CSx55: Distributed Systems [Thread Safety]

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Frequently asked questions from the previous class survey

- ☐ Are `collections.unmodifiableList` and its variants thread safe?

Topics covered in this lecture

- ☐ Concurrent collections
- ☐ Synchronizers
- ☐ Thread safety summary
- ☐ Distributed Servers
    - Performance
    - Amdahl's Law

CONCURRENT COLLECTIONS

Locking strategies:
`Hashtable` & `ConcurrentHashMap`

- `Hashtable`
  - Lock held for the *duration of each operation*
  - Restricting access to a *single thread at a time*
- `ConcurrentHashMap`
  - *Finer-grained locking* mechanism
  - **Lock striping**

Lock striping: How it works

- `ConcurrentHashMap` uses an **array of 16 locks**
  - Each lock guards 1/16th of the hash buckets
  - Bucket N guarded by lock N mod 16
- Assuming hash functions provide reasonable spreading characteristics
  - Demand for a given lock should reduce by 1/16
- Enables `ConcurrentHashMap` to support up to 16 (default) concurrent writers
  - A constructor that allows you to specify the concurrency level

Downsides of lock striping

- Locking the collection for exclusive access
  - More difficult and costly than a single lock
  - Done by acquiring locks in the **stripe set**
- When does `ConcurrentHashMap` need to do this?
  - If the map needs to be expanded, values need to be rehashed into a larger set of buckets

Concurrent collections and iterators

- Iterators are *weakly consistent* instead of fail-safe
  - Do not throw `ConcurrentModificationException`
- **Weakly consistent iterator**
  - Tolerates concurrent modification
  - Traverses elements as they existed when the iterator was created
  - May (no guarantees) reflect modifications after construction

But what are the trade-offs?

- **Semantics** of methods that operate on the entire `Map` have been *weakened* to reflect nature of collection
  - `size()` is allowed to return an approximation
  - `size()` and `isEmpty()`: These are far less useful in concurrent environments
- This allows *performance improvements* for the most important operations
  - `get`, `put`, `containsKey`, and `remove`

One feature offered by synchronized Map implementations?

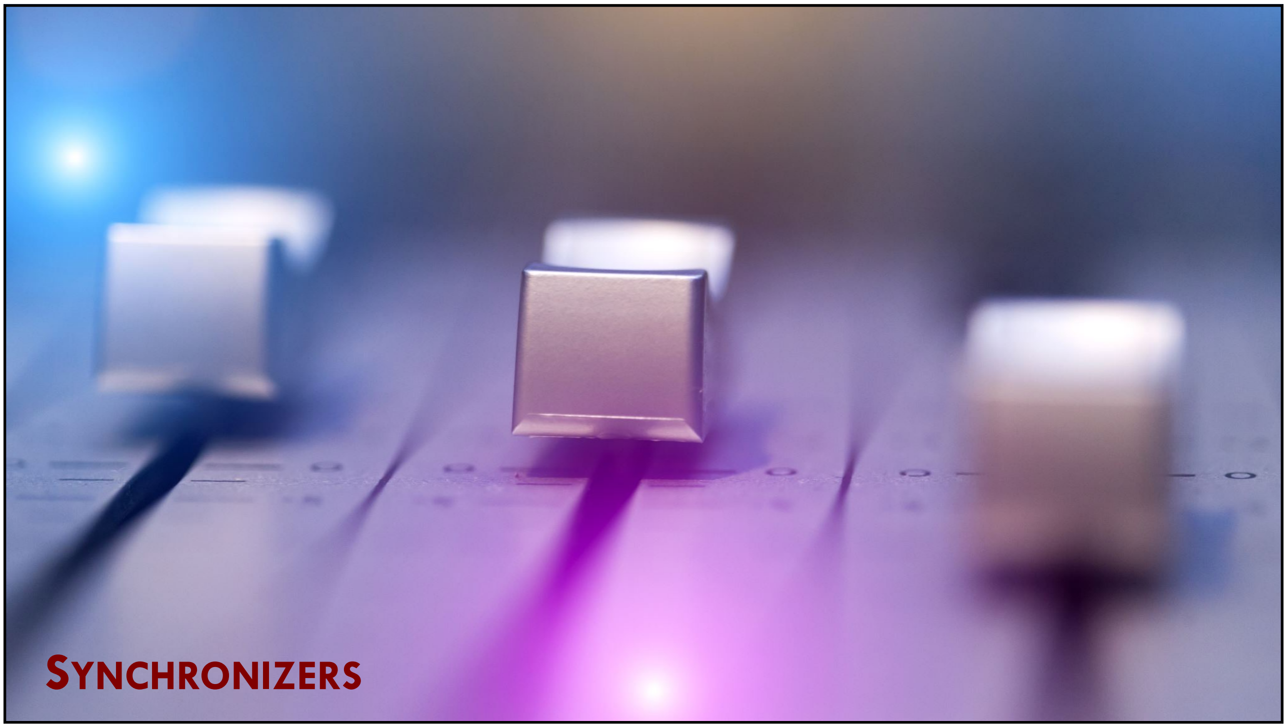
- Lock the map for exclusive access
  - With `Hashtable` and `synchronizedMap`, acquiring the Map lock prevents other threads from accessing it
- In most cases replacing `Hashtable` and `synchronizedMap` with `ConcurrentHashMap`?
  - Gives you getter scalability
- If you need to lock `Map` for exclusive access?
  - Don't use the `ConcurrentHashMap`!

