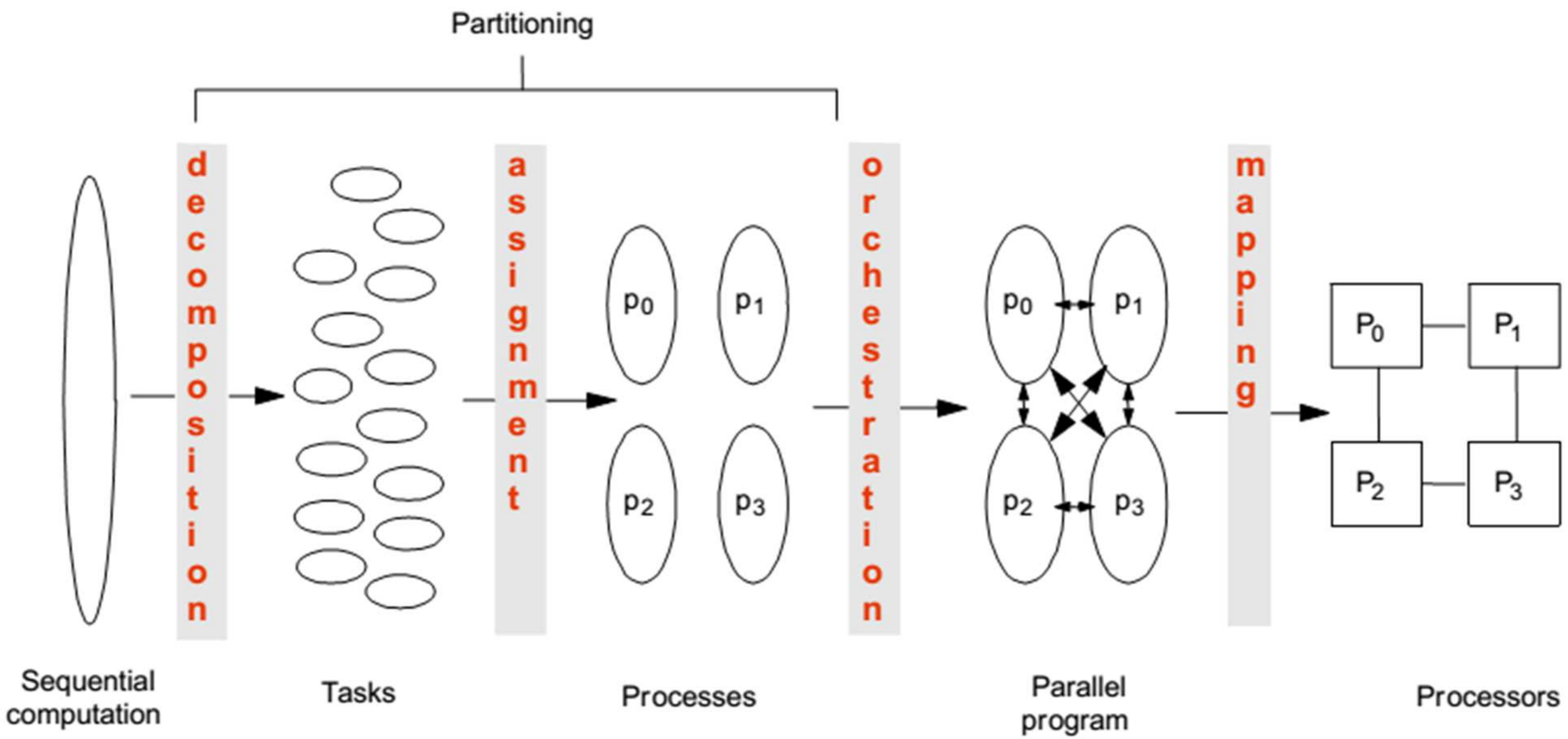
Design Patterns for Parallel Programming

Roberto Cavicchioli
roberto.cavicchioli@unimore.it

4 Common Steps to Creating a Parallel Program



Decomposition (Amdahl's Law)

- ✓ 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

Assignment (Granularity)

- ✓ Specify mechanism to divide work among core
  - – 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
  - – But complexity often affect decisions!

Orchestration and Mapping (Locality)

- ✓ Computation and communication concurrency
- ✓ Preserve locality of data
- ✓ Schedule tasks to satisfy dependences early

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

Patterns for Parallelizing Programs

4 Design Spaces

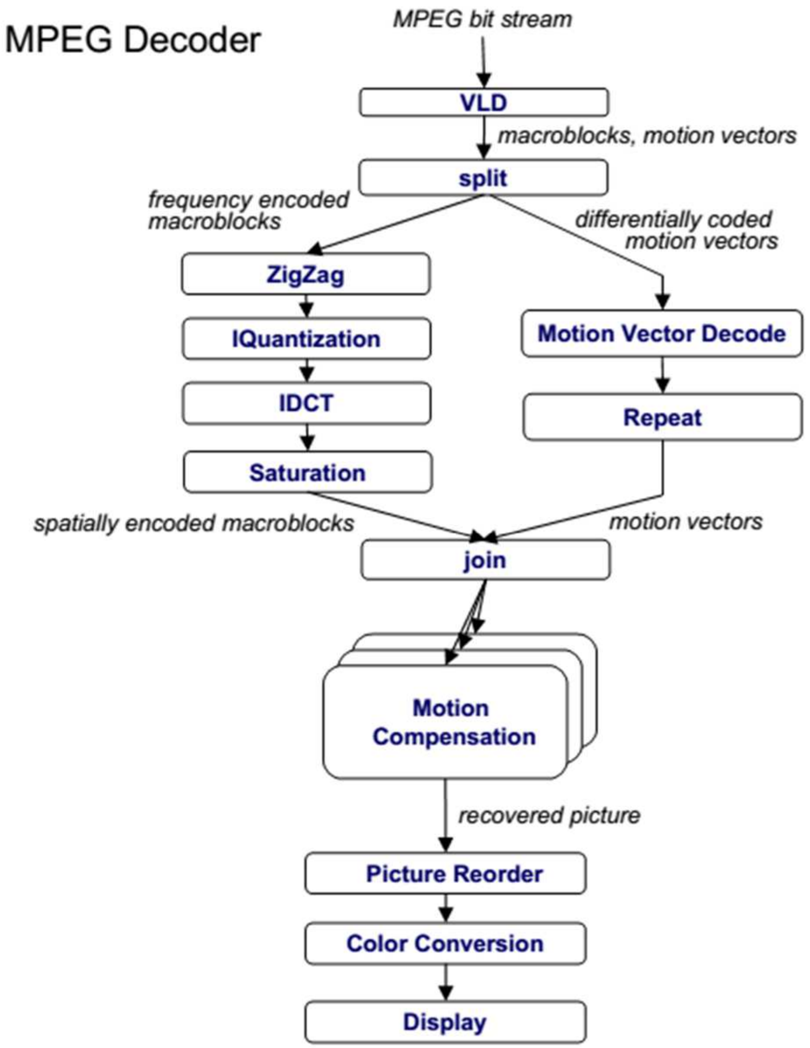
Algorithm Expression

- ✓ Finding Concurrency
  - – Expose concurrent tasks
- ✓ Algorithm structure
  - – Map tasks to processes to exploit parallel architecture

