Thread Parallelism

Shared Memory Patterns and Thread Parallelism Paradigms

COS 597C

Topics

- Synchronization Problems
  - Producer-Consumer Problem
  - Readers-Writers Problem
- Semaphores and their Implementation
- Data Races
- Shared Memory Patterns
- Parallelizing Computations
- Partitioning and Problem Decomposition
- Loop Parallelism

Producer-Consumer Problem

- Problem description
  - A producer: in an infinite loop and produce one item per iteration into the buffer
  - A consumer: in an infinite loop and consumes one item per iteration from the buffer
  - Buffer size: can only hold at most N items
  - Need to make sure that
    - Producer does not try to add data into the buffer when it is full
    - Consumer does not try to remove data from an empty buffer

Producer-Consumer Problem

```
int counter; //initialize to 0
 // Producer
 repeat
1      read the counter value
2      if(Counter < MAX_COUNT) {
3          increment the counter;
4          update the counter with the
           incremented value;
5          Store a value into the buffer
6          //ERROR if  buffer full
       }
       else{
7          wait
       }
   Until YY says stop
```

```
 // consumer
 repeat
1       read the counter value;
2       if(Counter > 0) {
3           decrement counter;
4           update the counter with the
            incremented value;
5           consume a value from buffer
6           //ERROR if buffer empty
            }
            else{
7           wait
        }
 Until YY says stop
```

Producer-Consumer Problem

```
int counter; //initialize to 0
Mutex m;
 // Producer
  repeat
1       Mutex_Lock(&m);
2       read the counter value
3       if(Counter < MAX_COUNT) {
4           increment the counter;
5           update the counter with the
            incremented value;
6          Store a value into the buffer
7           //ERROR if  buffer full
8           Mutex_Unlock(&m)
        }
        else{
9           wait
10      }
   Until YY says stop
```

```
 // consumer
  repeat
1       Mutex_lock(&m);
2       read the counter value;
3       if(Counter > 0) {
4           decrement counter;
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            incremented value;
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   Until YY says stop
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Producer-Consumer Problem

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        }
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10          wait
        }
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 // consumer
  repeat
1       Mutex_lock(&m);
2       read the counter value;
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4           decrement counter;
5           update the counter with the
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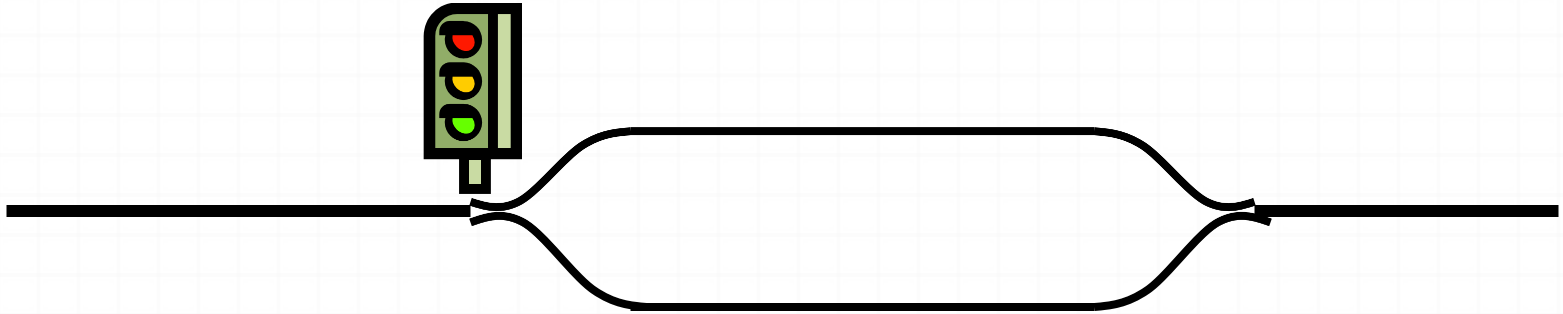
6           consume a value from buffer
7           //ERROR if buffer empty
8           Mutex_Unlock(&m)
            }
            else{
9           Mutex_Unlock(&m)
10          wait
        }
   Until YY says stop
```

Semaphores

- A synchronization variable that takes on positive integer values
- Two operations:
  - P(semaphore): an atomic operation that waits for semaphore to become greater than zero, then decrements by 1 (Dutch: *proberen*)
  - V(semaphore): an atomic operation that increments semaphore by 1 (Dutch: *verhogen)*



Producer-Consumer Problem

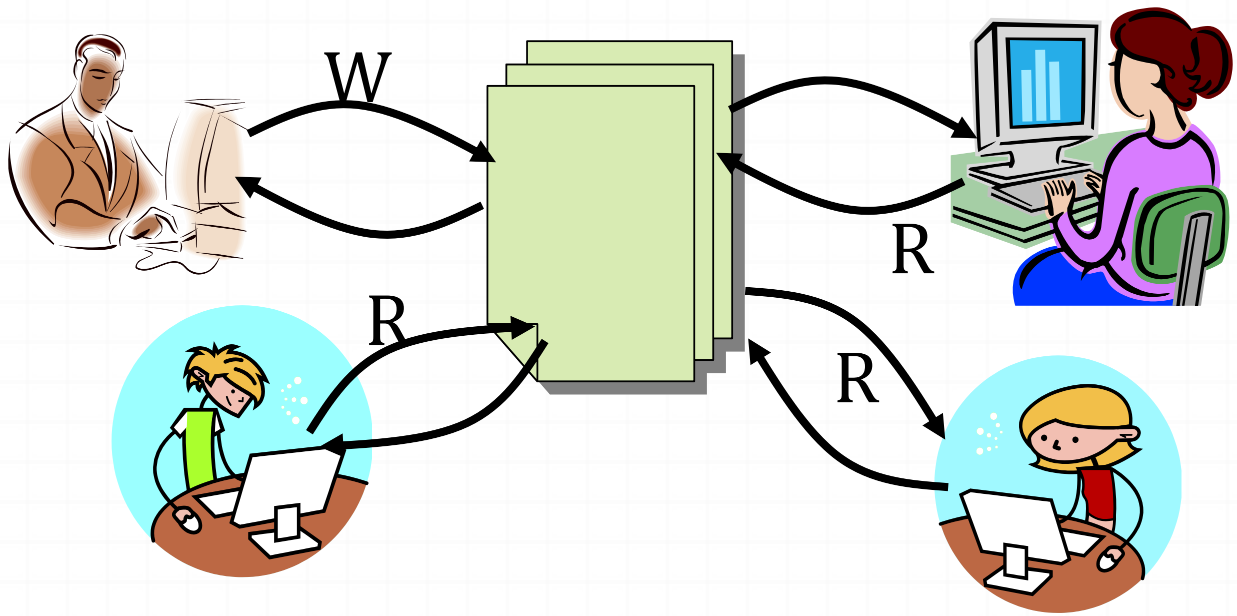
```
Semaphore Full = 0
Semaphore Empty = BUFFER_SIZE
Mutex m; //Equivalent to Semaphore m = 1

 // Producer
  repeat
1        P(&empty)
2        Mutex_lock(&m);
3        Enqueue new item in buffer
4        Mutex_Unlock(&m);
5        V(&full);
  Until YY says stop
```

```
 // consumer

  repeat
1        P(&full)
2        Mutex_lock(&m);
3        Deque item from buffer
4        Mutex_Unlock(&m);
5        V(&empty);
  Until YY says stop
```

