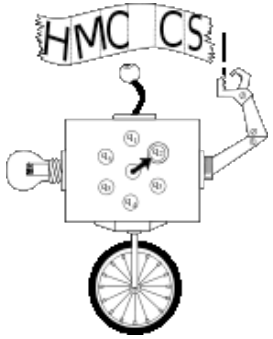

CS 181E: Fundamentals of Parallel Programming

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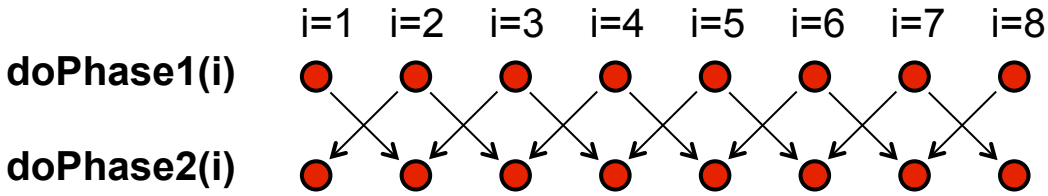
http://www.cs.hmc.edu/courses/2012/fall/cs181e/

Recap of Lecture 6

- Three observations related to Forall Barriers
- Point-to-point Synchronization and Phasers
- Phasers and Forall Loops, Single statement, Phaser Accumulators
- Signal statement and split-phase barriers

Worksheet #7 solution: Left-Right Neighbor Synchronization using Phasers



Complete the phased clause below to implement the left-right neighbor synchronization shown above

```
1. finish {
2.   phaser[] ph = new phaser[m+2];
3.   for(point [i]:[0:m+1]) ph[i] = new phaser();
4.   for(point [i] : [1:m])
5.    async phased(ph[i-1]<WAIT>,ph[i]<SIG>,ph[i+1]<WAIT>) {
6.      doPhase1(i);
7.      next;
8.      doPhase2(i);
9.    }
10.}
```

Summary of Module 1: Deterministic Shared-Memory Parallelism

- Serializable subset of HJ
  - {async, finish, future, forasync}
  - Erasure property: any HJ program written using the above constructs can be converted to an equivalent sequential program by erasing all parallel constructs
- Deadlock-free subset of HJ
  - {next, barriers, phasers, forall, async phased} + serializable subset
  - Deadlock-freedom property: any HJ program written using the above constructs is guaranteed to never deadlock
- Deterministic subset of HJ
  - {data driven futures, async await} + deadlock-free subset
  - Data-race-free structural determinism property: if any HJ program written using the above constructs is guaranteed to be data-race-free for a given input, then it must also be deterministic for that input i.e., all executions with the same input must generate the same output AND the same computation graph

Outline of Today's Lecture

- Critical Sections and the Isolated Statement
- Atomic Variables

Formal Definition of Data Races (Recap)

Formally, a data race occurs on location L in a program execution with computation graph *CG* if there exist steps (nodes) S1 and S2 in *CG* such that:

1. S1 does not depend on S2 and S2 does not depend on S1 i.e., there is no path of dependence edges from S1 to S2 or from S2 to S1 in *CG*, and
2. Both S1 and S2 read or write L, and at least one of the accesses is a write.

However, there are many cases in practice when two tasks may legitimately need to perform conflicting accesses to shared locations without incurring data races

- Special cases: finish accumulators, phaser accumulators, atomic variables
- How should conflicting accesses be handled in general?

Example of two tasks performing conflicting accesses

```
1.  class DoublyLinkedListNode {
2.   DoublyLinkedListNode prev, next;
3.   . . .
4.   void delete() {
5.     { // start of desired mutual exclusion region
6.       this.prev.next = this.next;
7.       this.next.prev = this.prev;
8.     } // end of desired mutual exclusion region
9.     . . .
10.  }
11. } // DoublyLinkedListNode
12. . . .
13. static void deleteTwoNodes(DoublyLinkedListNode L) {
14.  finish {
15.    DoublyLinkedListNode second = L.next;
16.    DoublyLinkedListNode third = second.next;
17.    async second.delete();
18.    async third.delete(); // conflicts with previous async
19.  }
20. }
```

How to enforce mutual exclusion?