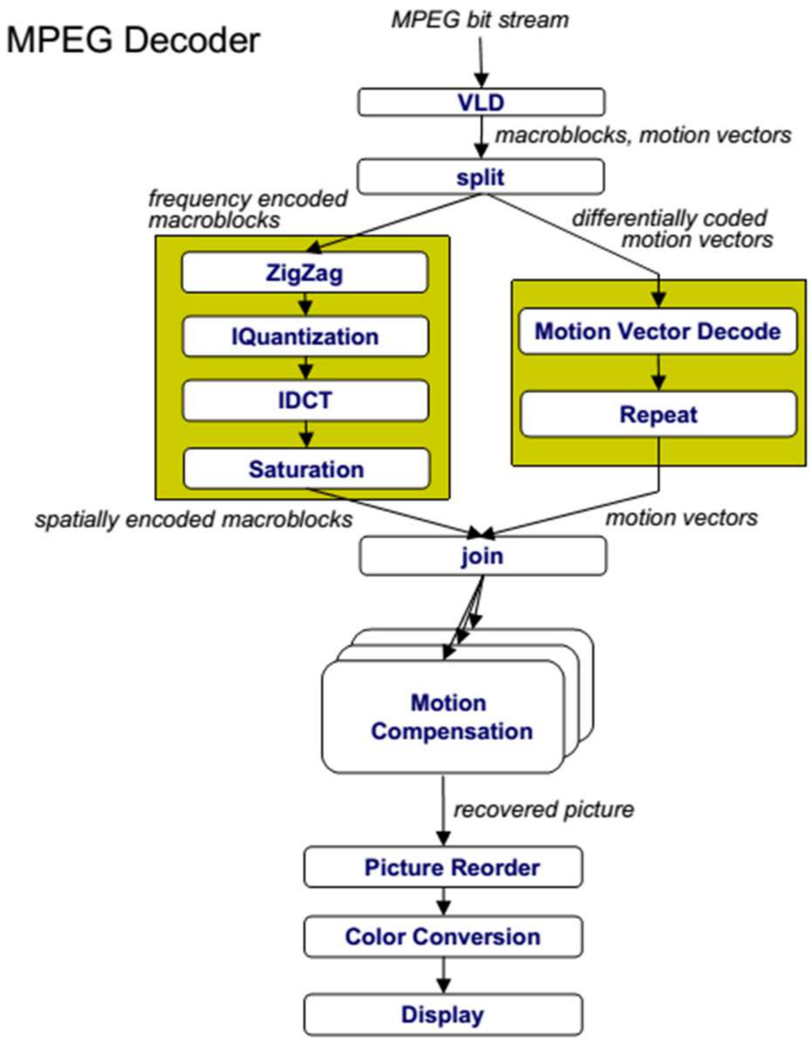
Software Construction

- ✓ 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?

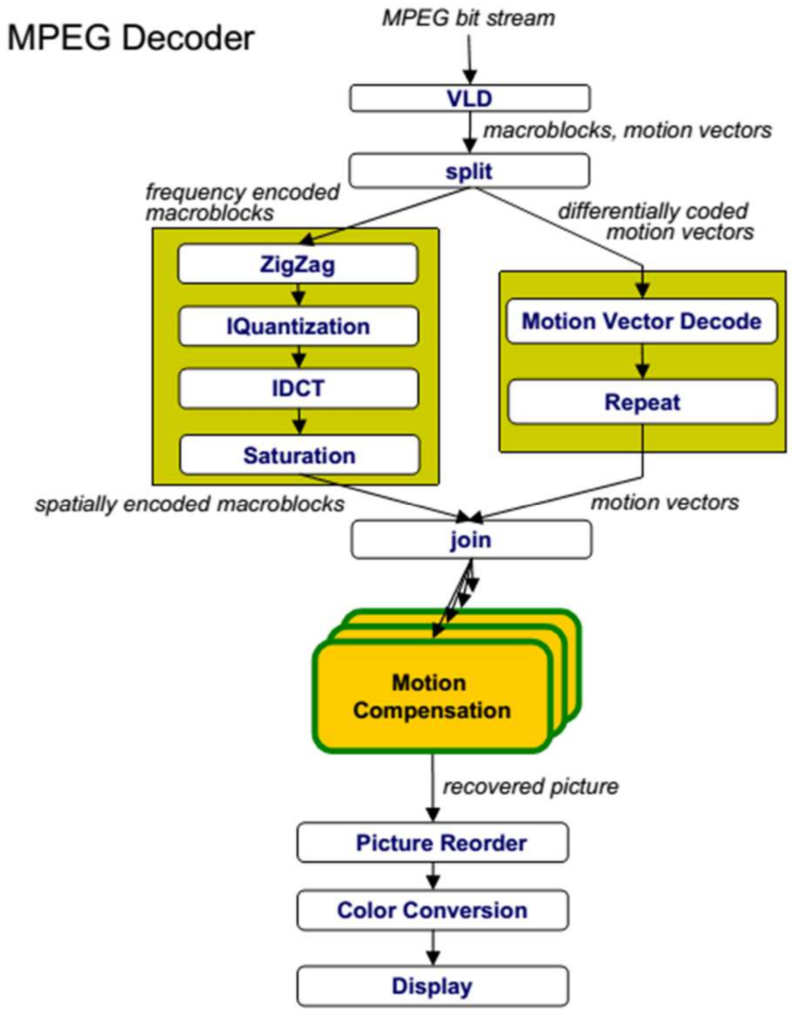


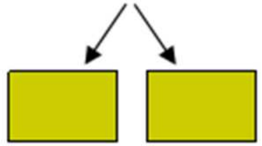
Here's my algorithm.
Where's the concurrency?



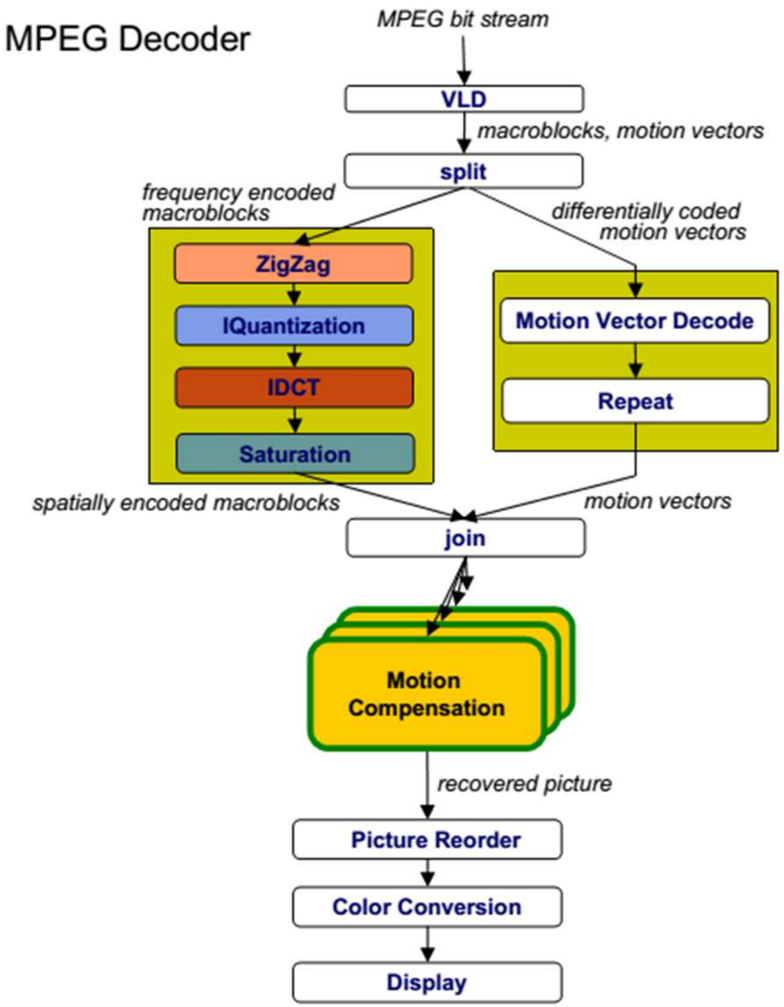
- ✓ Task decomposition
  - Independent coarse-grained computation
  - Inherent to algorithm
- ✓ Sequence of statements (instructions) that operate together as a group
  - Corresponds to some logical part of program
  - Usually follows from the way programmer thinks about a problem

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

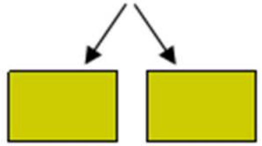


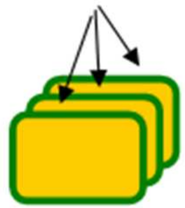
- ✓ Task decomposition 
  - Parallelism in the application
- ✓ Data decomposition
  - Same computation is applied to small data chunks derived from large data set

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

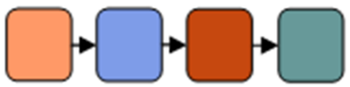


- ✓ Task decomposition
  - Parallelism in the application





- ✓ Data decomposition
  - Same computation many data
- ✓ Pipeline decomposition
  - Data assembly lines
  - Producer-consumer chains