Support for additional atomic `Map` operations

- Put-if-absent
- Remove-if-equal
- Replace-if-equal

`ConcurrentMap` interface

```
public interface ConcurrentMap<K,V> extends Map<K,V> {

   //Insert if no value is mapped from K
   V putIfAbsent(K key, V value);

   //Remove only if K is mapped to V
   boolean remove(K key, V value);

   //Replace value only if K is mapped to oldValue
   boolean replace(K key, V oldValue, V newValue);

   //Replace value only if K is mapped to some value
   V replace(K key, V newValue)

}
```



SYNCHRONIZERS

Synchronizers

- Are objects that **coordinate control flow** of threads based on its state
- Examples
  - Latches
  - Semaphores
    - Counting and binary
  - Barriers
    - Cyclic and Exchangers

Synchronizer: Structural properties

- **Encapsulate state** that determines whether threads arriving at the synchronizer should:
  - Be allowed to *pass* or wait
- Provide methods to **manipulate** state
- Provide methods to *wait* for the synchronizer *to enter desired state*

Latches

- Latch acts as a **gate**
  - Until latch reaches terminal state; *gate is closed* and no threads can pass
  - In the **terminal state**: gate *opens* and allows all threads to pass
- Once the latch reaches terminal state?
  - *Cannot change state* again
  - Remains *open forever*

When to use latches

- Ensure that a computation does not proceed until all resources that it needs are initialized
- Service does not start until other services *that it depends on* have started
- Waiting until all parties in an activity are ready to proceed
  - Multiplayer gaming

CountDownLatch

- Allows one or more threads to **wait for a set of events to occur**
- Latch state has a counter initialized to positive number
  - This is the number of events to wait for
- `countDown()` decrements the counter indicating that an event has occurred
  - `await()` method waits for the counter to reach **0**

Using CountDownLatch

```
public class TestHarness {
   public long timeTasks(int nThreads, final Runnable task)
     throws InterruptedException {
     final CountDownLatch startGate = new CountDownLatch(1);
     final CountDownLatch endGate=new CountDownLatch(nThreads);

     for (int i=0; i < nThreads; i++) {
       Thread t = new Thread() {
         public void run() {
           try {
            startGate.await();
            task.run();
           } finally {
              endGate.countDown();
           }
         }
       };
      t.start();
     }
   long start = System.nanoTime();
   startGate.countDown();
   endGate.await();
   long end = System.nanoTime();
   return end-start;
}
```