- The predominant approach to ensure mutual exclusion proposed many years ago is to enclose the code region in a critical section.
  - "In concurrent programming a critical section is a piece of code that accesses a shared resource (data structure or device) that must not be concurrently accessed by more than one thread of execution. A critical section will usually terminate in fixed time, and a thread, task or process will have to wait a fixed time to enter it (aka bounded waiting). Some synchronization mechanism is required at the entry and exit of the critical section to ensure exclusive use, for example a semaphore."
  - Source: http://en.wikipedia.org/wiki/Critical_section

HJ isolated statement

isolated <body>

- Isolated statement identifies a critical section
- Two tasks executing isolated statements must perform them in mutual exclusion
  - ➔Weak isolation guarantee: mutual exclusion applies to (isolated, isolated) pairs of statement instances, but not to (isolated, non-isolated) and (non-isolated, non-isolated) pairs of statement instances
  - — That's why we call this construct "isolated" instead of "atomic"
- Isolated statements may be nested (redundant)
- Isolated statements must not contain any other parallel statement that performs a blocking operation: finish, future get, next, async await
  - —Non-blocking operations (e.g., async) are fine
- Isolated statements can never deadlock

Use of isolated to fix previous example with conflicting accesses

```
1.  class DoublyLinkedListNode {
2.   DoublyLinkedListNode prev, next;
3.   . . .
4.   void delete() {
5.     isolated { // start of mutual exclusion region (critical section)
6.       this.prev.next = this.next;
7.       this.next.prev = this.prev;
8.     } // end of mutual exclusion region (critical section)
9.     . . .
10.  }
11. } // DoublyLinkedListNode
12. . . .
13. static void deleteTwoNodes(DoublyLinkedListNode L) {
14.  finish {
15.    DoublyLinkedListNode second = L.next;
16.    DoublyLinkedListNode third = second.next;
17.    async second.delete();
18.    async third.delete();
19.  }
20. }
```

Parallel Spanning Tree Algorithm using isolated statement

```
1. class V  {
2.   V [] neighbors; // adjacency list for input graph
3.   V parent; // output value of parent in spanning tree
4.   boolean tryLabeling(V n) {
5.     isolated if (parent == null) parent=n;
6.     return parent == n;
7.   } // tryLabeling
8.   void compute() {
9.     for (int i=0; i<neighbors.length; i++) {
10.      V child = neighbors[i];
11.      if (child.tryLabeling(this))
12.          async child.compute(); //escaping async
13.     }
14.  } // compute
15.} // class V
16.. . .
17.root.parent = root; // Use self-cycle to identify root
18.finish root.compute();
19.. . .
```

Example graph (root=1, spanning tree edge shown as arrow from child to parent)