Readers-Writers Problem



A Shared Database

- Two classes of users:
  - Readers – never modify database
  - Writers – read and modify database
- Is using a single lock on the whole database sufficient?
  - Like to have many readers at the same time
  - Only one writer at a time

Readers-Writers Problem

- Deals with situations in which many threads much access the same shared memory at one time
  - No thread may access the shared object for reading or writing while another thread is writing to it
  - Concurrent reads are allowed
- First Readers-Writers problem: No reader shall be kept waiting if the shared object is currently open for reading
- Second Readers-Writers problem: No writer, once added to the queue, shall be kept waiting longer than absolutely necessary

Readers-Writers Problem

- Basic structure of a solution:
  - `Reader()`
    ```
    Wait until no writers
    Access data base
    Check out – wake up a waiting writer
    ```
  - `Writer()`
    ```
    Wait until no active readers or writers
    Access database
    Check out – wake up waiting readers or writer
    ```
  - State variables (Protected by a lock called “lock”):
    - int AR: Number of active readers; initially = 0
    - int WR: Number of waiting readers; initially = 0
    - int AW: Number of active writers; initially = 0
    - int WW: Number of waiting writers; initially = 0
    - Condition okToRead = NIL
    - Condition okToWrite = NIL

Readers-Writers Problem

```
Reader() {
    // First check self into system
    lock.Acquire();
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      okToRead.wait(&lock); // Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;                   // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
      okToWrite.signal();   // Wake up one writer
    lock.Release();
  }
```

Readers-Writers Problem

```
Writer() {
   // First check self into system
   lock.Acquire();
   while ((AW + AR) > 0) { // Is it safe to write?
      WW++;                // No. Active users exist
      okToWrite.wait(&lock);// Sleep on cond var
      WW--;                // No longer waiting
   }
   AW++;                   // Now we are active!
   lock.release();
   // Perform actual read/write access
   AccessDatabase(ReadWrite);
   // Now, check out of system
   lock.Acquire();
   AW--;                   // No longer active
   if (WW > 0){            // Give priority to writers
      okToWrite.signal();  // Wake up one writer
   } else if (WR > 0) {    // Otherwise, wake reader
      okToRead.broadcast();// Wake all readers
   }
   lock.Release();
}
```

Implementation of Semaphores

- No existing hardware implements semaphores directly
- Semaphores are built up in software using some lower-level synchronization primitive provided by hardware
- Uniprocessor solution: Disable interrupts

```
typedef struct {
   int count;
   queue q; /* queue of threads waiting on this
            semaphore */
} Semaphore;
```

Implementation of Semaphores

```
void P(Semaphore s){
  Disable interrupts;
  if (s->count > 0) {
    s->count -= 1;
    Enable interrupts;
    return;
  }
  Add(s->q, current
  thread);
  sleep(); // re-dispatch
  Enable interrupts;
}
```

```
void V(Semaphore s){
  Disable interrupts;
  if (isEmpty(s->q)) {
    s->count += 1;
  } else {
    thread = RemoveFirst(s-
    >q);
   wakeup(thread); /* put
   thread on the ready queue
   */
  }
  Enable interrupts;
}
```

Implementation of Semaphores

- Multiprocessor Solution:
  - Can’t turn off all other processors
  - Can’t just turn off interrupts to get low-level mutual exclusion
- Most CISC Machines provide some sort of atomic read-modify-write instruction
  - test&set
  - swap
  - compare&swap

Implementation of Semaphores

- Modern RISC machines do not provide read-modify-write instructions
- Instead they provide a weaker mechanism that does not guarantee atomicity but detects interference
  - *load-linked* instruction (ldl): Loads a word from memory and sets a per-processor flag associated with that word (usually stored in the cache)
  - store operations to the same memory location (by any processor) reset all processor's flags associated with that word.
  - *store-conditionally* instruction (stc): Stores a word iff the processor's flag for the word is still set; indicates success or failure.

Implementation of Semaphores

- Atomic Read-Modify-Write Example in MIPS

```
atomic_inc:
    ll $t0, 0($a0)         # load linked
    addiu $t1, $t0, 1      # increment
    sc $t1, 0($a0)         # store cond'l
    beqz $t1, atomic_inc
                           # loop if failed
```

Different Implementations for Mutual Exclusion

Using ldl/stc

```
int lock;
..
while (ldl(&lock) != 0 ||
!stc(&lock, 1));
..
critical section
..
lock = 0;
```

Using Test And Set

```
int lock;
..
while (TAS(&lock, 1) != 0);
..
critical section
..
lock = 0;
```

Using ldl/stc to Implement Semaphores

```
typedef struct {
  int lock;  /*Initially 0*/
  int count;
  queue q; /* queue of threads waiting on this
  semaphore */
} Semaphore;
```

Using ldl/stc to Implement Semaphores

```
void P(Semaphore s) {
  Disable interrupts;
  while (ldl(s->lock) != 0 ||
  !stc(s->lock, 1));
  if (s->count > 0) {
    s->count -= 1;
    s->lock = 0;
    Enable interrupts;
    return;
  }
  Add(s->q, current thread);
  s->lock = 0;
  sleep(); /* re-dispatch */
  Enable interrupts;
}
```

```
void V(Semaphore s){
  Disable interrupts;
  while (ldl(s->lock) != 0 ||
  !stc(s->lock, 1));
  if (isEmpty(s->q)) {
    s->count += 1;
  } else {
    thread = RemoveFirst(s->q);
    wakeup(thread); /* put
    thread on the ready queue
    */
  }
  s->lock = 1;
  Enable interrupts;
}
```

What is a Data Race?

- Two concurrent accesses to a memory location at least one of which is a write.
- Example: Data race between a read and a write

```
int x = 1;
Parallel.Invoke(
                () => { x = 2; },
                () => { System.Console.WriteLine(x); }
              );
```

writes x

reads x

- Outcome nondeterministic or worse
  - may print 1 or 2, or arbitrarily bad things on a relaxed memory model

Data Races and Happens-Before

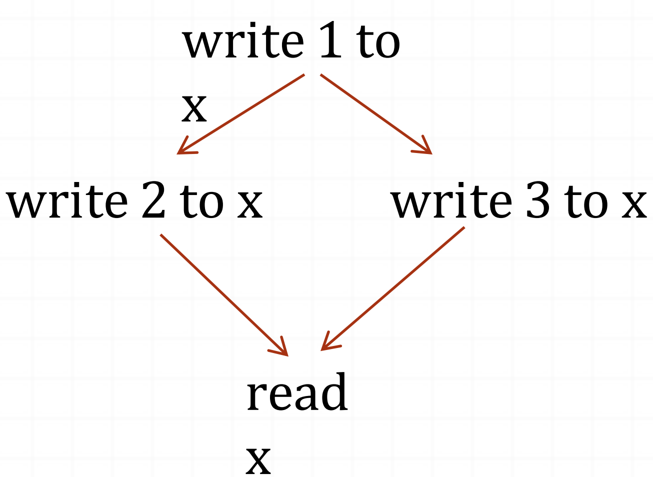
- Example of a data race with two writes:

```
int x = 1;
Parallel.Invoke( () => { x = 2; },
                 () => { x = 3;  }  );
System.Console.WriteLine(x);
```