Semaphores

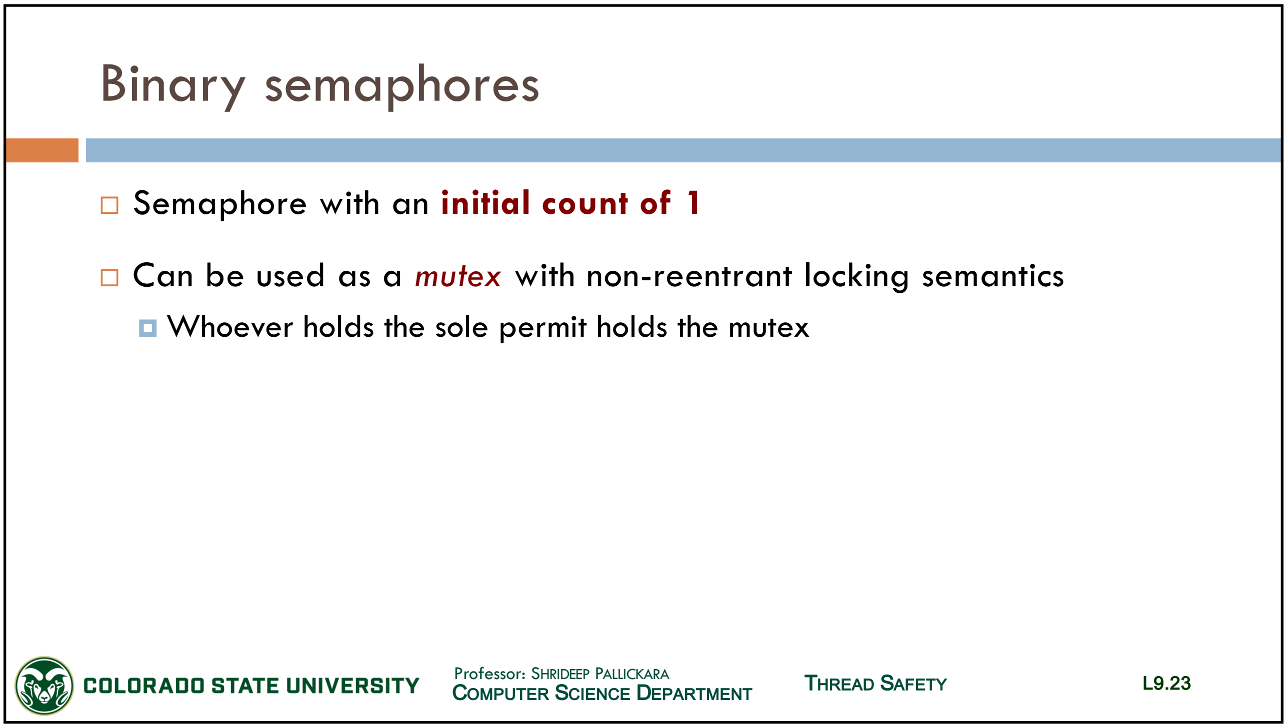
- Counting semaphores control the **number of activities** that can:
  - Access a certain resource
  - Perform a given action
- Used to implement resource pools or impose bounds on a collection

Semaphores

- Manage a set of virtual **permits**
  - Initial number passed to the constructor
- Activities *acquire* and *release* permits
- If **no permits** are available?
  - `acquire` *blocks* until one is available
- The `release` method returns a permit to the semaphore

Semaphores are useful for implementing resource pools

- Block if the pool is empty
  - Unblock if the pool is non-empty
- Initialize a semaphore to the **pool size**
- `acquire` a permit before trying to fetch a resource from pool
- `release` the permit after putting the resource back in pool
- `acquire` **blocks** until the pool is non-empty



Binary semaphores

- Semaphore with an **initial count of 1**
- Can be used as a *mutex* with non-reentrant locking semantics
  - Whoever holds the sole permit holds the mutex