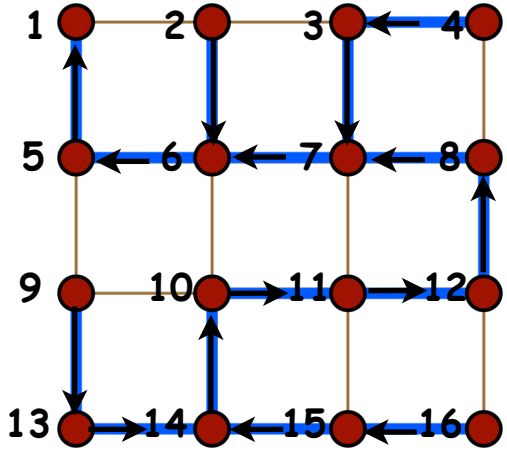


Figure source: http://en.wikipedia.org/wiki/Spanning_tree

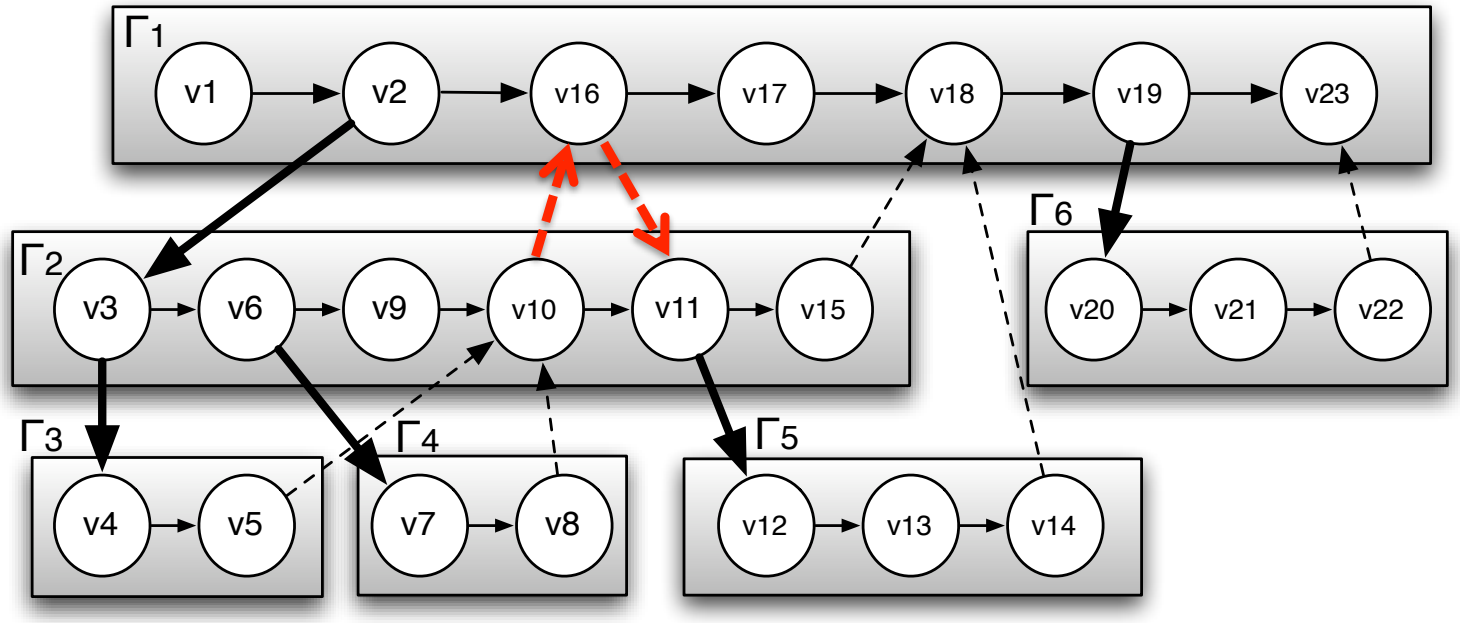
Semantics of Exceptions and Async's within an Isolated Statement

```
1.  isolated {
2.    int t1 = p.x;
3.    p.x++;
4.    // Task execution terminates with NullPointerException
5.    // if q==null (as in non-isolated case)
6.    int t2 = q.x;
7.    q.x--;
8.    // Async creation (but not execution) is part of mutual
9.    // exclusion construct.  Async can logically be executed
10.   // at end of isolated statement.
11.   async { ... t1 ... t2 ... }
12.   . . .
13. } // isolated
```

Serialized Computation Graph for Isolated Statements

- Model each instance of an isolated statement as a distinct step (node) in the CG.
- Need to reason about the order in which interfering isolated statements are executed
  - Complicated because the order may vary from execution to execution
- Introduce Serialized Computation Graph (SCG) that includes a specific ordering of all interfering isolated statements.
  - SCG consists of a CG with additional serialization edges.
  - Each time an isolated step, S', is executed, we add a serialization edge from S to S' for each "interfering" isolated step, S
    - Two isolated statements always interfere with each other
    - Interference of "object-based isolated" statements depends on object sets
  - An SCG represents a set of executions in which all interfering isolated statements execute in the same order.

Example of Serialized Computation Graph with Serialization Edges for v10-v16-v11 order



Continue edge Spawn edge Join edge

Serialization edge

v10: isolated { x ++; y = 10; }
v11: isolated { x++; y = 11; }
v16: isolated { x++; y = 16; }

Data race definition can be applied to Serialized Computation Graphs (SCGs) just like regular CGs

- Need to consider all possible orderings of interfering isolated statements to establish data race freedom

Properties of isolated statements

How small or big should an isolated statement be?