- We visualize the ordering of memory accesses with a happens-before graph:

There is no path between
(write 2 to x) and (write 3 to x),
thus they are concurrent,
thus they create a data race

(note: the read is not in a data race)



Quiz: Where are the data races?

```
Parallel.For(1,2,
i => {
    x = a[i];
});
```

```
Parallel.For(1,2,
i => {
    a[i] = x;
});
```

```
Parallel.For(1,2,
i => {
    a[i] = a[i+1];
});
```

Quiz: Where are the data races?

```
Parallel.For(1,2,
i => {
    x = a[i];
});
```

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Parallel.For(1,2,
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Parallel.For(1,2,
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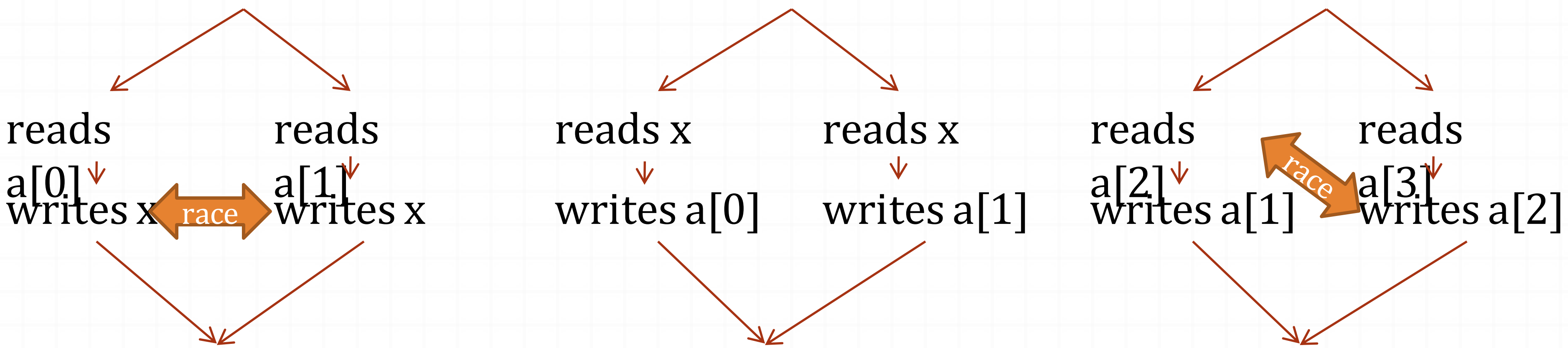
});
```



Race between two writes.

No Race between two reads.

Race between a read and a write.

Data Races can be hard to spot

```
Parallel.For(0, 10000,
    i => {a[i] = new Foo();})
```

- Code looks fine... at first.

Data Races can be hard to spot

```
Parallel.For(0, 10000,
    i => {a[i] = new Foo();})
```

- Problem: we have to follow calls... even if they look harmless at first (like a constructor).

