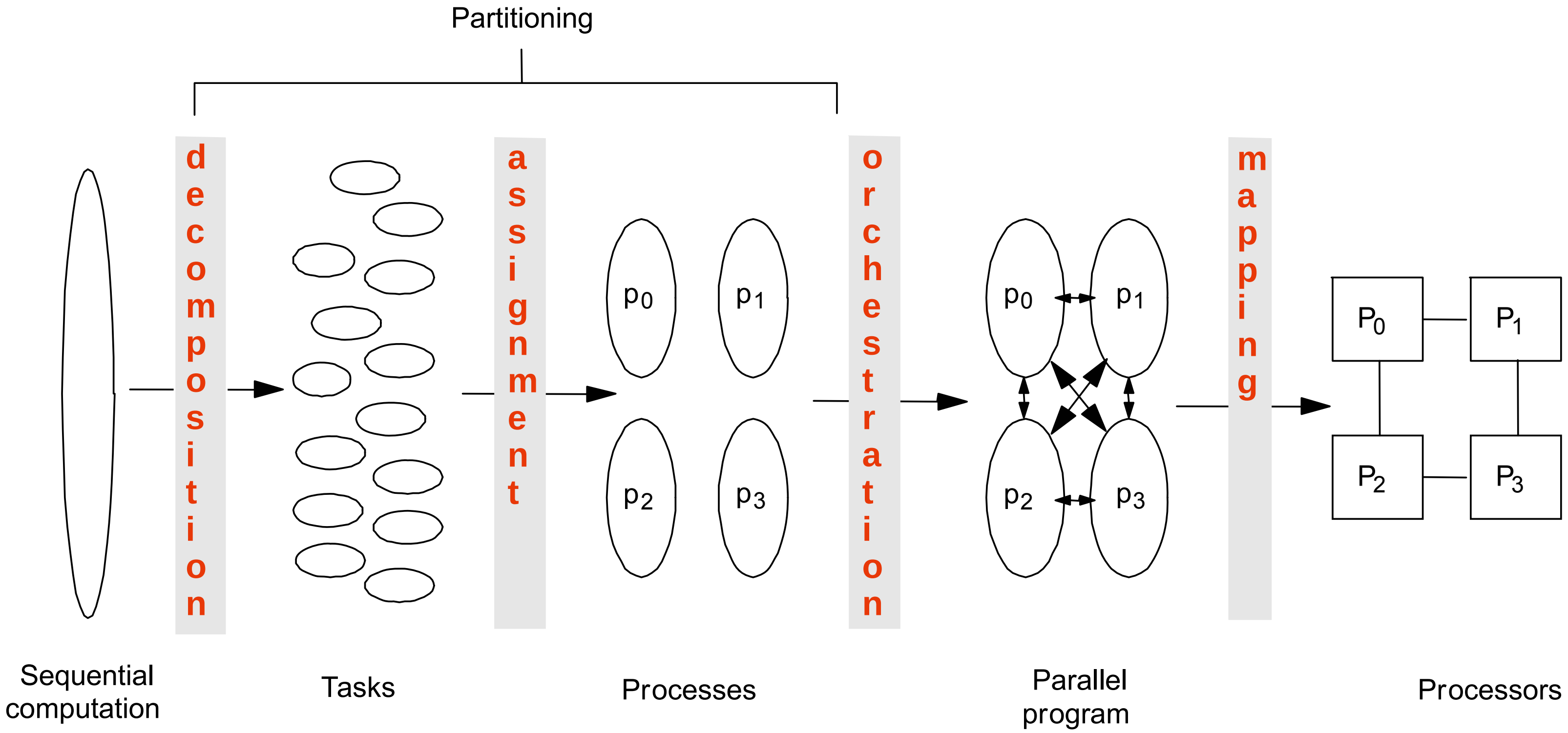
6.189 IAP 2007

Lecture 6

Design Patterns for Parallel Programming I

4 Common Steps to Creating a Parallel Program



Partitioning

decomposition

assignment

orchestration

mapping

Sequential computation

Tasks

Processes

Parallel program

Processors

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)