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

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

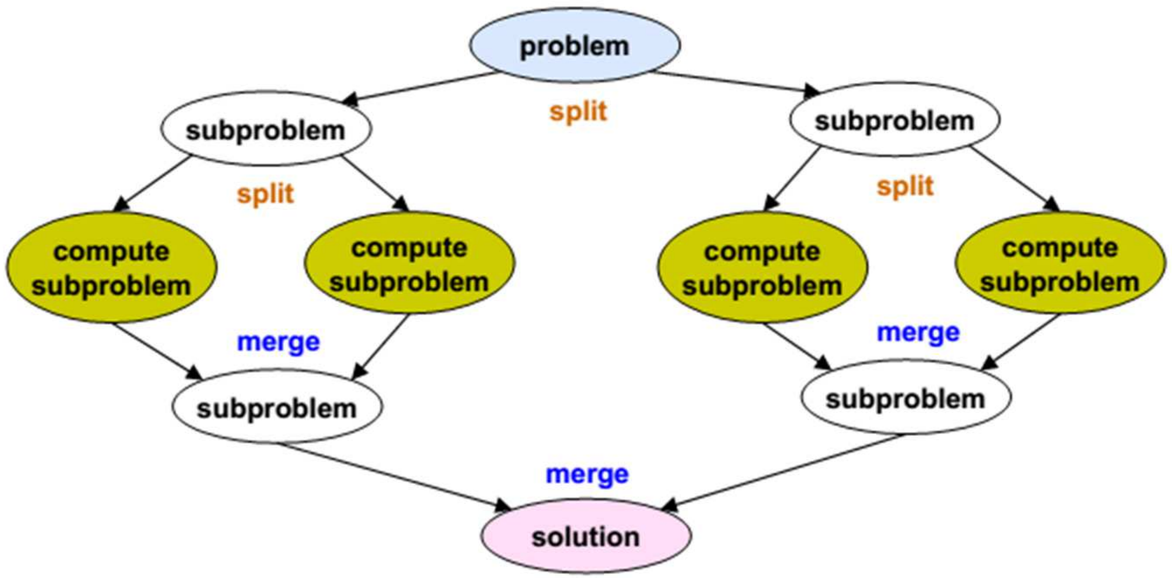
Common Data Decompositions

✓ Array data structures

– Decomposition of arrays along rows, columns, blocks

✓ 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

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

Re-engineering for Parallelism

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)

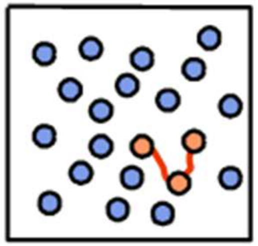
Reengineering for Parallelism

- ✓ 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**
  - Pattern provides guidance

Example: Molecular dynamics

- ✓ Simulate motion in large molecular system
  - – Used for example to understand drug-protein interactions
- ✓ Forces
  - – Bonded forces within a molecule
  - – Long-range forces between atoms



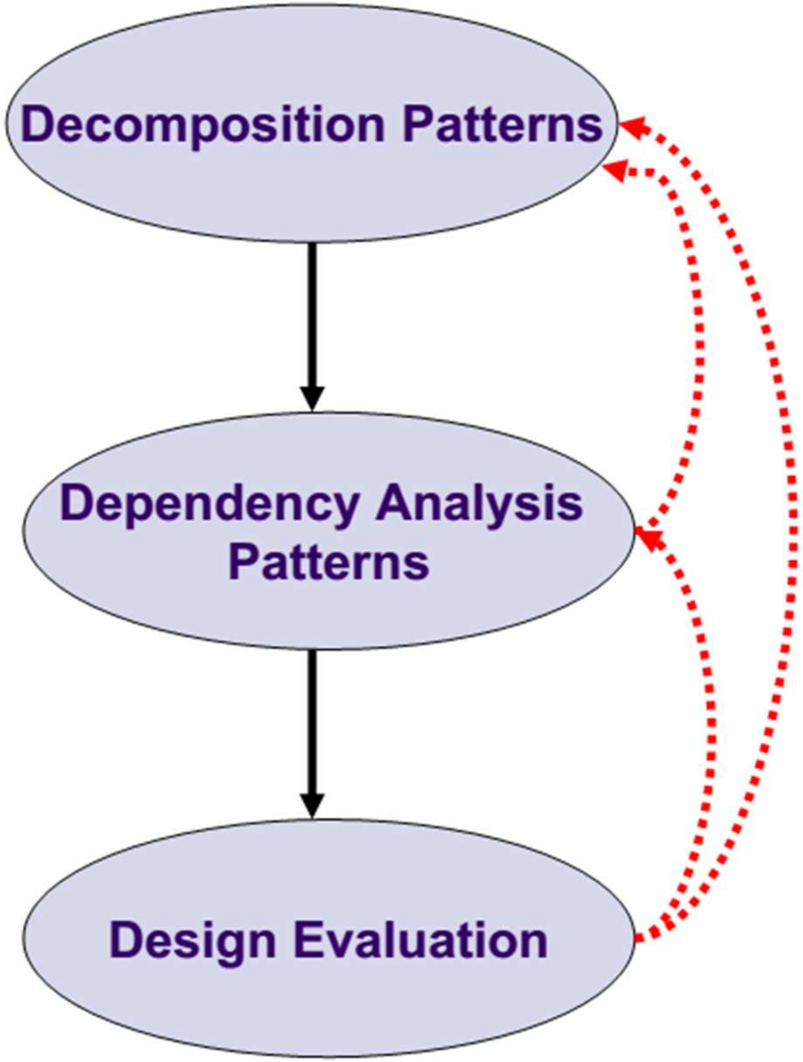
- ✓ Naïve algorithm has n^2 interactions: not feasible
- ✓ Use cutoff method: only consider forces from neighbors that are “close enough”

Sequential Molecular Dynamics Simulator

```
// pseudo code
real[3,n] atoms
real[3,n] force
int [2,m] neighbors

function simulate(steps)
   for time = 1 to steps and for each atom
         Compute bonded forces
         Compute neighbors
         Compute long-range forces
         Update position
   end loop
end function
```