```
class Foo {
       private static int counter;
       private int unique_id;
       public Foo()
       {
              unique_id = counter++;
       }
}
```

Data Race on static field !

Avoiding Data Races

- The three most frequent ways to avoid data races on a variable
  - Make it ***isolated***
    - variable is only ever accessed by one task
  - Make it ***immutable***
    - variable is only ever read
  - Make it ***synchronized***
    - Use a lock to arbitrate concurrent accesses

Programming with Shared Memory

- Keep abstraction level HIGH
- Temptation: ad-hoc parallelization
  - Add tasks or parallel loops all over the code
  - Discover data races/deadlocks, fix them one-by-one
- Problem (depending on the programmer):
  - Complexity adds up quickly
  - Easy to get cornered by deadlocks, atomicity violations, data races
  - These bugs are often hard to expose

Programming with Shared Memory

- Use well-understood, simple high-level patterns

Architectural Patterns

Localize shared state

- **Producer-Consumer**
- **Pipeline**
- **Worklist**

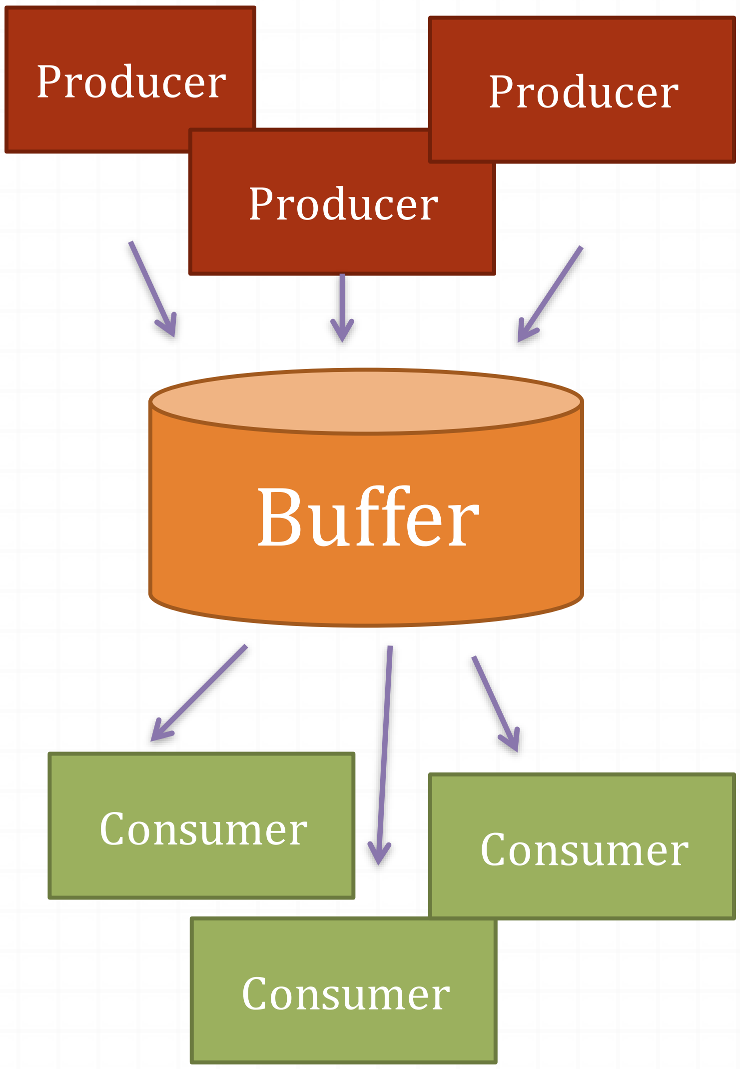
Replication Patterns

Make copies of shared state

- **Immutable Data**
- **Double Buffering**

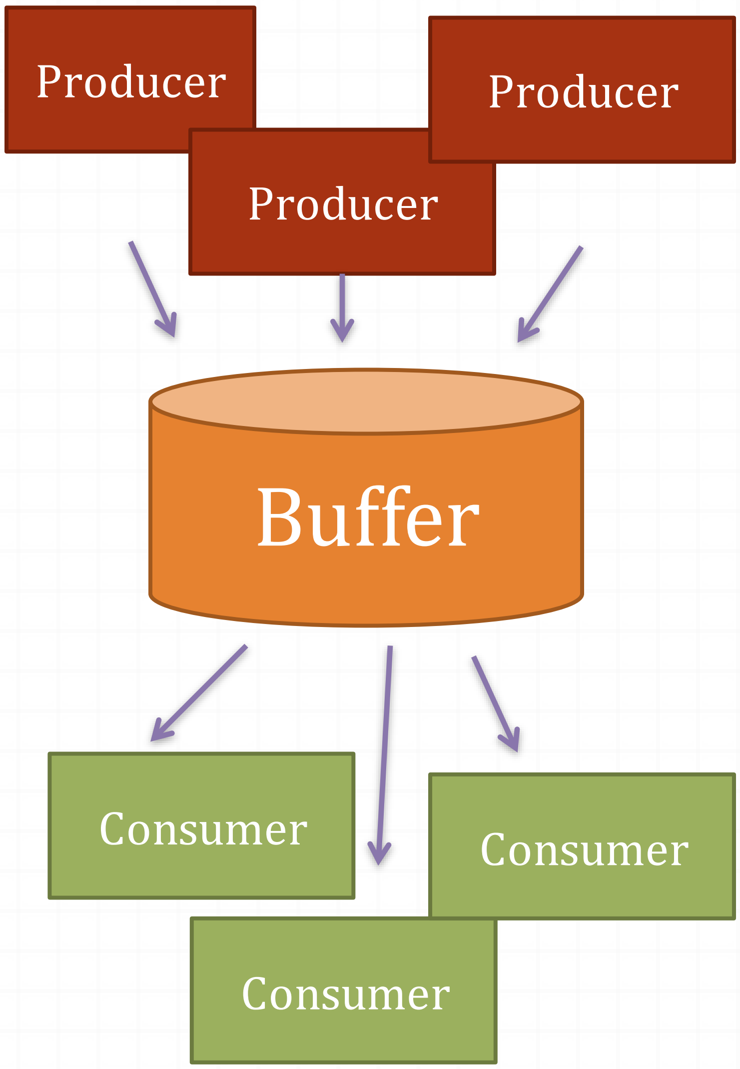
Producer-Consumer Pattern

- Also called the Bounded Buffer problem
- One or more producers add items to the buffer
- One or more consumers remove items from the buffer



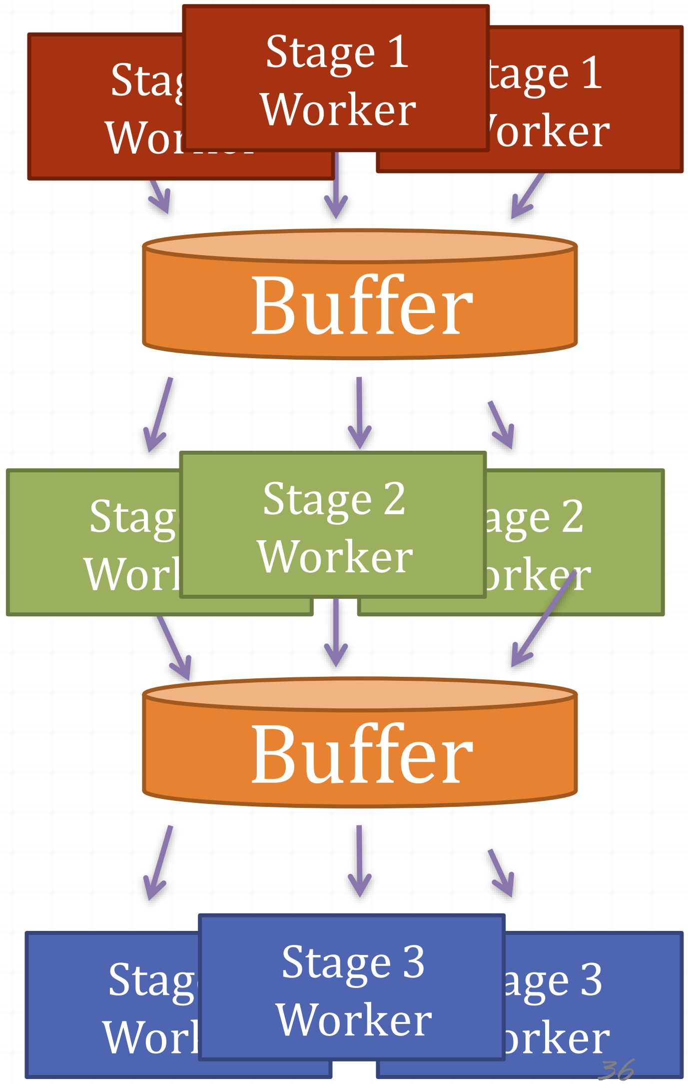
Producer-Consumer Pattern

1. Item is local to Producer before insertion into buffer
2. Item is local to Consumer after removal from buffer
3. What about buffer?
   - Buffer is thread-safe
   - Blocks when full/empty