Using Semaphores to bound a collection

```
public BoundedHashSet<T> {
   private final Set<T> set;
   private final Semaphore sem;
   public BoundedHashSet(int bound) {
     this.set = Collections.synchronizedSet(new HashSet<T>());
     sem = new Semaphore(bound);
   }
   public boolean add(T o) throws InterruptedException {
     sem.acquire();
     boolean wasAdded = false;
     try {
       wasAdded = set.add(o);
       return wasAdded;
     } finally {
         if (!wasAdded) sem.release();
     }
   }
   public boolean remove(Object o) {
     boolean wasRemoved = set.remove(o);
     if (wasRemoved) sem.release();
     return wasRemoved;
  }
}
```

Barriers

- Barriers are similar to latches in that they **block a group of threads** till an event has occurred
- All threads must come together at **barrier point** *at the same time* to proceed
  - Latches wait for *events*, barriers ***wait for other threads***

Barriers and dinner …

- Family rendezvous protocol
- Everyone meet at Panera @ 6:00 pm;
  - Once you get there, stay there … till everyone shows up
  - Then we'll figure out what we do next

Barriers

- Often used in simulations where work to calculate one step can be done in parallel
  - But all work associated with a given step must complete before advancing to the next step
- All threads complete step k, before moving on to step $k+1$

`CyclicBarrier`

- Allows a fixed number of parties to *rendezvous* at a fixed point
- Useful in **parallel iterative algorithms**
  - Break problem into fixed number of independent subproblems
- Creation of a `CyclicBarrier`

```
Runnable  cyclicBarrierAction = ... ;
CyclicBarrier cyclicBarrier =
                  new CyclicBarrier(2,  cyclicbarrierAction);
```

Using Cylic Barriers

```
class Solver {
   final int N;     final CyclicBarrier barrier;
   class Worker implements Runnable {
     int myRow;
     Worker(int row) { myRow = row; }
     public void run() {
       while (!done()) {
         processRow(myRow);
         try {
           barrier.await();
          } catch (BrokenBarrierException ex) {
           ...
         }
       }
     }
   }
   public Solver(float[][] matrix) {
     data = matrix;     N = matrix.length;
     barrier = new CyclicBarrier(N, new Runnable() { public void run() {
                                                   mergeRows(...);  } });
     for (int i = 0; i < N; ++i)
       new Thread(new Worker(i)).start(); //DO NOT START THREAD in constructor.
     waitUntilDone();
   }
```

Source: From the Java API

Exchanger

- Another type of barrier
- Two-party barrier
- Parties **exchange data** at the barrier point
- Useful when asymmetric activities are performed
  - Producer-consumer problem
- When 2 threads exchange objects via Exchanger
  - Safe publication of objects to other party

THREAD SAFETY SUMMARY

Thread Safety: Summary [1/4]