Finding Concurrency Design Space

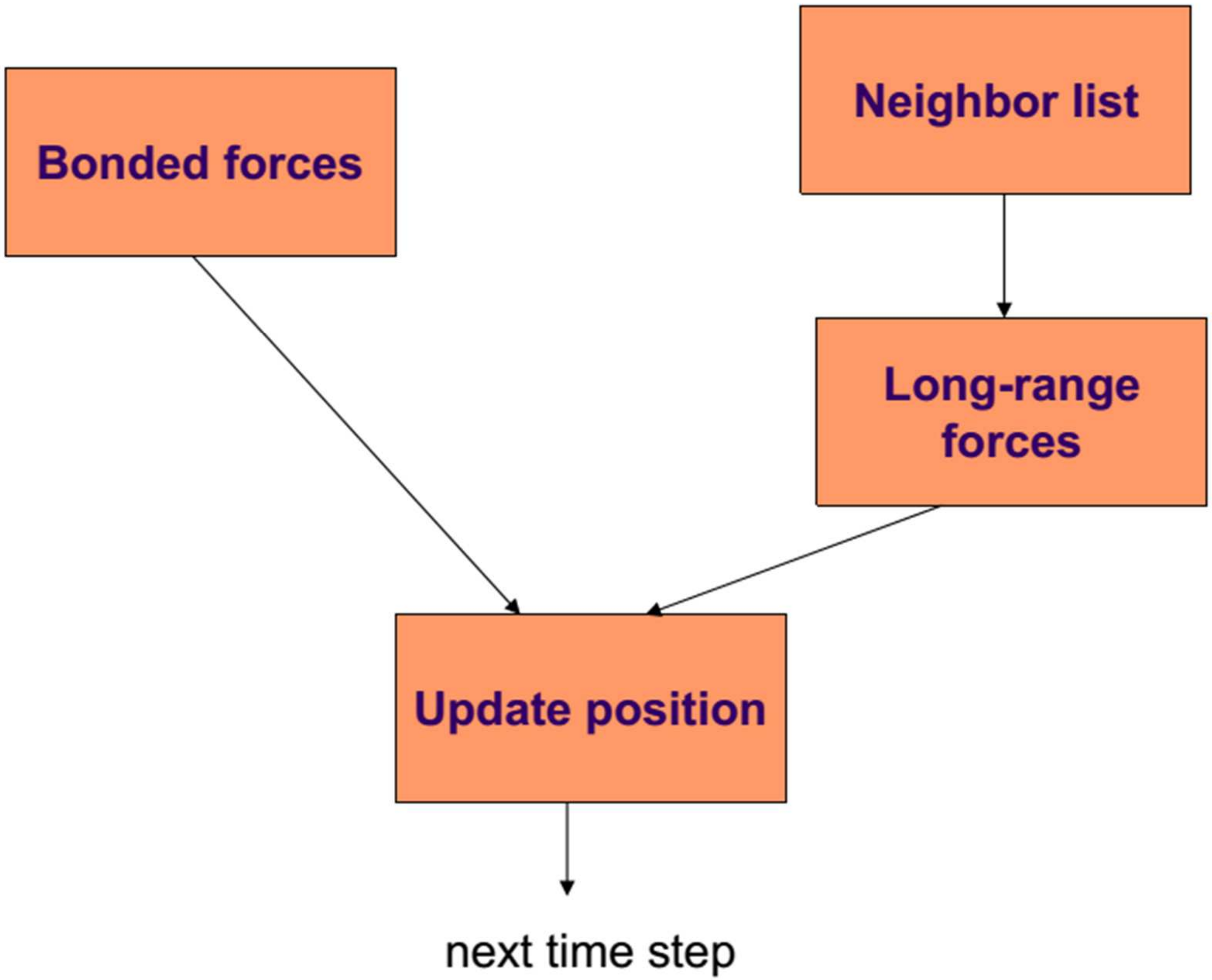


Decomposition Patterns

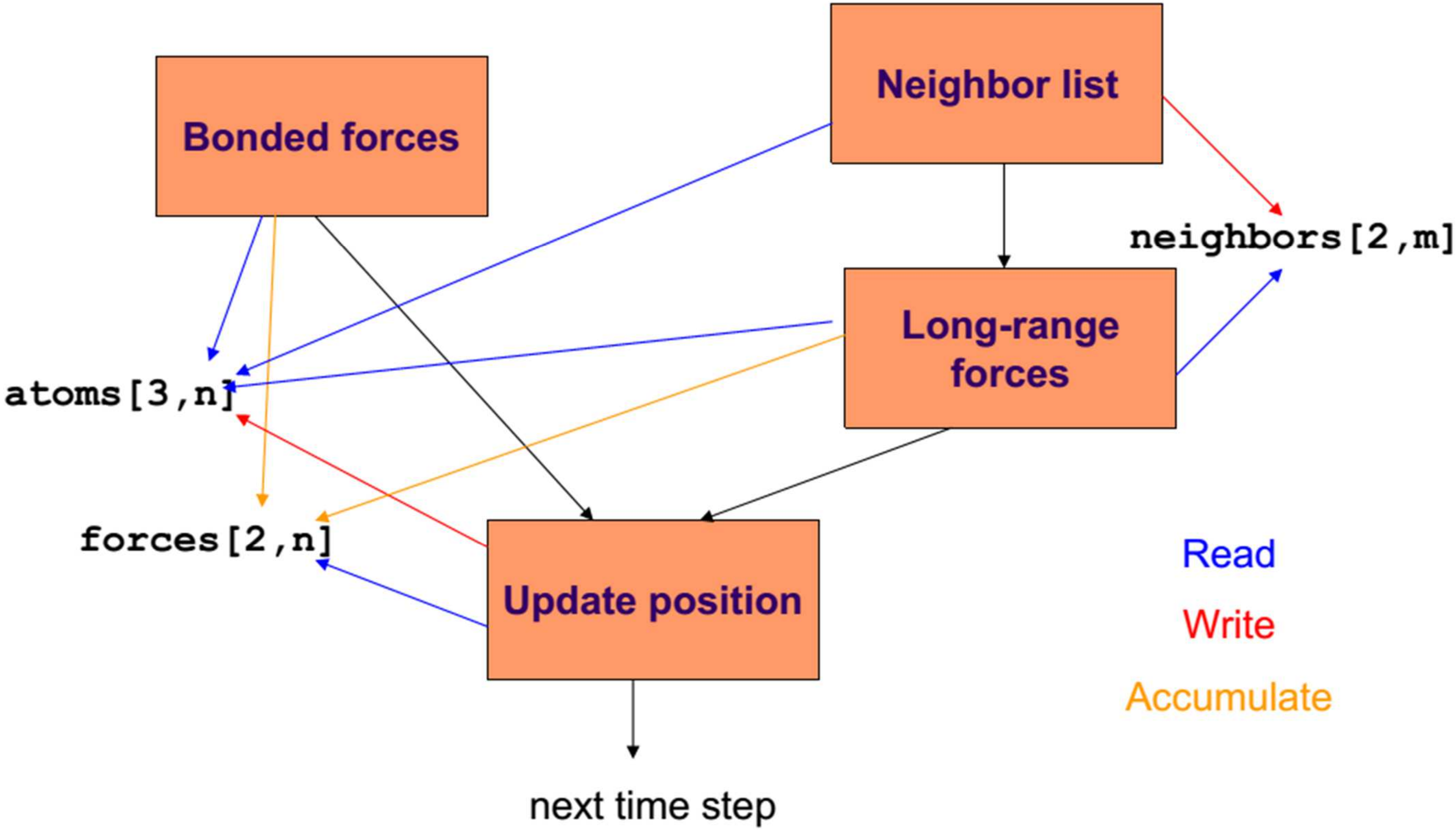
- ✓ Main computation is a loop over atoms
- ✓ Suggests task decomposition
  - – Task corresponds to a loop iteration
    - Update a single atom
  - – Additional tasks
    - Calculate bonded forces
    - Calculate long range forces
  - – Find neighbors
  - – Update position
- ✓ There is data shared between the tasks

```
for time = 1 to steps and
  for each atom
     Compute bonded forces
     Compute neighbors
     Compute long-range forces
     Update position
end loop
```

Understand Control Dependences



Understand Data Dependences



Evaluate Design

- ✓ What is the target architecture?
  - – Shared memory, distributed memory, message passing, …
- ✓ Does data sharing have enough special properties (read only, accumulate, temporal constraints) that we can deal with dependences efficiently?
- ✓ If design seems OK, move to next design space

Dependence Analysis

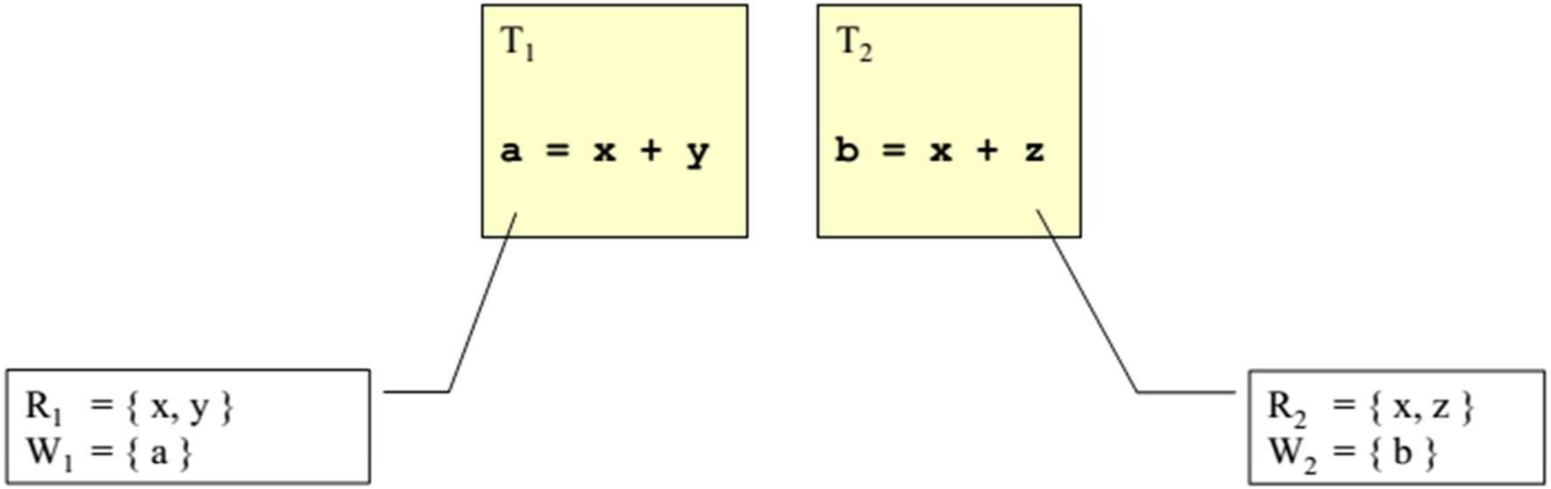
- Given two tasks how to determine if they can safely run in parallel?