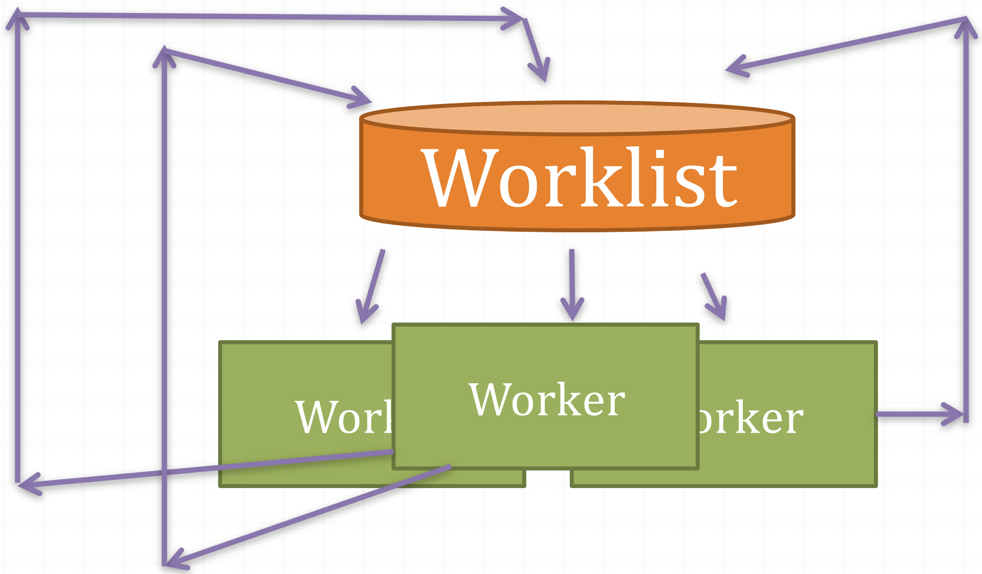
Pipeline Pattern

- Generalization of Producer-Consumer
  - One or more workers per stage
  - First stage = Producer
  - Last stage = Consumer
  - Middle stages consume and produce



Worklist Pattern

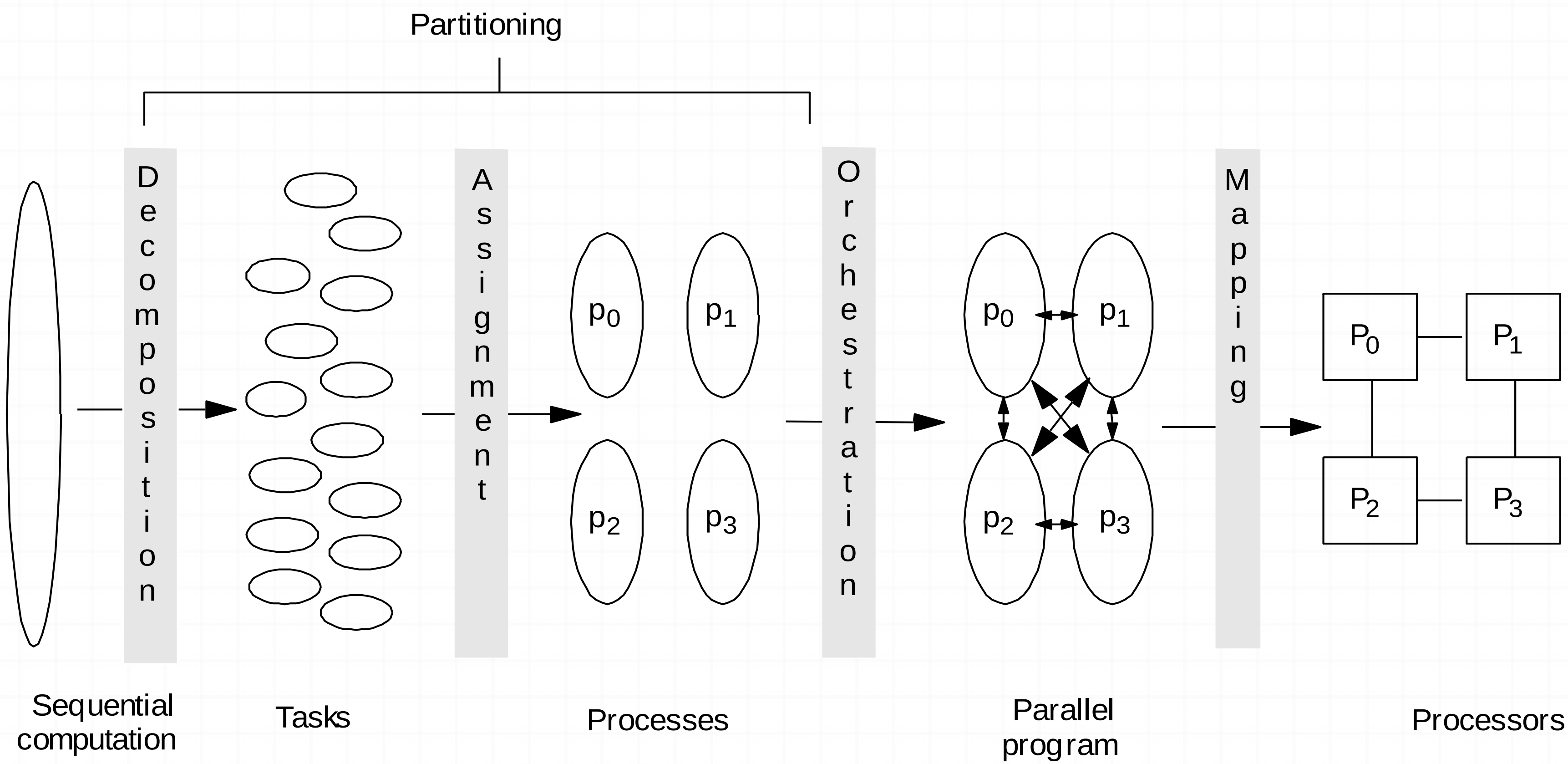
- Worklist contains items to process
  - Workers grab one item at a time
  - Workers may add items back to worklist
  - No data races: items are local to workers



Immutability

- Remember: concurrent reads do not conflict
- Idea: never write to shared data
  - All shared data is immutable (read only)
  - To modify data, must make a fresh copy first
  - Copy-On-Write

Parallelizing Computations



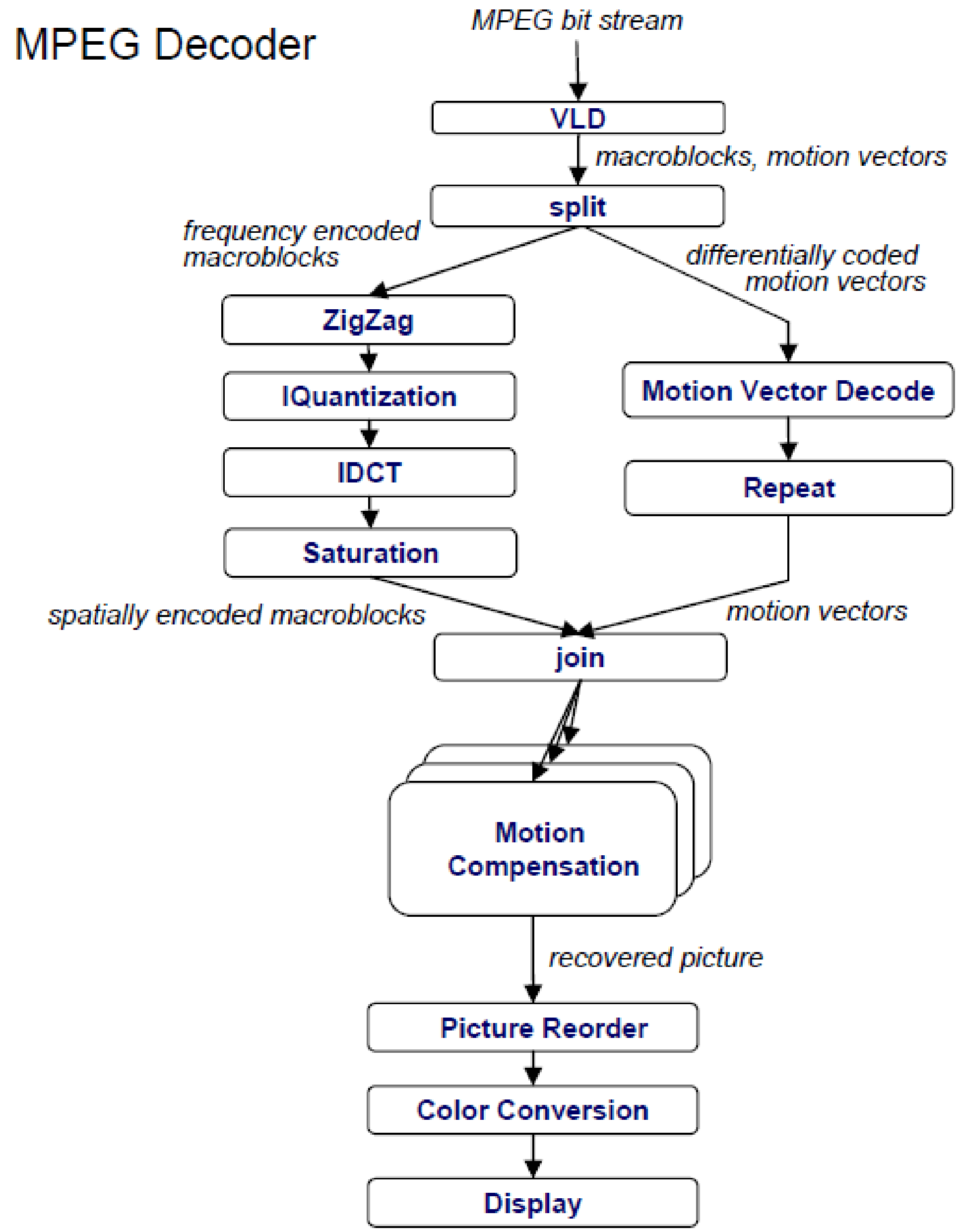
Decomposition of computation in tasks
Assignment of tasks to processes

Orchestration of data access, communication, synchronization
Mapping processes to processors

Partitioning

- Identify concurrency and decide at what level to exploit it
- Break up computations 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
- Decomposition independent of architecture or programming model
- Structured approaches usually work well
  - Remember: Shared memory design patterns

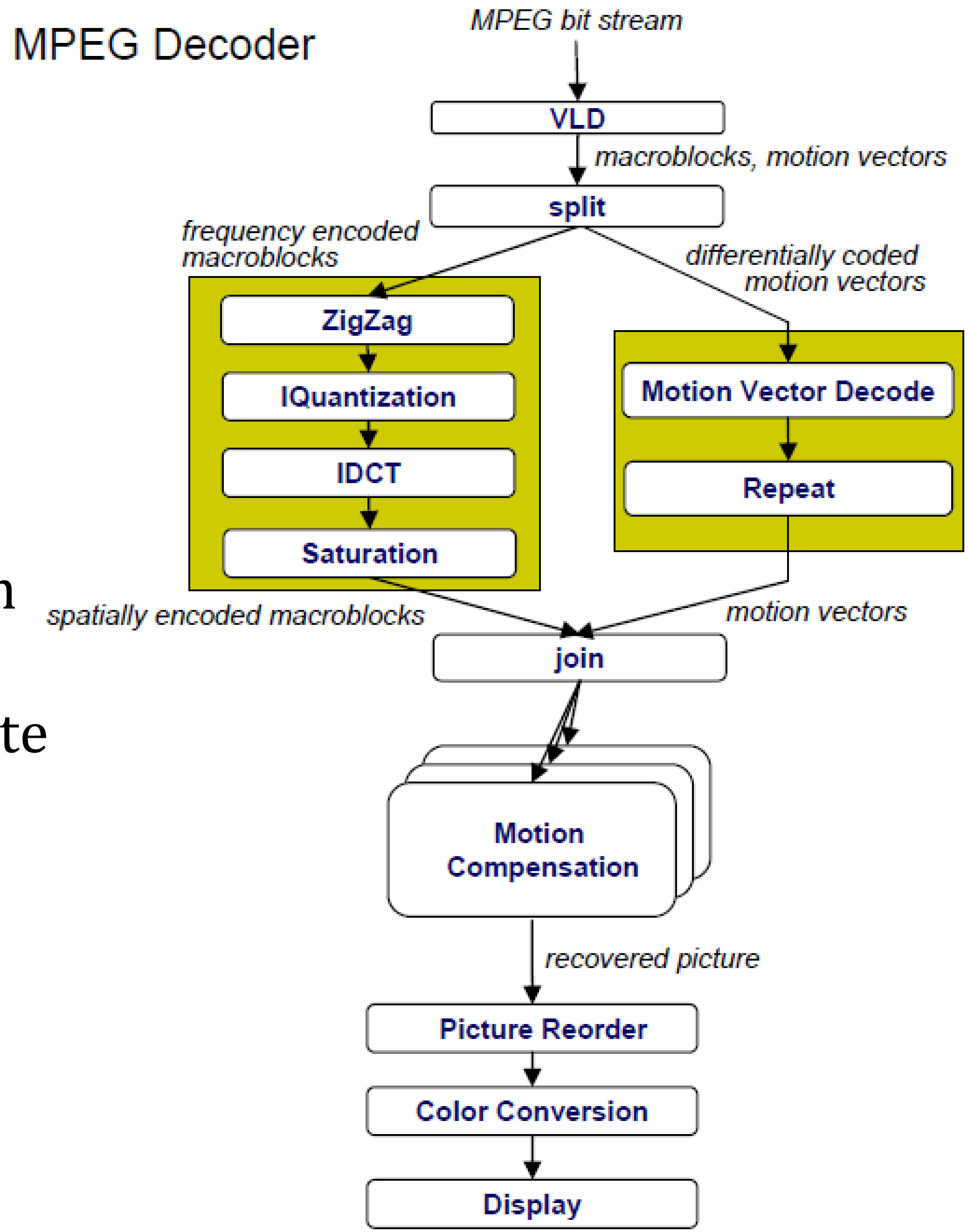
An Example: Decomposition



An Example: Decomposition

Task decomposition

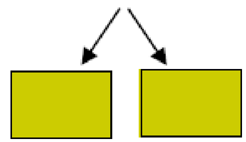
- Independent coarse-grained computation
- Inherent to the algorithm
- Sequence of statements (instructions) that operate together as a group
- Corresponds to some logical part of program



An Example: Decomposition

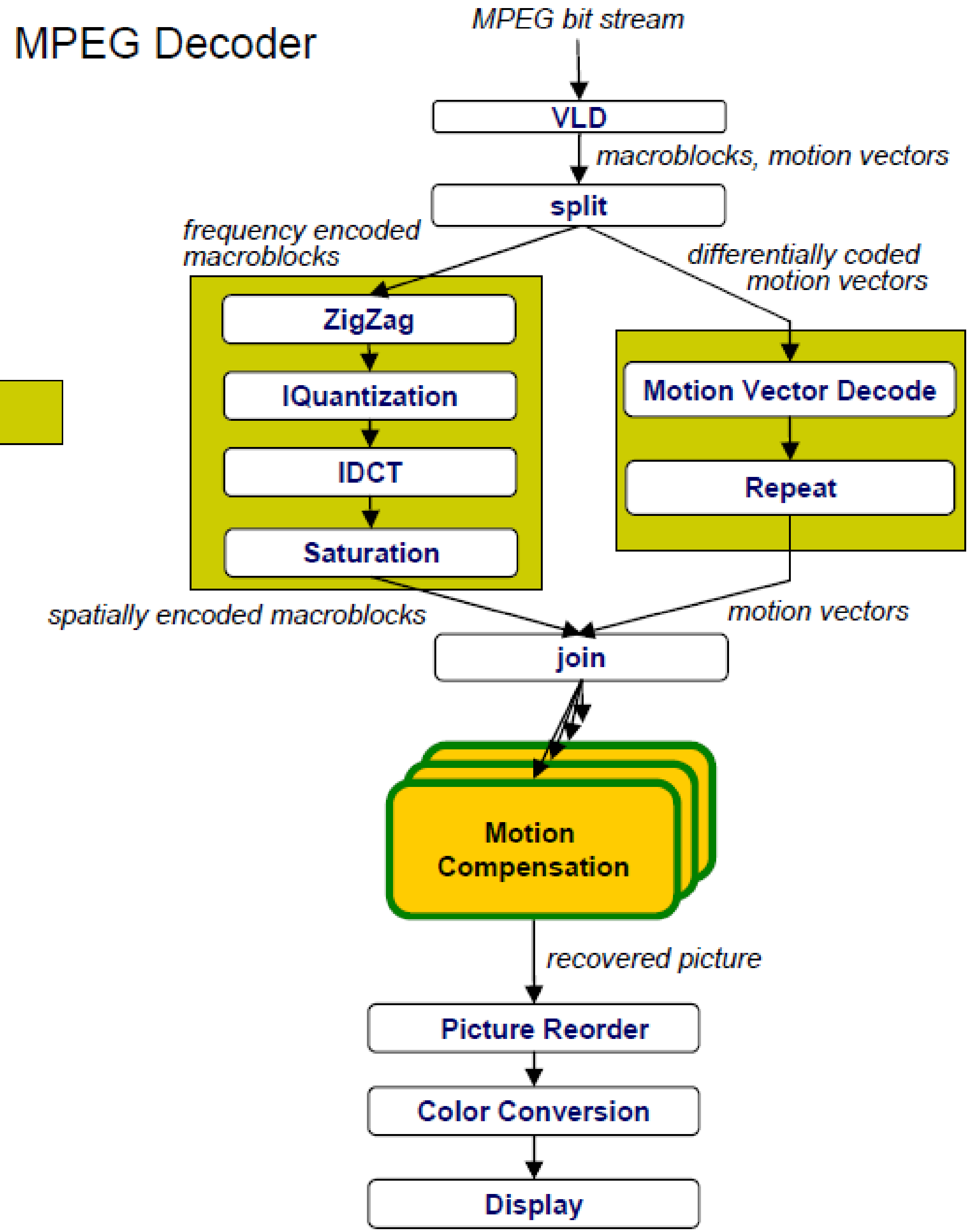
Task decomposition

- Parallelism in the application