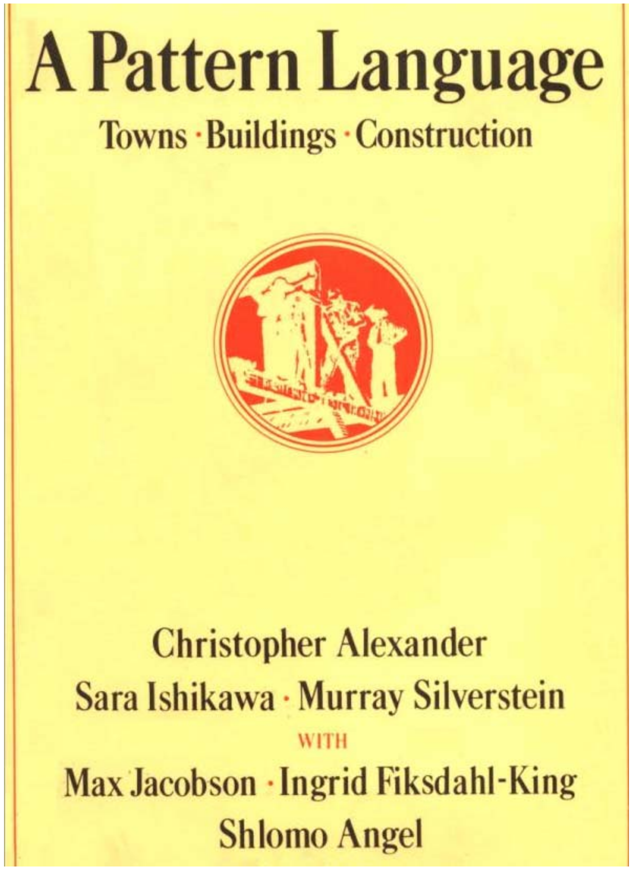
- Computation and communication concurrency
- Preserve locality of data
- Schedule tasks to satisfy dependences early

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

History

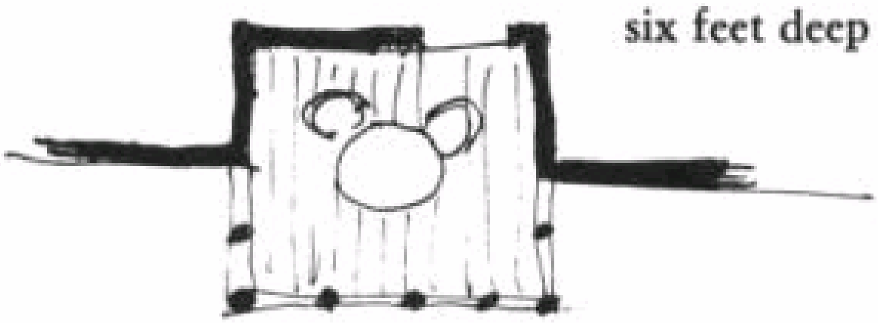
- Berkeley architecture professor Christopher Alexander
- In 1977, patterns for city planning, landscaping, and architecture in an attempt to capture principles for “living” design



Example 167 (p. 783): 6ft Balcony

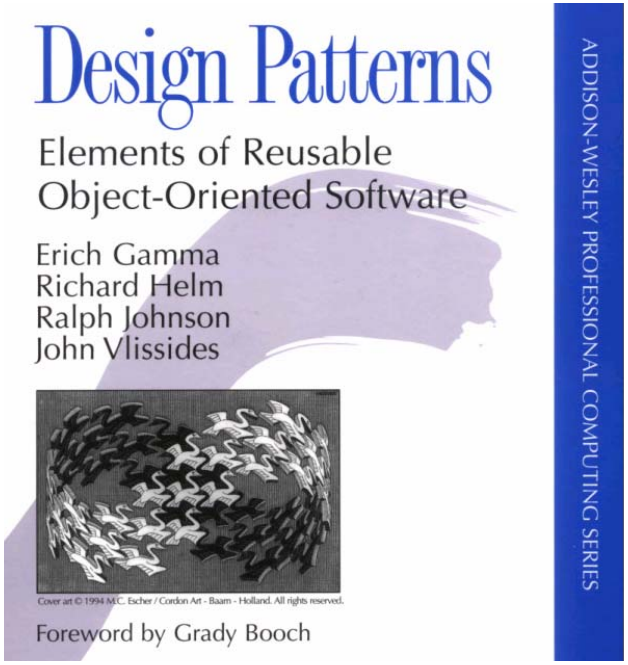
Therefore:

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



Design Patterns

Elements of Reusable
Object-Oriented Software

Erich Gamma
Richard Helm
Ralph Johnson
John Vlissides

Cover art © 1994 M.C. Escher / Cordon Art - Baarn - Holland. All rights reserved.