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



$$R_1 \cap W_2 = \phi$$

$$R_2 \cap W_1 = \phi$$

$$W_1 \cap W_2 = \phi$$

Algorithm Structure Design Space

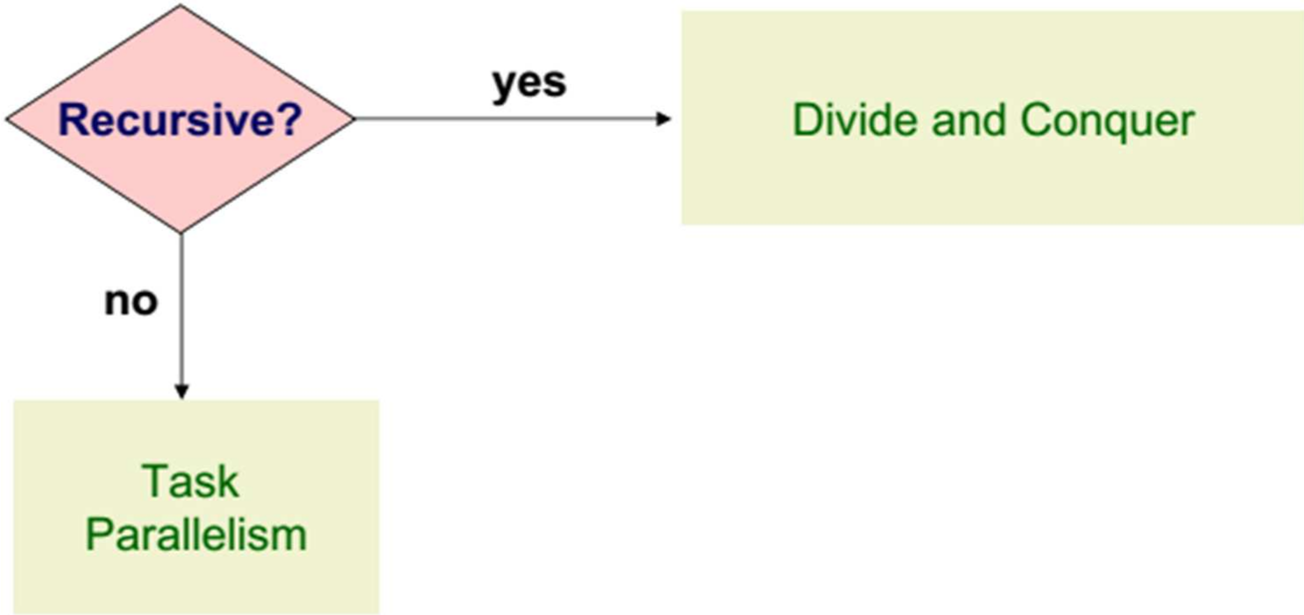
- ✓ Given a collection of concurrent tasks, what's the next step?
- ✓ Map tasks to units of execution (e.g., threads)

- ✓ 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?

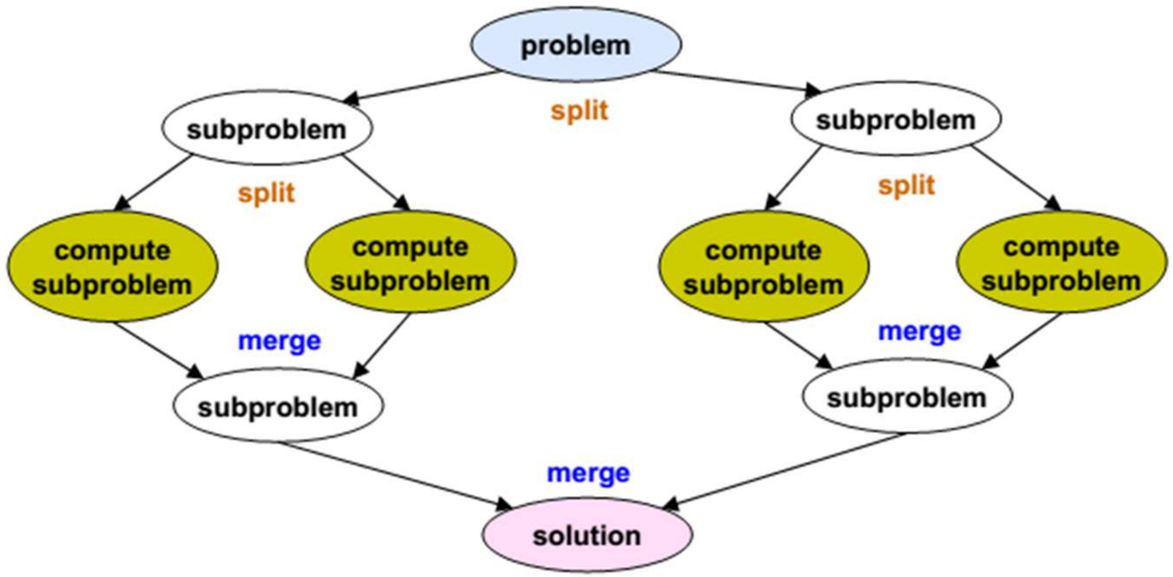


Task Parallelism

- ✓ Ray tracing
  - – Computation for each ray is a separate and independent
- ✓ 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

