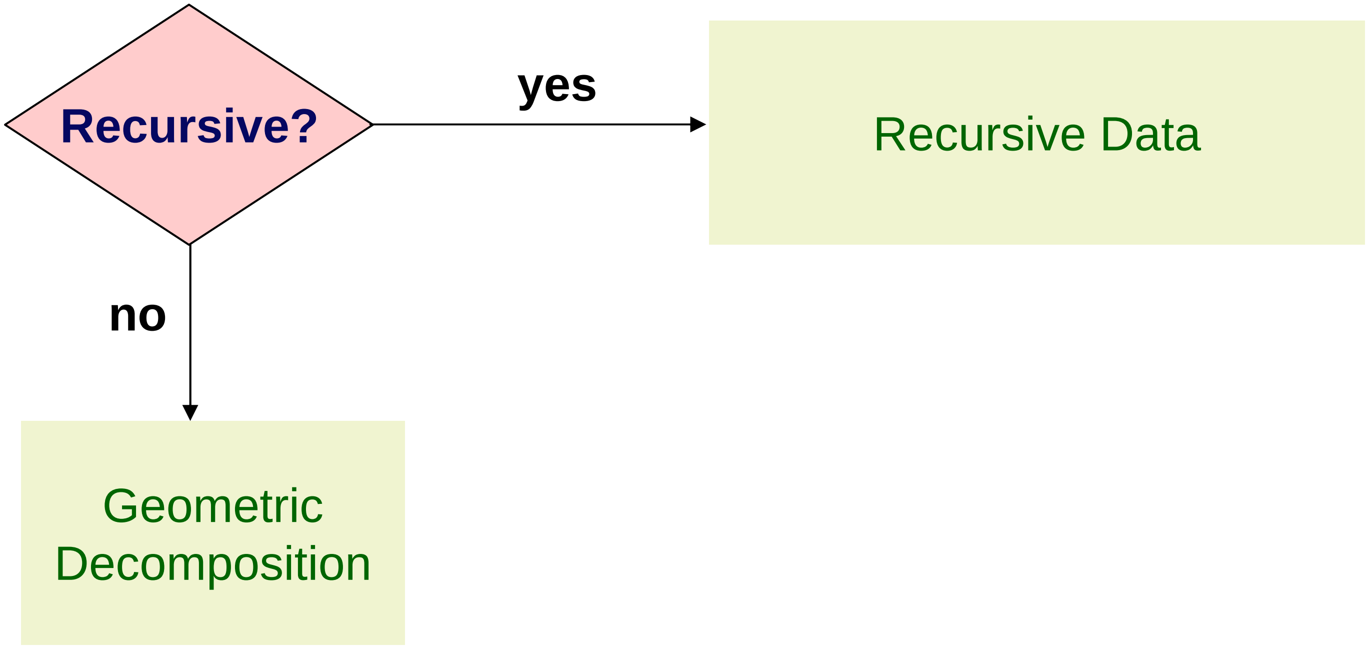
Divide and Conquer

- 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

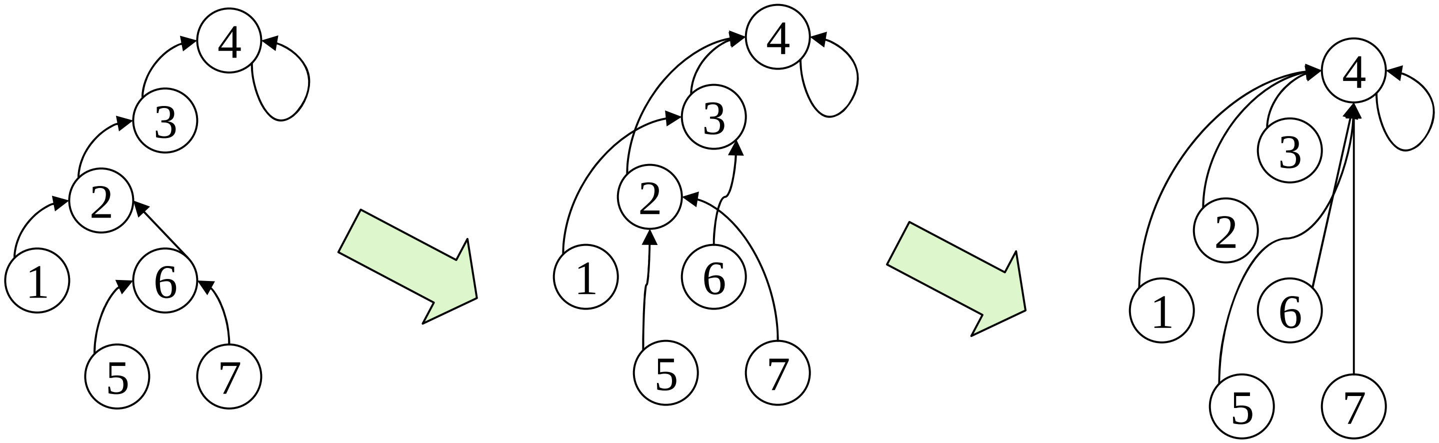
Recursive Data