Foreword by Grady Booch

ADDISON-WESLEY PROFESSIONAL COMPUTING SERIES

Patterns for Parallelizing Programs

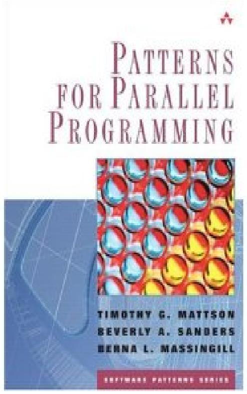
4 Design Spaces

Algorithm Expression

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

Software Construction

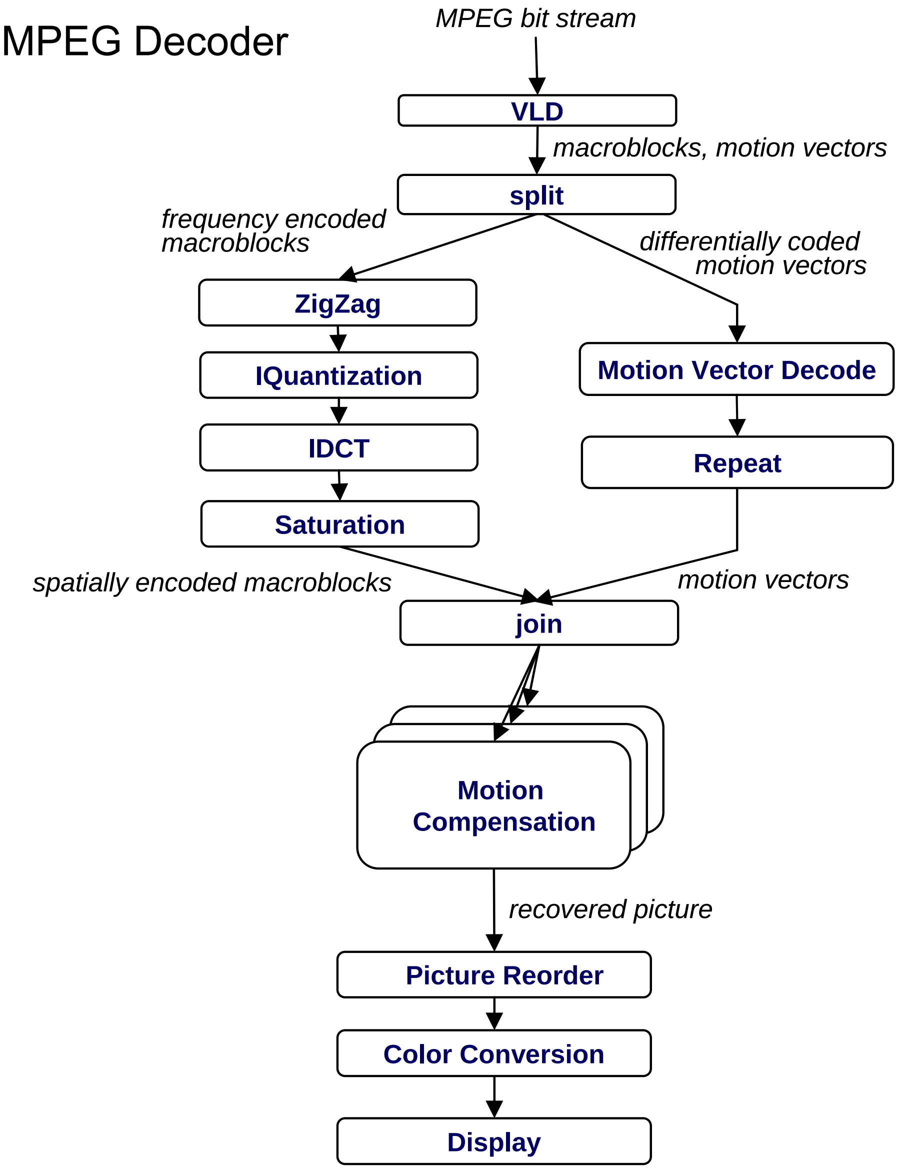
- Supporting Structures
  - Code and data structuring patterns
- Implementation Mechanisms
  - Low level mechanisms used to write parallel programs