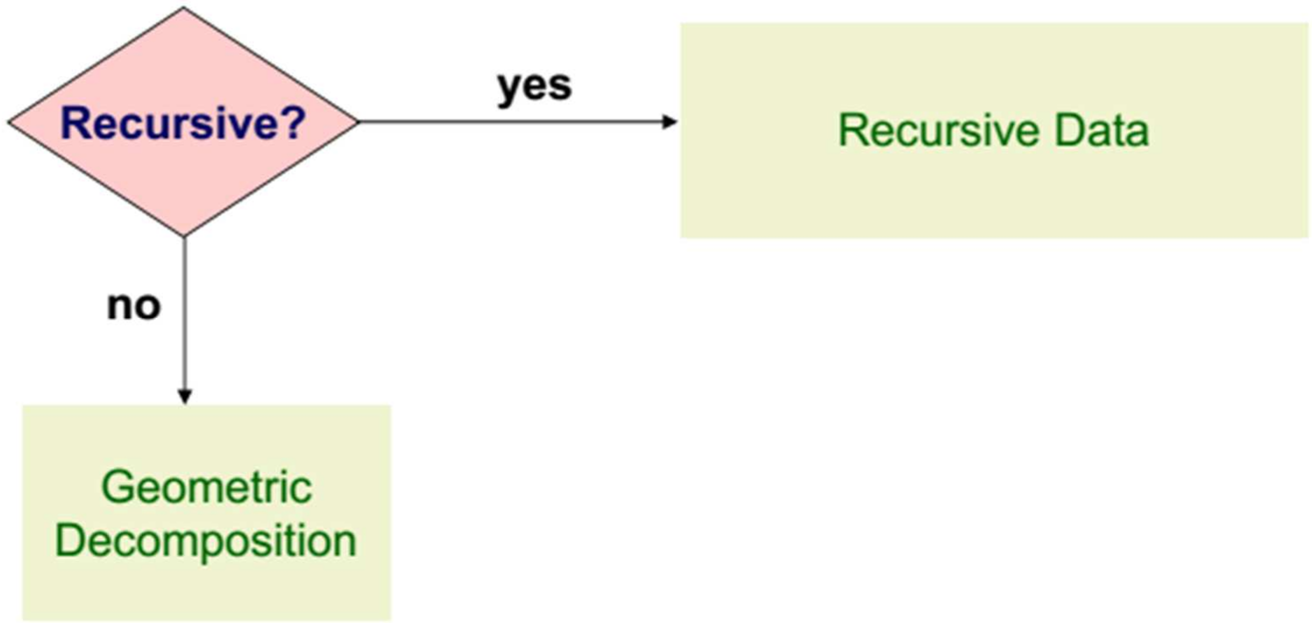
Divide and Conquer

- ✓ 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



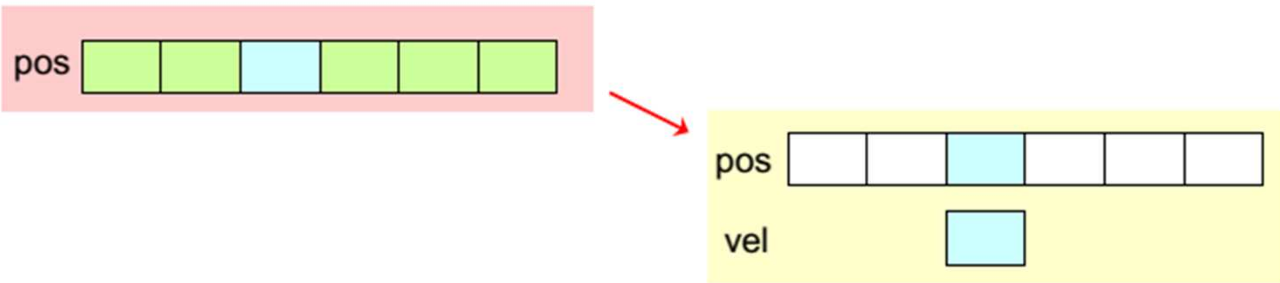
Geometric Decomposition

- ✓ Gravitational body simulator
  - – Calculate force between pairs of objects and update accelerations

```
VEC3D acc[NUM_BODIES] = 0;

for (i = 0; i < NUM_BODIES - 1; i++) {
  for (j = i + 1; j < NUM_BODIES; j++) {
    // Displacement vector
    VEC3D d = pos[j] – pos[i];
    // Force
    t = 1 / sqr(length(d));
    // Components of force along displacement
    d = t * (d / length(d));

    acc[i] += d * mass[j];
    acc[j] += -d * mass[i];
  }
}
```

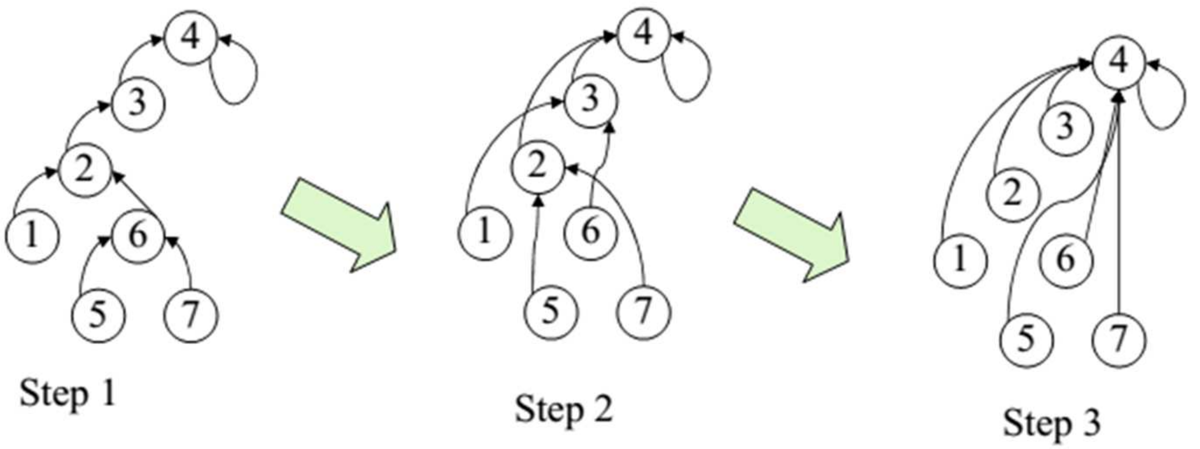


Recursive Data

- ✓ 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)



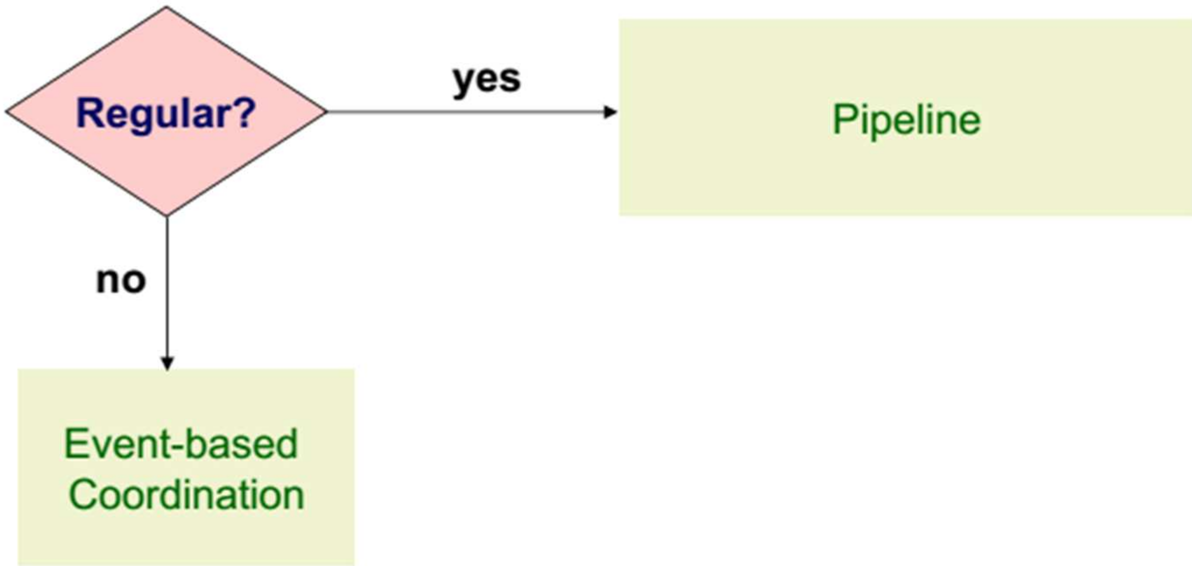
Work vs. Concurrency Tradeoff

- ✓ 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 likely for applications that use this pattern

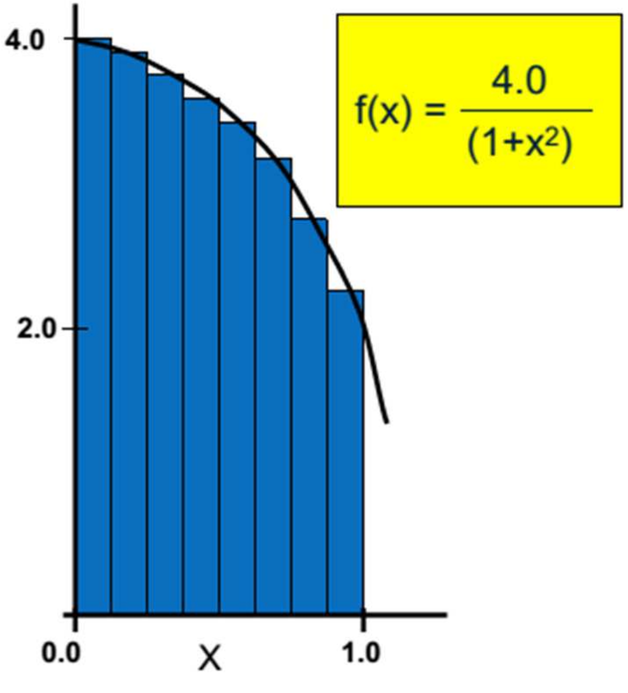
Supporting Structures

- ✓ SPMD
- ✓ Loop parallelism
- ✓ Master/Worker
- ✓ Fork/Join

SPMD Pattern

- ✓ Single Program Multiple Data: create a single source-code image that runs on each processor
  - Initialize
  - Obtain a unique identifier
  - Run the same program each processor
    - Identifier and input data differentiate behavior
  - Distribute data
  - Finalize

Example: Parallel Numerical Integration




```
static long num_steps = 100000;

void main()
{
     int i;
     double pi, x, step, sum = 0.0;

     step = 1.0 / (double) num_steps;
     for (i = 0; i < num_steps; i++){
          x = (i + 0.5) * step;
          sum = sum + 4.0 / (1.0 + x*x);
     }
     pi = step * sum;
     printf("Pi = %f\n", pi);
}
```

Computing Pi With Integration (MPI)

```
static long num_steps = 100000;
void main(int argc, char* argv[])
{
    int i_start, i_end, i, myid, numprocs;
    double pi, mypi, x, step, sum = 0.0;
    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    MPI_BCAST(&num_steps, 1, MPI_INT, 0, MPI_COMM_WORLD);
    i_start = my_id∗ (num_steps/numprocs)
    i_end = i_start + (num_steps/numprocs)
    step = 1.0 / (double) num_steps;
    for (i = i_start; i < i_end; i++) {
          x = (i + 0.5) ∗ step
          sum = sum + 4.0 / (1.0 + x∗x);
    }
    mypi = step * sum;
    MPI_REDUCE(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);
    if (myid == 0)
          printf("Pi = %f\n", pi);
    MPI_Finalize();
}
```