- Too small ➔ may lose invariants desired from mutual exclusion
- Too big ➔ limits parallelism

Deadlock freedom guarantees

- Observation: no combination of the following HJ constructs can create a deadlock cycle among tasks
  - isolated + {async, finish, future, forasync, next, barriers, phasers, forall, async phased}
- There are only two HJ constructs that can lead to deadlock
  - async await (data-driven tasks)
  - explicit phaser wait operation (advanced construct)

Implementations of isolated statement

- isolated statements are convenient for the programmer but pose significant challenges for the language implementation
  - —Implementation does not know ahead of time if two dynamic instances of isolated statements will interfere or not
- HJ implementation used in COMP 322 takes a simple single-lock approach to implementing isolated statements
  - —Entry to isolated statement is treated as an acquire() operation on the lock
  - —Exit from isolated statement is treated as a release() operation on the lock
  - —Though correct, this approach essentially implements isolated statements as critical sections, thereby serializing all interfering and non-interfering isolated statement instances

Three cases of contention among isolated statements

1. Low contention: when isolated statements are executed infrequently
   - A single-lock approach as in HJ is often the best solution. No visible benefit from other techniques because they incur overhead that is not needed since contention is low.
2. Moderate contention (no hot spot): when the serialization of all isolated statements in a single-lock approach limits the performance of the parallel program due to Amdahl's Law, but a finer-grained approach that only serializes interfering isolated statements results in good scalability
   - Atomic variables and object-based isolation usually do well in this scenario since the benefit obtained from reduced serialization outweighs any extra overhead incurred.
3. High contention (one or more hot spots): when interfering isolated statements dominate the program execution time
   - Best approach in such cases is to find an alternative construct/algorithm to isolated e.g., use of finish/phaser accumulators

Object-based isolation in HJ

`isolated(<object-list>) <body>`

- In this case, programmer specifies list of objects for which isolation is required
- Mutual exclusion is only guaranteed for instances of isolated statements that have a non-empty intersection in their object lists
  - —Standard isolated is equivalent to isolated(*) by default i.e., isolation across all objects
- Implementation can choose to distinguish between read/write accesses for further parallelism
  - —Current HJ implementation supports object-based isolation, but does not exploit read/write distinction

DoublyLinkedListNode Example revisited with Object-Based Isolation

```
1.  class DoublyLinkedListNode {
2.   DoublyLinkedListNode prev, next;
3.   . . .
4.   void delete() {
5.     isolated(this.prev, this, this.next) { // object-based isolation
6.       this.prev.next = this.next;
7.       this.next.prev = this.prev;
8.     }
9.     . . .
10.  }
11. } // DoublyLinkedListNode
12. . . .
13. static void deleteTwoNodes(DoublyLinkedListNode L) {
14.  finish {
15.    DoublyLinkedListNode second = L.next;
16.    DoublyLinkedListNode third = second.next;
17.    async second.delete();
18.    async third.delete();
19.  }
20. }
```

Outline of Today's Lecture

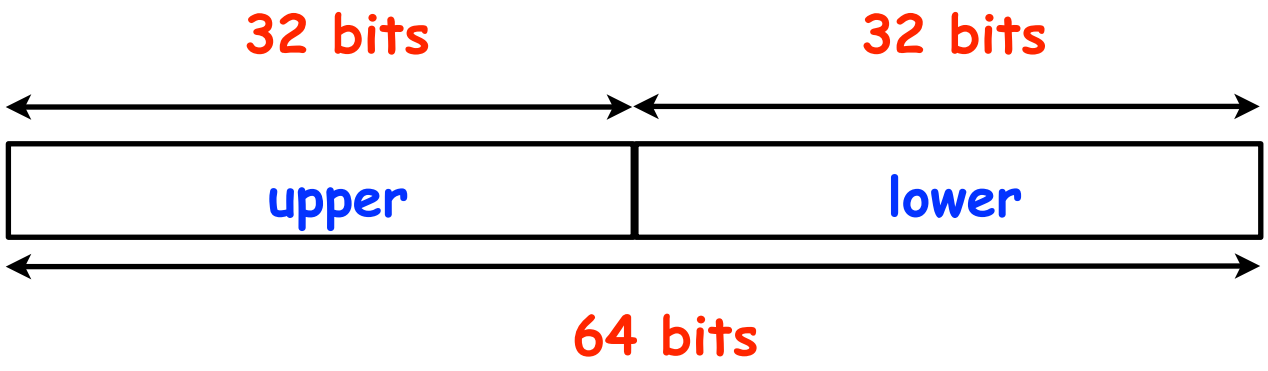
- Critical Sections and the Isolated Statement
- Atomic Variables