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

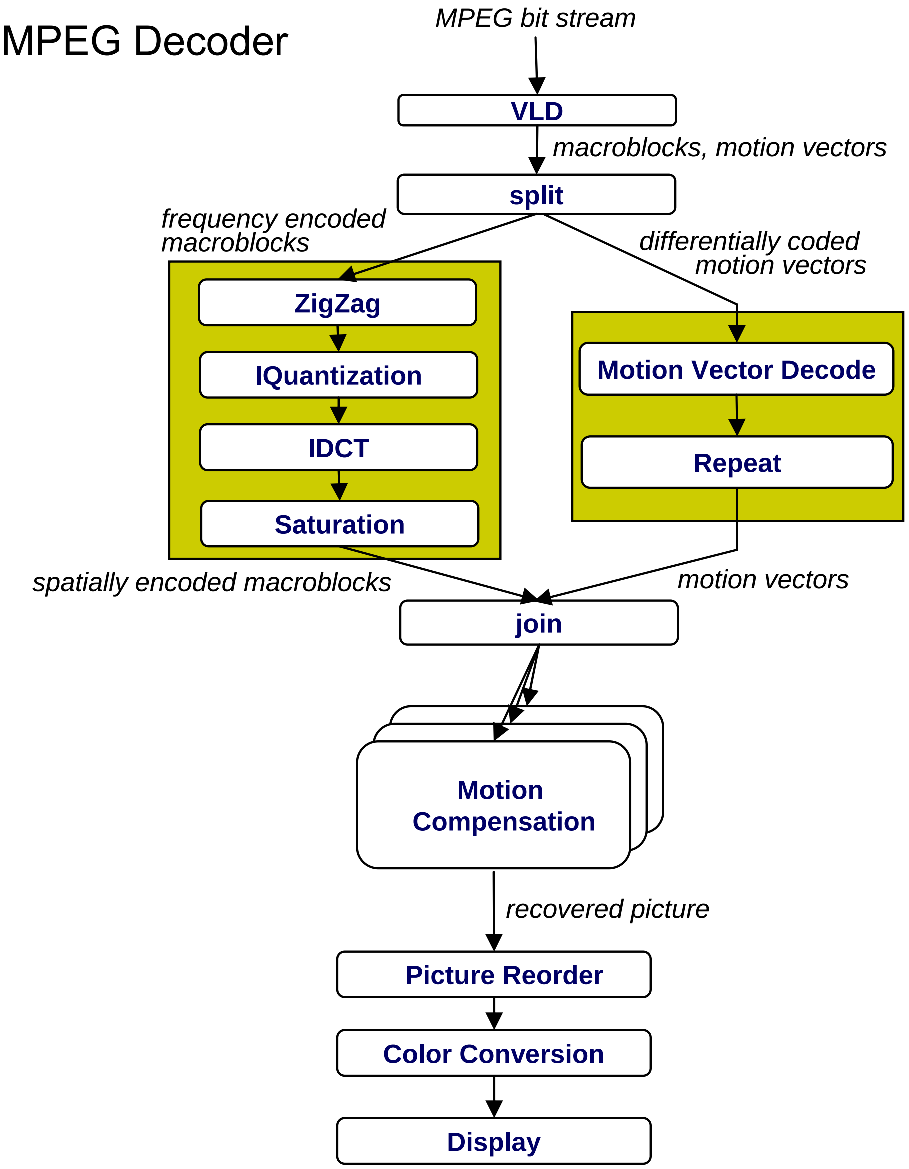
Here's my algorithm.
Where's the concurrency?

MPEG Decoder



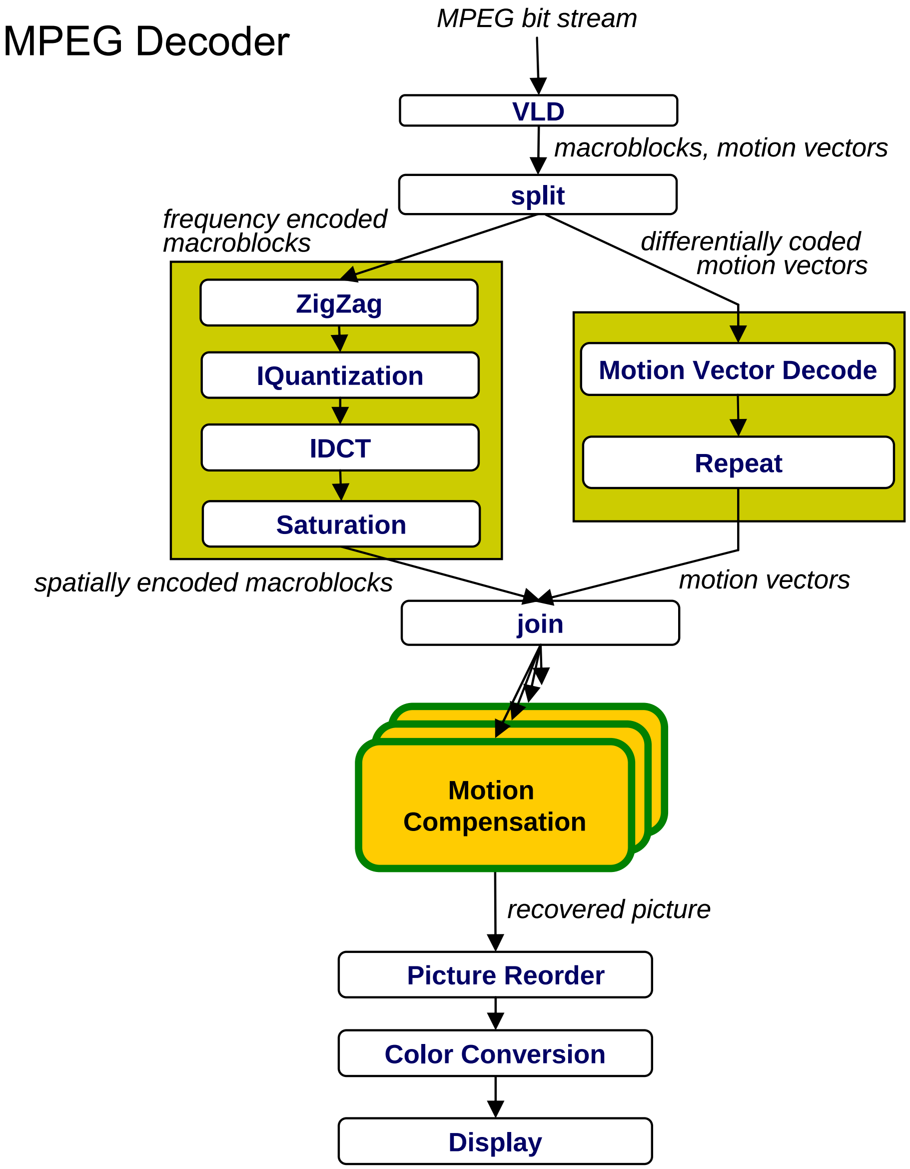
Here’s my algorithm.
Where’s the concurrency?