WARNING!! Block vs Cyclic work distribution

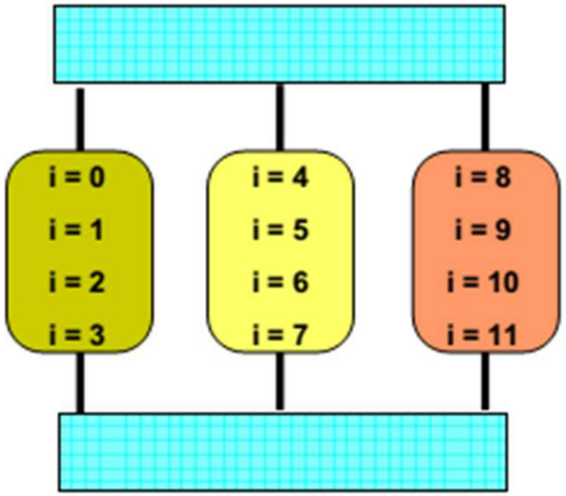
SPMD Challenges

- ✓ Split data correctly
- ✓ Correctly combine the results
- ✓ Achieve an even distribution of the work
- ✓ For programs that need dynamic load balancing, an alternative pattern is more suitable

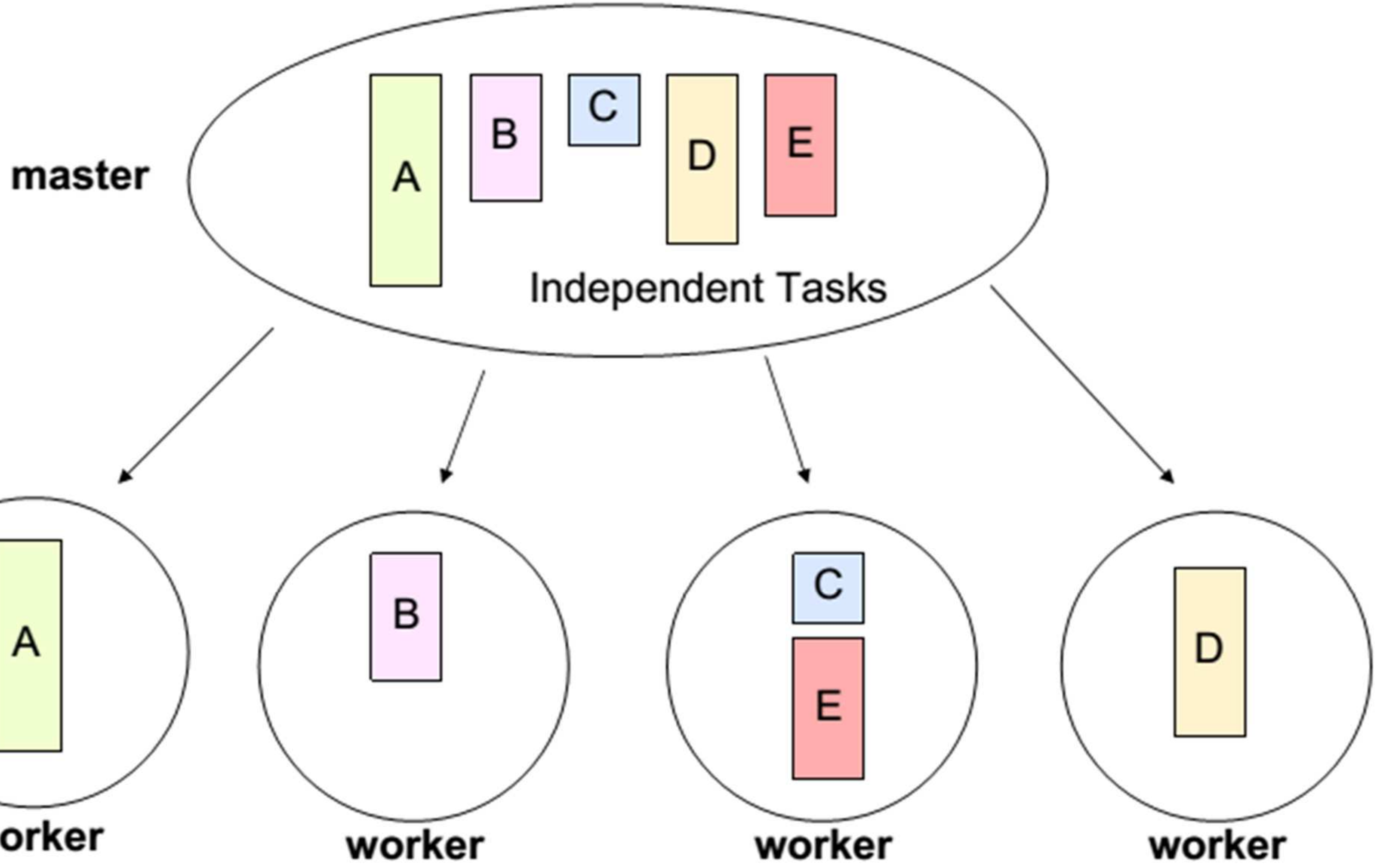
Loop Parallelism Pattern

- ✓ Many programs are expressed using iterative constructs
  - – Programming models like OpenMP provide directives to automatically assign loop iteration to execution units
  - – Especially good when code cannot be massively restructured

```
#pragma omp parallel for
for(i = 0; i < 12; i++)
      C[i] = A[i] + B[i];
```



Master/Worker Pattern



Master/Worker Pattern

- ✓ Particularly relevant for problems using task parallelism pattern where task have no dependencies
  - – Embarrassingly parallel problems
- ✓ Main challenge in determining when the entire problem is complete

Fork/Join Pattern

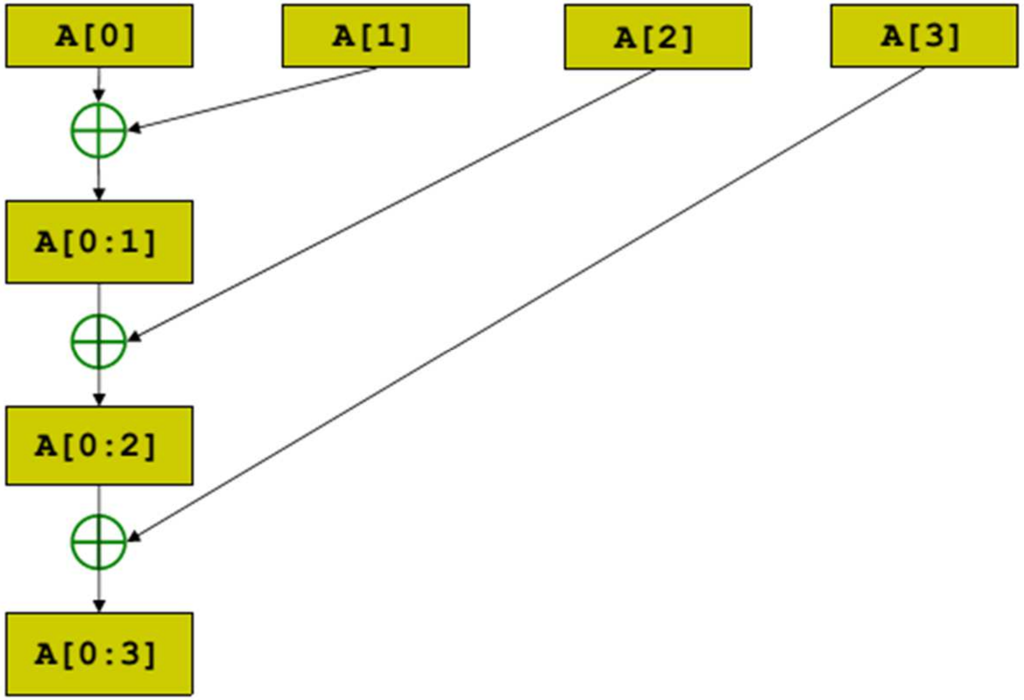
- ✓ Tasks are created dynamically
  - – Tasks can create more tasks
- ✓ Manages tasks according to their relationship
- ✓ Parent task creates new tasks (fork) then waits until they complete (join) before continuing on with the computation