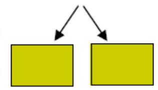


Data decomposition

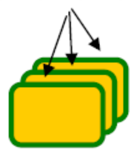
- Same computation is applied to small data chunks derived from a large data set



An Example: Decomposition

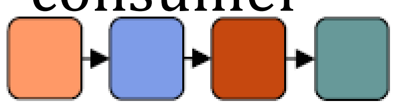
Task decomposition 

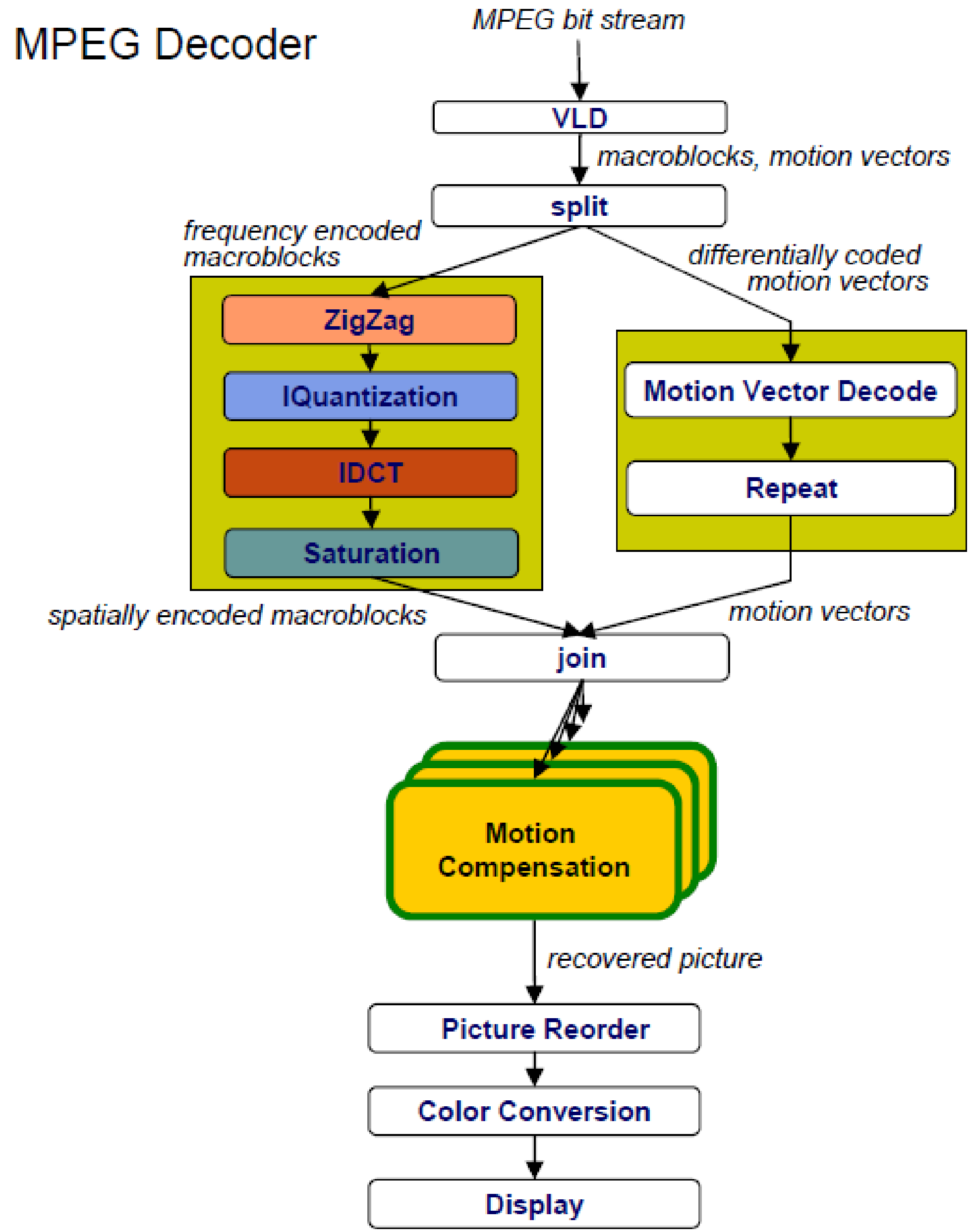
- Parallelism in the application

Data decomposition 

- Same computation many data

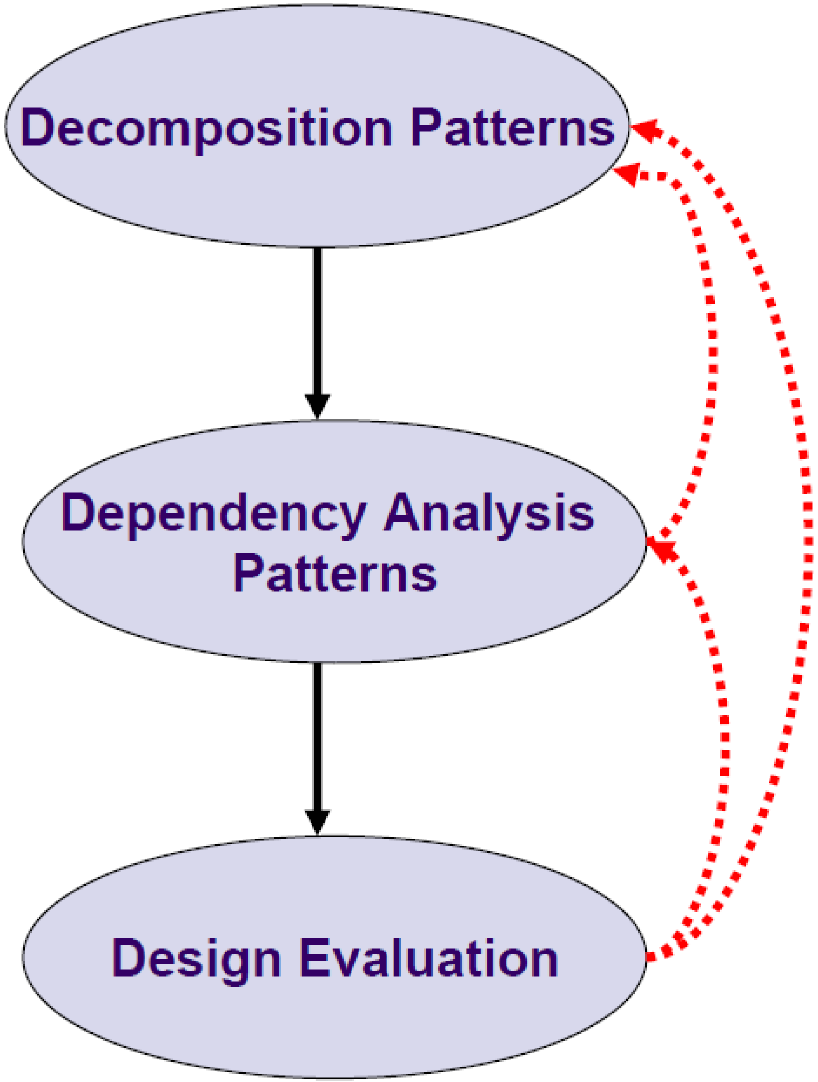
Pipeline decomposition

- Data assembly lines
- Producer-consumer chains 
- Usually observed in case of regular, one-way, mostl stable data flow



Finding Concurrency Design Space

- Programs often naturally decompose into tasks
- Two common decompositions:
  - Function calls
  - Distinct loop iterations
- Dependence Analysis: Given two tasks, how to determine if they can run in parallel?



Data Dependence

- Assuming statements S1 and S2, S2 is data-dependent on S1 if:

  $[I(S1) \cap O(S2)] \cup [O(S1) \cap I(S2)] \cup [O(S1) \cap O(S2)] \neq \emptyset$

Where,

  I(Si) is the set of memory locations read by Si, and

  O(Sj) is the set of memory locations written by Sj

  and there is a feasible runtime execution path from S1 to S2

- Called Bernstein Condition

Types of Data Dependence

- True dependence

O(S1) ∩ I (S2) , S1-> S2 and S1 writes something read by S2

- Anti-dependence

I(S1) ∩ O(S2) , mirror relationship of true dependence

- Output dependence

O(S1) ∩ O(S2), S1->S2 and both write the same memory location

Control Dependence

- There is a control dependence between two statements S1 and S2 if
  - S1 could be possibly executed before S2
  - The outcome of S1 execution will determine whether S2 will be executed