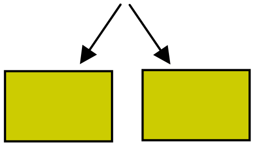
MPEG Decoder



- 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?

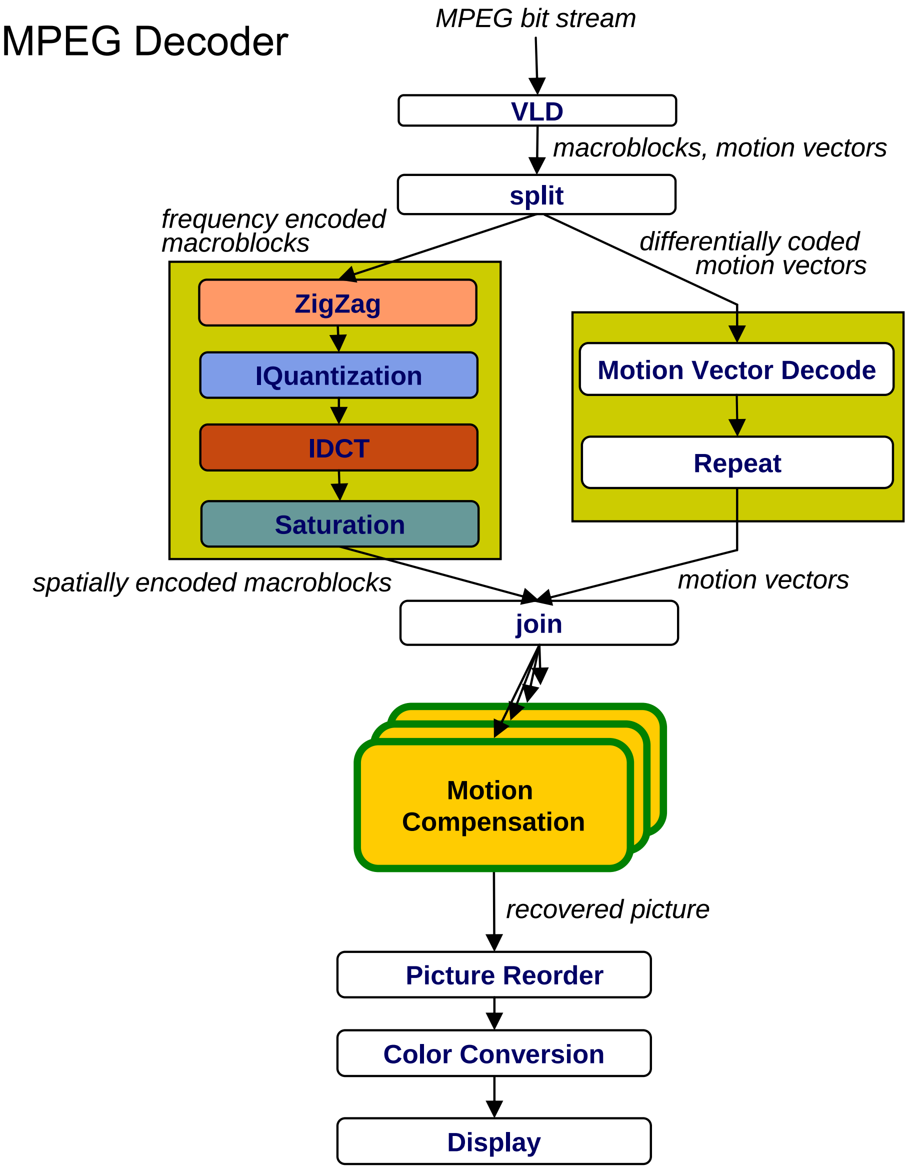




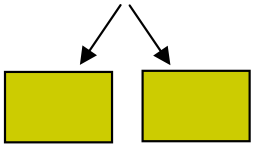
- Task decomposition
  - Parallelism in the application
- Data decomposition
  - Same computation is applied to small data chunks derived from large data set

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

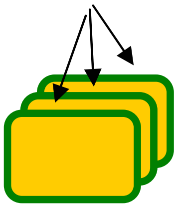
MPEG Decoder



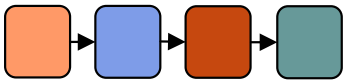
- Task decomposition
  - Parallelism in the application