Atomicity in standard vs. atomic variables

- Reads and write for reference variables and primitives (except `long` and `double`) are atomic
- Basic safety guarantee: No "out-of-thin-air" values for references and primitives (except for `long` and `double`)
  - A read always returns a value written by some task, some time in the past (except for `long` and `double`)
- Atomic variables support compound atomic operations that go beyond single read/write accesses
  - Operations on atomic variables can be safely invoked by parallel tasks, but (like isolated statements) they may increase the critical path length of your parallel program
    - Not a problem if the remaining parallel (non-atomic) work is large

Why reads and writes on long/double values may be non-atomic

```
1. long x; // upper = lower = 0
2. async { x = 1L << 32 + 1L; } // lower=1; upper=1;
3. async { x = 2L << 32 + 2L; } // lower=2; upper=2;
4. async { System.out.println(x); }
5. // Possible output value includes
6. // 1L << 32 + 2L (lower=2, upper=1)
```



java.util.concurrent library

- Atomic variables
  - Efficient implementations of special-case patterns of isolated statements
- Concurrent Collections:
  - Queues, blocking queues, concurrent hash map, …
  - Data structures designed for concurrent environments
- Executors, Thread pools and Futures
  - Execution frameworks for asynchronous tasking
- Locks and Conditions
  - More flexible synchronization control
  - Read/write locks
- Synchronizers: Semaphore, Latch, Barrier, Exchanger, Phaser
  - Tools for thread coordination
- WARNING: only a small subset of the full java.util.concurrent library can safely be used in HJ programs
  - Atomic variables are part of the safe subset
  - We will study the full library later this semester as part of Java Concurrency

java.util.concurrent.atomic.AtomicInteger

- Constructors
  - `new AtomicInteger()`
    - Creates a new AtomicInteger with initial value 0
  - `new AtomicInteger(int initialValue)`
    - Creates a new AtomicInteger with the given initial value
- Selected methods
  - `int addAndGet(int delta)`
    - Atomically adds delta to the current value of the atomic variable, and returns the new value
  - `int getAndAdd(int delta)`
    - Atomically returns the current value of the atomic variable, and adds delta to the current value
- Similar interfaces available for `LongInteger`

Summing Values from Multiple Async's in same Finish Scope

- How can we perform a sum on values generated by dynamic async statements?
- Example 1: compute sum of elem values from async tasks in a loop

```
finish while (...)
  async { ...; elem = ...; ...; }
```

- Example 2: compute sum of elem values from async tasks in a recursive method

```
void visit(...)
{ ...; elem = ...; async visit(...); ...; }
... finish visit(...); ...
```

- One approach is to use finish-accumulators (deterministic); another is to use atomic variables (non-deterministic by default)

Solution for Examples 1 and 2 using AtomicInteger

```
1.  import java.util.concurrent.atomic.AtomicInteger;
2.  // Example 1: compute sum from async tasks in a loop
3.  AtomicInteger a1 = new AtomicInteger();
4.    finish while(...)
5.     async { ...; elem = ...; a1.addAndGet(elem); ...; }
6.  // Example 2: compute sum in a recursive method
7.  AtomicInteger a2 = new AtomicInteger();
8.  void visit(...)
9.  { ...; elem = ...; a2.addAndGet(elem);
10.    async visit(...); ...;
11. }
12. ... finish visit(...); ...
```