```
A: while(node){
B:   node = node->next;
C:   res = work(node);
D:   write(res);
   }
```

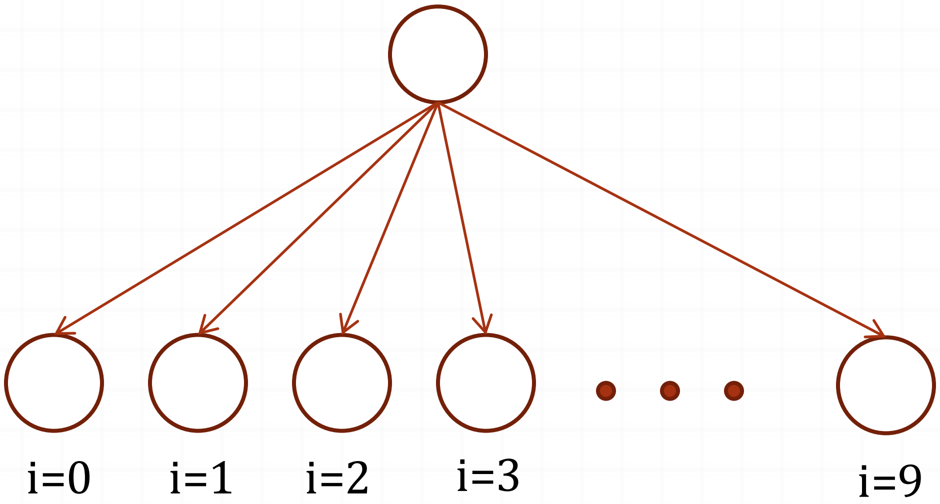
Loop Parallelism Patterns

- Many programs are expressed using iterative constructs
- Loops are a major part of most programs
- Loop parallelism especially useful when code cannot be massively restructured
- Different techniques:
  - DOALL
  - DOACROSS
  - DSWP (Decoupled Software Pipelining)

DOALL

Consider the following loop