- 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

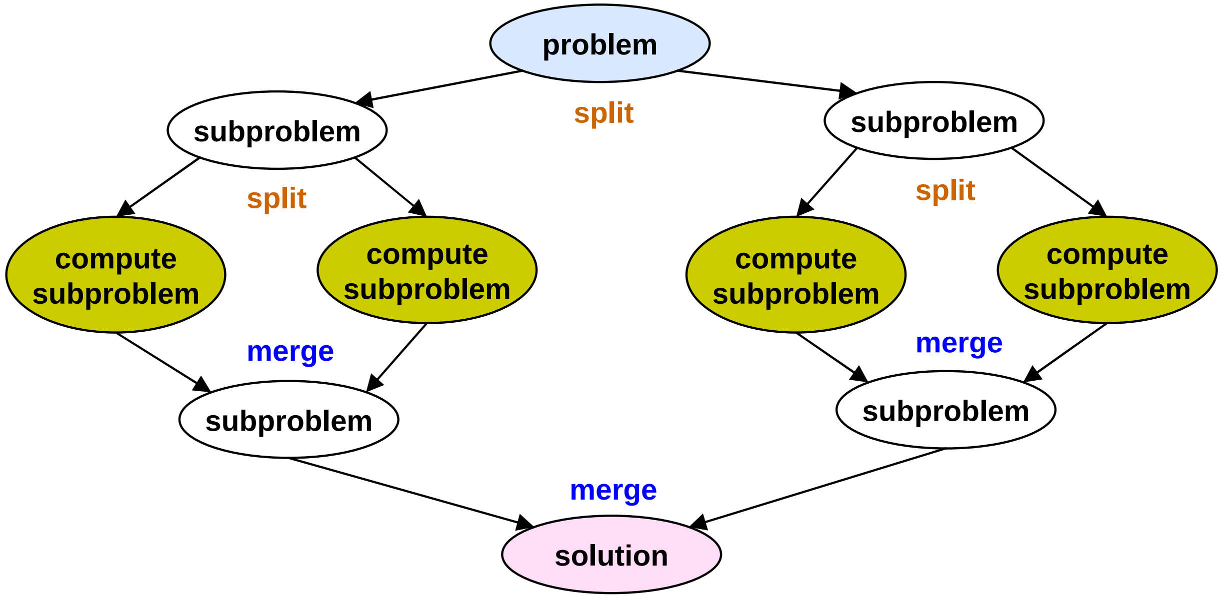
Guidelines for Data Decomposition

- 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

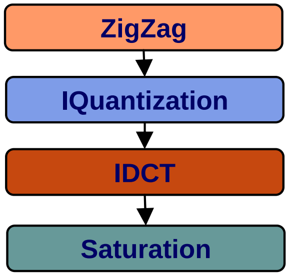
- Recursive data structures
  - Example: decomposition of trees into sub-trees



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

6.189 IAP 2007

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

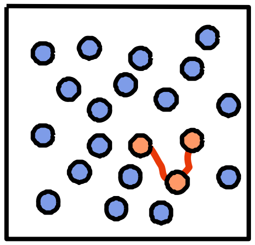
- Define a testing protocol

- 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



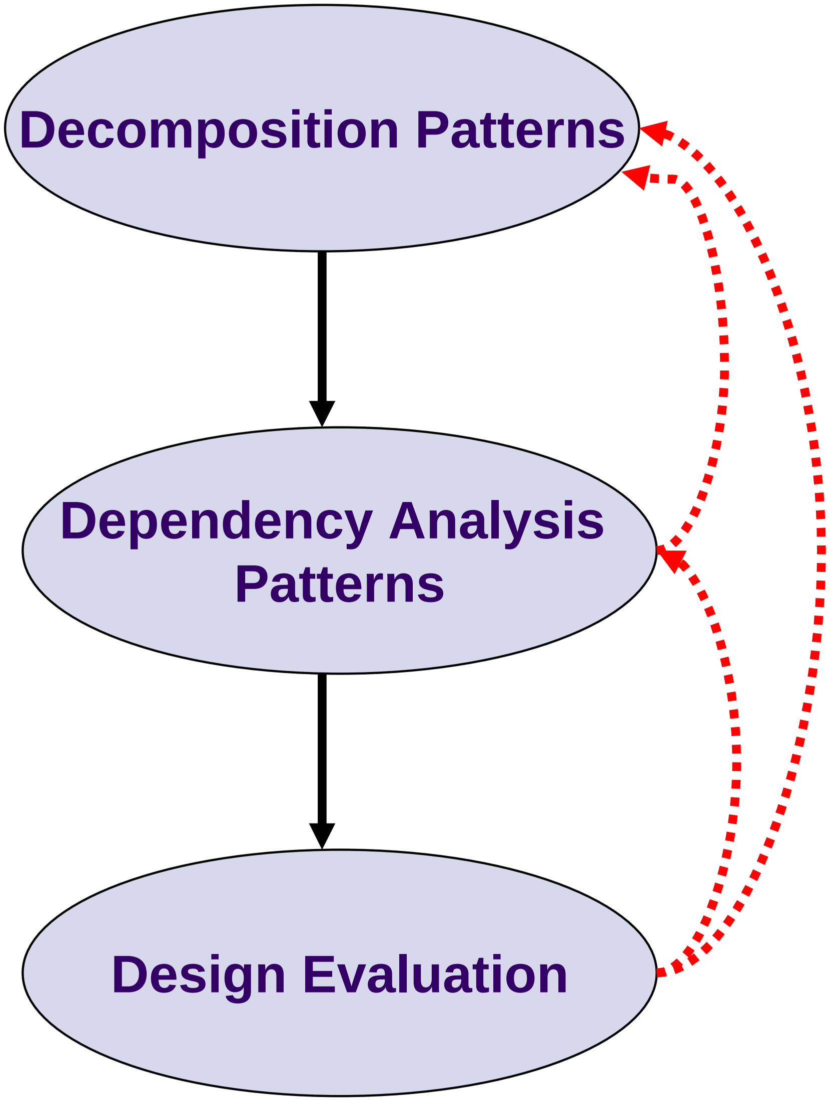
- Naïve algorithm has n^2 interactions: not feasible
- Use cutoff method: only consider forces from neighbors that are "close enough"