Communication Patterns

- ✓ Point-to-point
- ✓ Broadcast
- ✓ Reduction

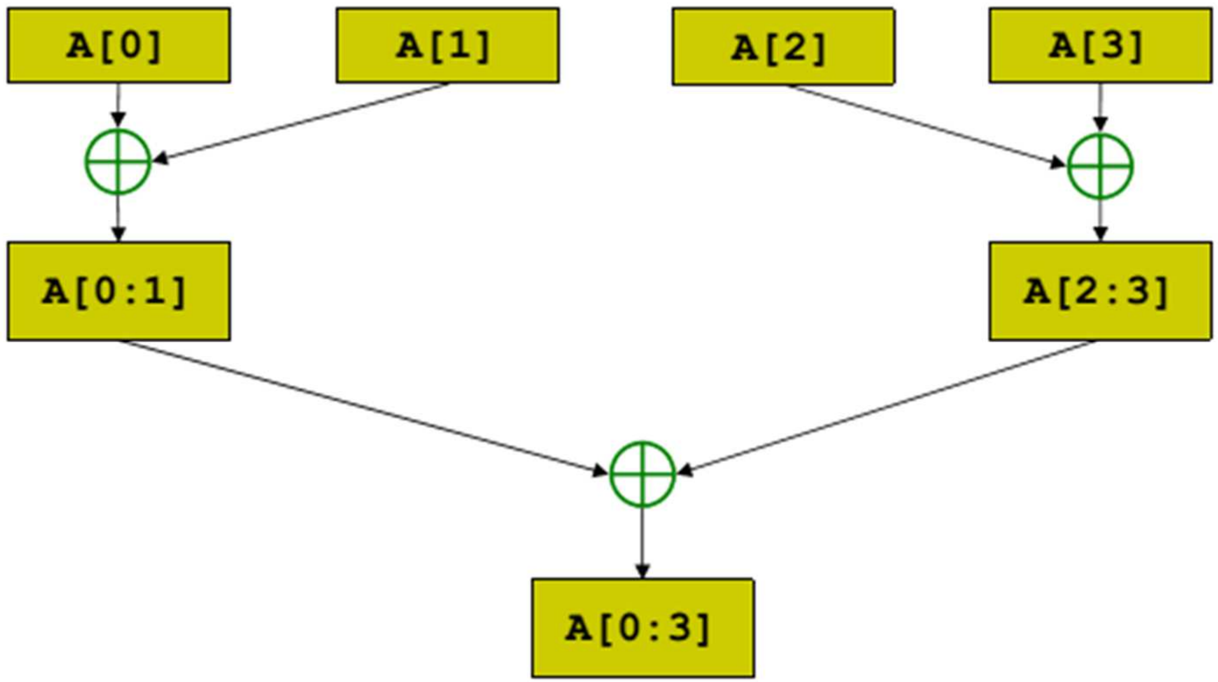
Serial Reduction

- ✓ When reduction operator is not associative
- ✓ Usually followed by a broadcast of result



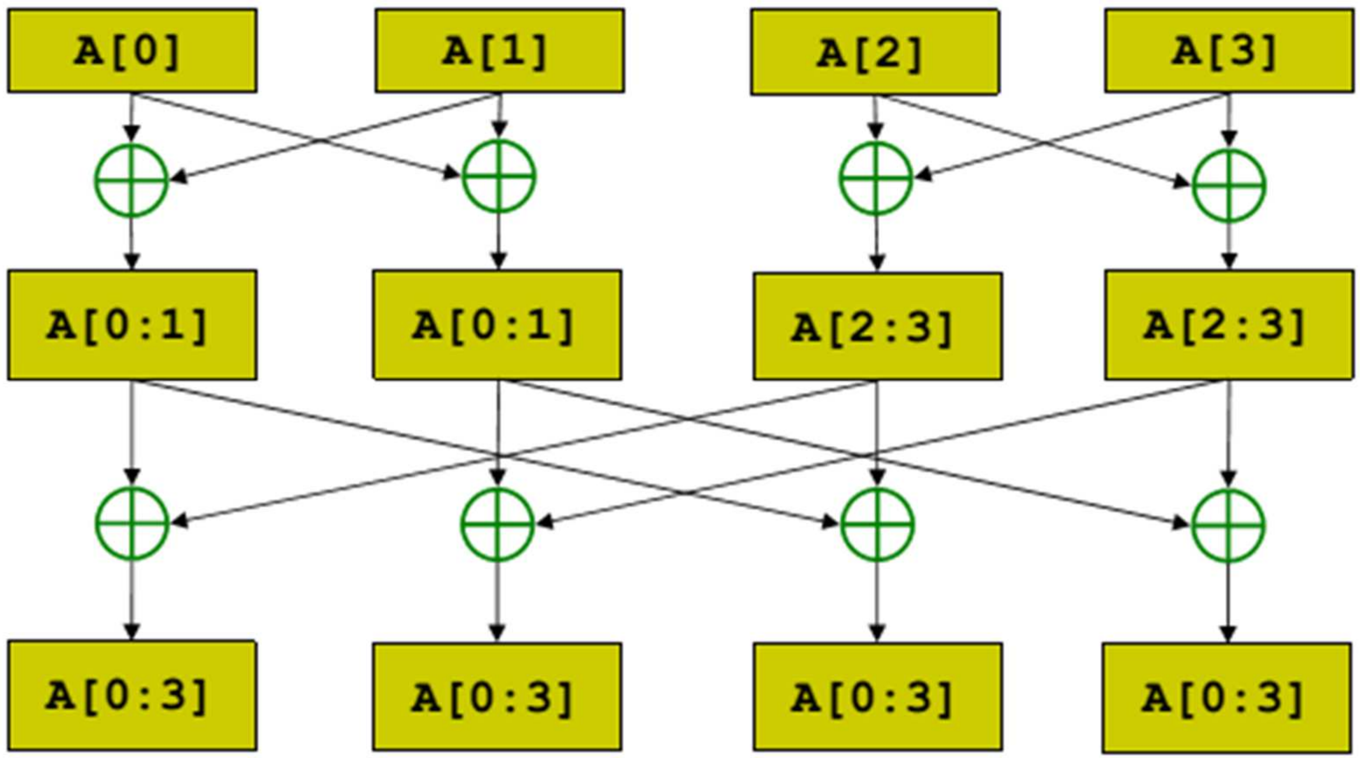
Tree-based Reduction

- ✓ n steps for 2^n units of execution
- ✓ When reduction operator is associative
- ✓ Especially attractive when only one task needs result



Recursive-doubling Reduction

- ✓ n steps for 2^n units of execution
- ✓ If all units of execution need the result of the reduction



Recursive-doubling Reduction

- ✓ Better than tree-based approach with broadcast
  - – Each units of execution has a copy of the reduced valutat the end of n steps
  - – In tree-based approach with broadcast
    - Reduction takes n steps
    - Broadcast cannot begin until reduction is complete
    - Broadcast takes n steps (architecture dependent)
    - O(n) vs. O(2n)

Algorithm Structure and Organization

- ✓ Patterns can be hierarchically composed so that a program uses more than one pattern

	Task parallelism	Divide and conquer	Geometric decomposition	Recursive data	Pipeline	Event-based coordination
SPMD	****	***	****	**	***	**
Loop Parallelism	****	**	***			
Master/ Worker	****	**	*	*	****	*
Fork/ Join	**	****	**		****	****

Design methodology: Top-Down

- ✓ We know that a system is composed of more than one sub-systems and it contains a number of components. Further, these sub-systems and components may have their on set of sub-system and components and creates hierarchical structure in the system.
- ✓ Top-down design takes the whole software system as one entity and then decomposes it to achieve more than one sub-system or component based on some characteristics. Each sub-system or component is then treated as a system and decomposed further. This process keeps on running until the lowest level of system in the top-down hierarchy is achieved.
- ✓ Top-down design starts with a generalized model of system and keeps on defining the more specific part of it. When all components are composed the whole system comes into existence.
- ✓ Top-down design is more suitable when the software solution needs to be designed from scratch and specific details are unknown.

Design methodology: Bottom-Up

- ✓ The bottom up design model starts with most specific and basic components. It proceeds with composing higher level of components by using basic or lower level components. It keeps creating higher level components until the desired system is not evolved as one single component. With each higher level, the amount of abstraction is increased.

- ✓ Bottom-up strategy is more suitable when a system needs to be created from some existing system, where the basic primitives can be used in the newer system.

- ✓ Both, top-down and bottom-up approaches are not practical individually. Instead, a good combination of both is used.