```
int arr[10], op[10];
int i = 0;
while(i<10) {
    op[i] = arr[i]*arr[i];   (A)
    i++;
}
```

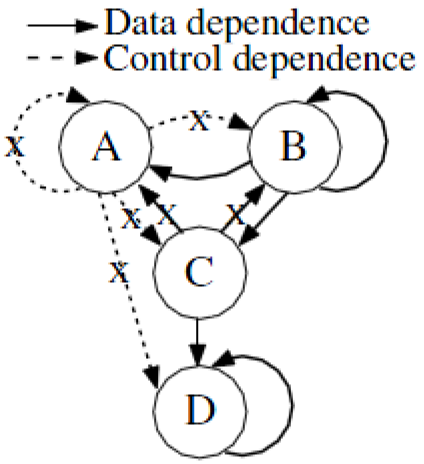


With Inter-Iteration Dependences?

Consider the following loop

```
A: while(node){
B:   node = node->next;
C:   res = work(node);
D:   write(res);
   }
```

Here, work may modify list



Program
Dependence Graph
for the loop

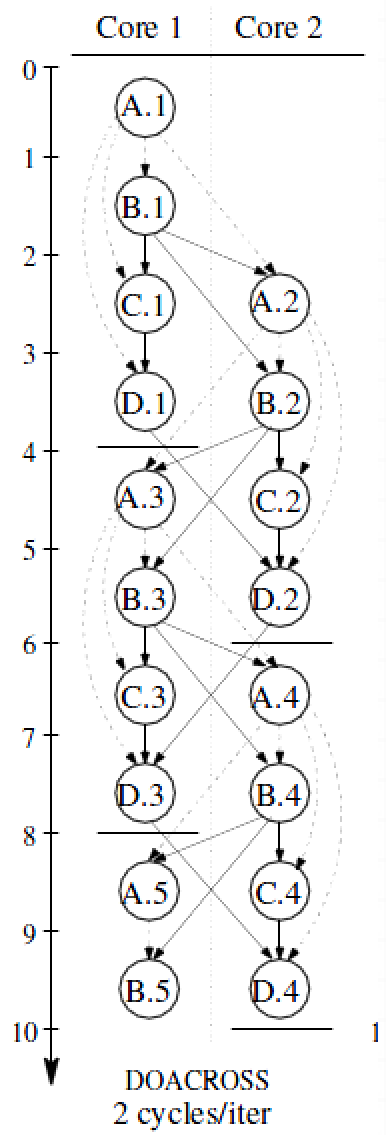
DOACROSS

Consider the following loop

```
A: while(node){
B:   node = node->next;
C:   res = work(node);
D:   write(res);
   }
```

Here, work may modify list

Communication latency =
1 cycle/iteration



Decoupled Software Pipelining (DSWP)

Consider the following loop

```
A: while(node){
B:   node = node->next;
C:   res = work(node);
D:   write(res);
   }
```

Here, work may modify list

Communication latency =
1 cycle/iteration