- 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)



Step 1

Step 2

Step 3

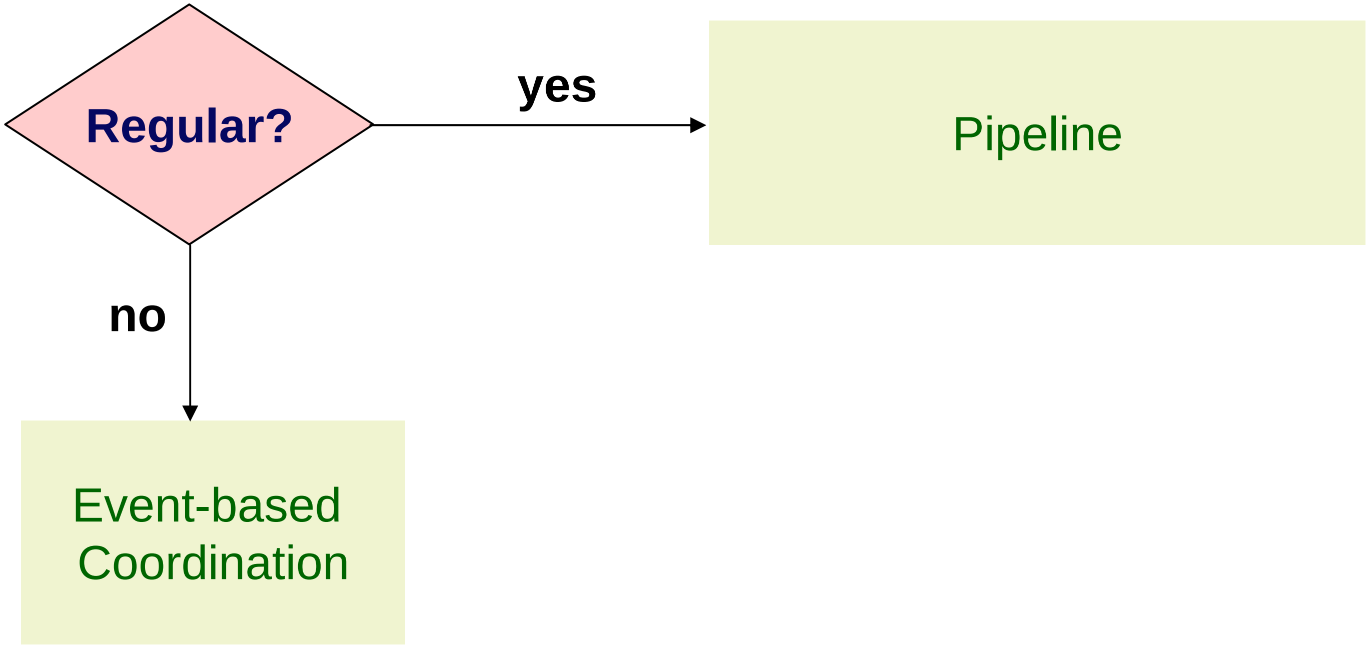
Work vs. Concurrency Tradeoff

- 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