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

Dependency Analysis Patterns

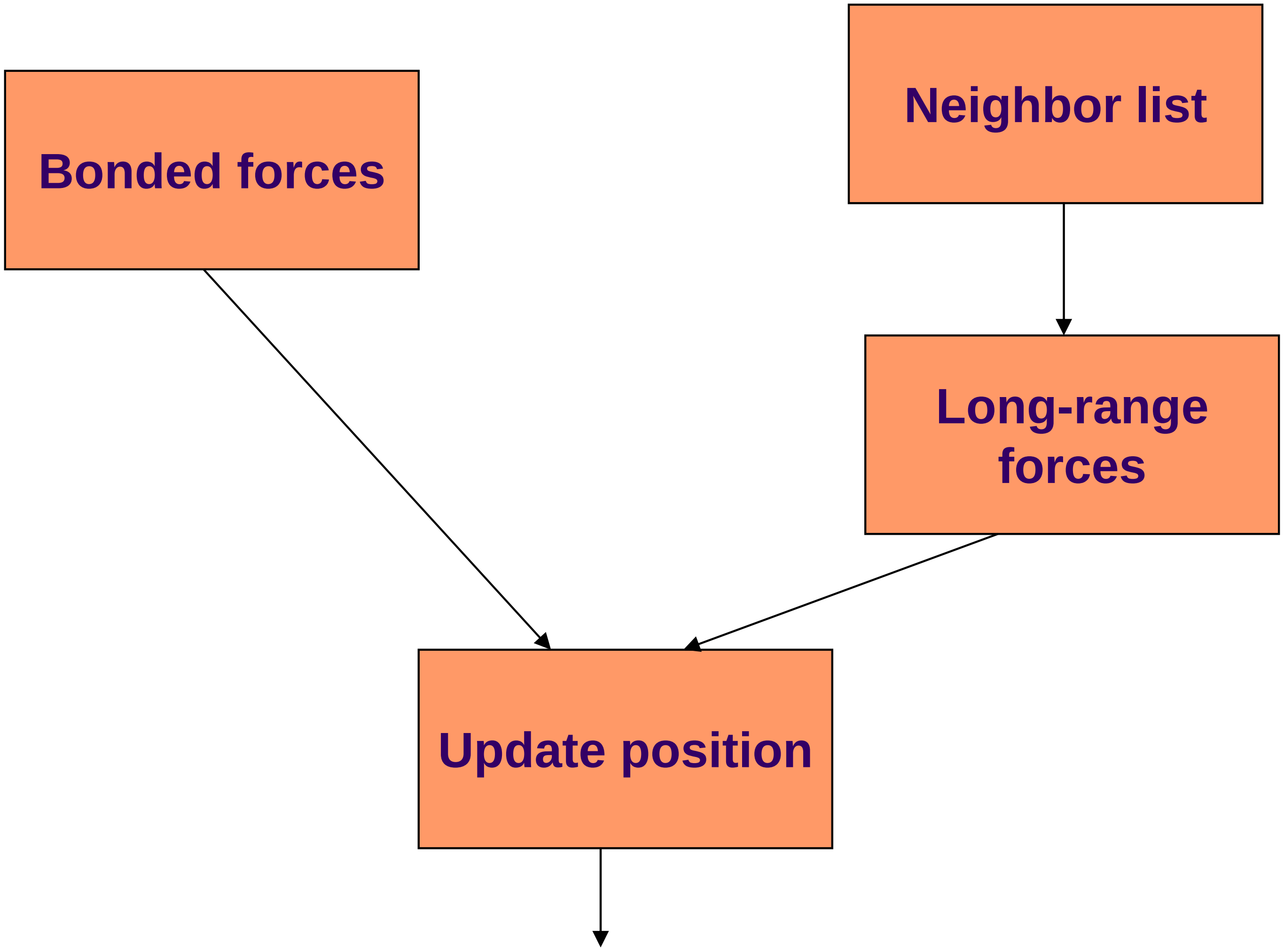
Design Evaluation

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



Bonded forces

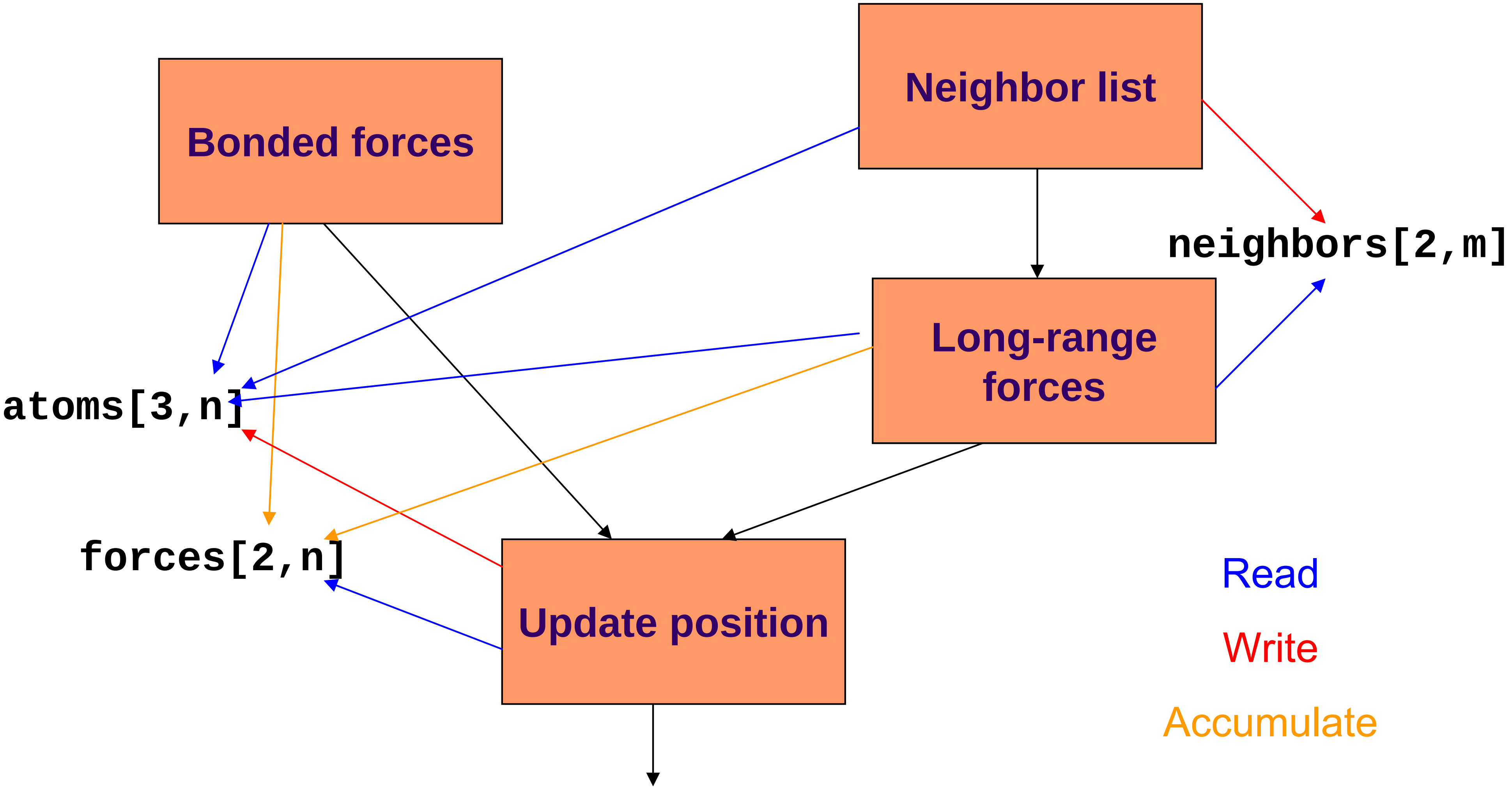
Neighbor list

Long-range forces

Update position

next time step

Understand Data Dependences



Bonded forces

Neighbor list

`neighbors[2,m]`

Long-range forces

`atoms[3,n]`

`forces[2,n]`

Update position

next time step

Read

Write

Accumulate

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