Work-Sharing Pattern using AtomicInteger

```
1.  import java.util.concurrent.atomic.AtomicInteger;
2.  . . .
3.  String[] X = ... ; int numTasks = ...;
4.  AtomicInteger a = new AtomicInteger();
5.  . . .
6.  finish for (int i=0; i<numTasks; i++ )
7.    async {
8.      do {
9.         int j = a.getAndAdd(1);
10.        // can also use a.getAndIncrement()
11.        if (j >= X.length) break;
12.        . . . // Process X[j]
13.     } while (true);
14.   } // finish-for-async
```

java.util.concurrent.AtomicInteger methods and their equivalent isolated statements

`j.u.c.atomic` Class and Constructors	`j.u.c.atomic` Methods	Equivalent HJ `isolated` statements
AtomicInteger	int j = v.**get**();	int j; `isolated` (v) j = v.val;
	v.**set**(newVal);	`isolated` (v) v.val = newVal;
AtomicInteger()	int j = v.**getAndSet**(newVal);	int j; `isolated` (v) { j = v.val; v.val = newVal; }
// init = 0	int j = v.**addAndGet**(delta);	`isolated` (v) { v.val += delta; j = v.val; }
	int j = v.**getAndAdd**(delta);	`isolated` (v) { j = v.val; v.val += delta; }
AtomicInteger(init)	boolean b = v.**compareAndSet**(expect,update);	boolean b; `isolated` (v) if (v.val==expect) {v.val=update; b=true;} else b = false;

Methods in java.util.concurrent.AtomicInteger class and their equivalent HJ isolated statements. Variable v refers to an AtomicInteger object in column 2 and to a standard non-atomic Java object in column 3. val refers to a field of type int.

java.util.concurrent. AtomicReference methods and their equivalent isolated statements

j.u.c.atomic Class and Constructors	j.u.c.atomic Methods	Equivalent HJ isolated statements
AtomicReference	Object o = v.**get**();	Object o; isolated (v) o = v.ref;
	v.**set**(newRef);	isolated (v) v.ref = newRef;
AtomicReference() // init = null	Object o = v.**getAndSet**(newRef);	Object o; isolated (v) { o = v.ref; v.ref = newRef; }

AtomicReference(init)	boolean b =
	v.**compareAndSet**
	(expect,update);
		boolean b;
		isolated (v)
		if (v.ref==expect) {v.ref=update; b=true;}
		else b = false;

Methods in java.util.concurrent.AtomicReference class and their equivalent HJ isolated statements. Variable v refers to an AtomicReference object in column 2 and to a standard non-atomic Java object in column 3. ref refers to a field of type Object.

AtomicReference<T> can be used to specify a type parameter.

Parallel Spanning Tree Algorithm using AtomicReference

```
1. class V  {
2.   V [] neighbors; // adjacency list for input graph
3.   AtomicReference parent; // output value of parent in spanning tree
4.   boolean tryLabeling(V n) {
5.     return parent.compareAndSet(null, n);
6.   } // tryLabeling
7.   void compute() {
8.     for (int i=0; i<neighbors.length; i++) {
9.       V child = neighbors[i];
10.      if (child.tryLabeling(this))
11.          async child.compute(); //escaping async
12.     }
13.  } // compute
14.} // class V
15.. . .
16.root.parent = root; // Use self-cycle to identify root
17.finish root.compute();
18.. . .
```

Worksheet #8 (to be done in pairs): Insertion of isolated for correctness

Name 1: _____ Name 2: _____

The goal of IsolatedPRNG is to implement a single Pseudo Random Number Generator object that can be shared by multiple tasks. Show the isolated statement(s) that you can insert in method nextSeed() to avoid data races and guarantee proper semantics.

```
class IsolatedPRNG {
  private int seed;
  public int nextSeed() {
    int retVal;

    retVal = seed;

    seed = nextInt(retVal);

    return retVal;
  } // nextSeed()
  . . .
} // IsolatedPRNG
```

```
main() { // Pseudocode
  // Initial seed = 1
  IsolatedPRNG r = new IsolatedPRNG(1);
  async { print r.nextSeed(); ... }
  async { print r.nextSeed(); ... }
} // main()
```