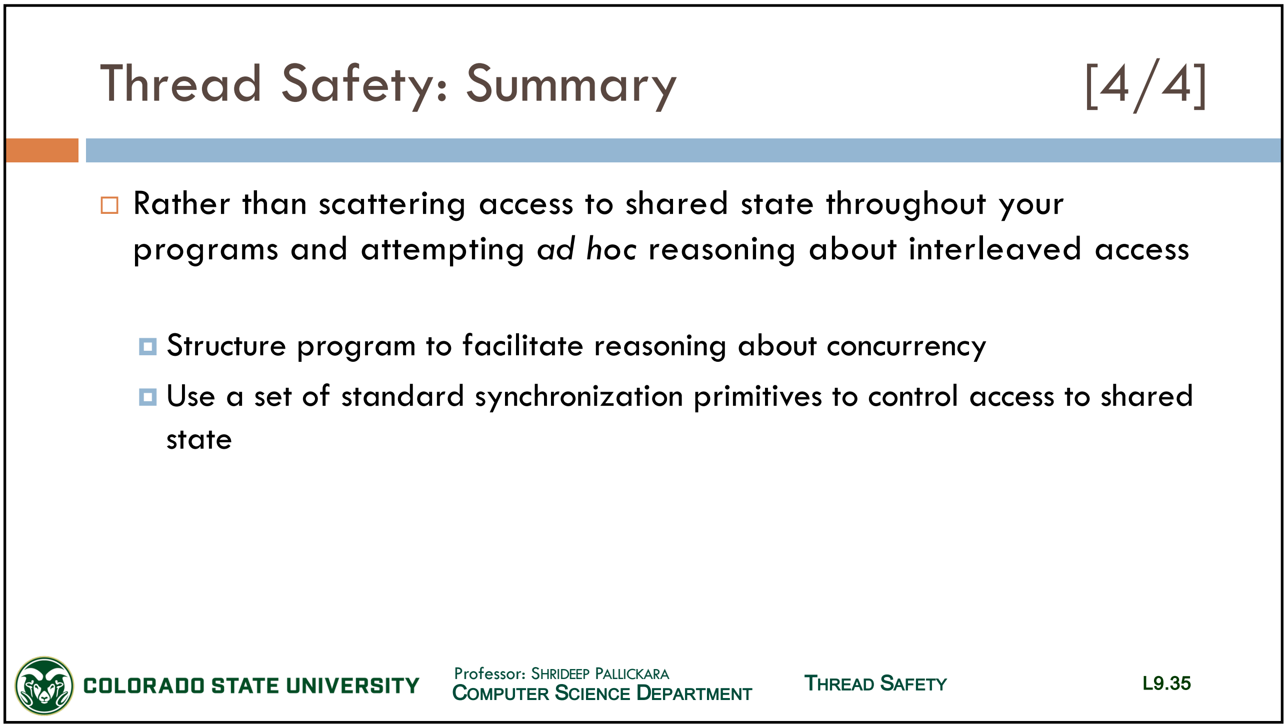
- It's all about *mutable*, *shared* **state**
  - The less mutable state there is, the easier it is to ensure thread-safety
- Make fields **`final`** unless they need to be mutable
- **Immutable** objects are automatically thread-safe
- **Encapsulation** makes it practical to manage complexity

Thread Safety: Summary [2/4]

- Guard each mutable variable with a **lock**
- Guard all variables in an invariant with the ***same lock***
- Hold locks for the *duration* of compound actions

Thread Safety: Summary [3/4]

- Program that accesses mutable variables from multiple threads without synchronization?
  - Broken program
- Include thread-safety in the design process
  - Document if your class is not thread-safe
- Document your synchronization policy



Thread Safety: Summary [4/4]

- Rather than scattering access to shared state throughout your programs and attempting *ad hoc* reasoning about interleaved access
  - Structure program to facilitate reasoning about concurrency
  - Use a set of standard synchronization primitives to control access to shared state

PERFORMANCE

Measures of performance

- Service time
- Latency

How fast?

- Throughput
- Capacity

How much?

- Efficiency
- Scalability

Performance and Scalability

- Tuning for performance
  - Do **same** work with **less** effort
  - Caching, choice of algorithms $O(n^2)$ to $O(nlogn)$

How fast?

- Scalability
  - Find ways to parallelize problem
  - Do **more** work with **more** resources

How much?

HOW FAST and HOW MUCH

- Are separate and can (at times) be at **odds** with each other
- To scale or for better hardware utilization
  - We often end up **increasing** the amount of work for each task
  - Divide tasks into multiple **pipelined** tasks
    - Orchestration overhead

The quest for performance

- What do you mean by **faster**?
- Under what **conditions**?
  - Small or large datasets
  - Perform measurements to substantiate arguments
- **How often** do these conditions arise?
- What are the **hidden costs**?
  - Development/maintenance risks
  - Tradeoffs
  - Ripple effects of decision

Avoid premature optimizations

- ☐ First make it **right, then fast**
- ☐ **Measure**, don't guess
- ☐ Quest for performance is one of the biggest source of **bugs**

AMDAHL'S LAW

How much can we speed things up?

- Harvesting crops
  - The more the number of workers
  - The faster the crop can be harvested
- But some things are fundamentally serial
  - Adding additional workers does not make the crop grow faster

The right tool for the right job: Everything is not a nail

- Make sure that problem is **amenable** to parallel decomposition
- Most programs have a **mix** of parallelizable and serial portions

Amdahl's law describes how much a program can be theoretically sped up

- F : Fraction of components that must be executed serially
- N : Number of available processors

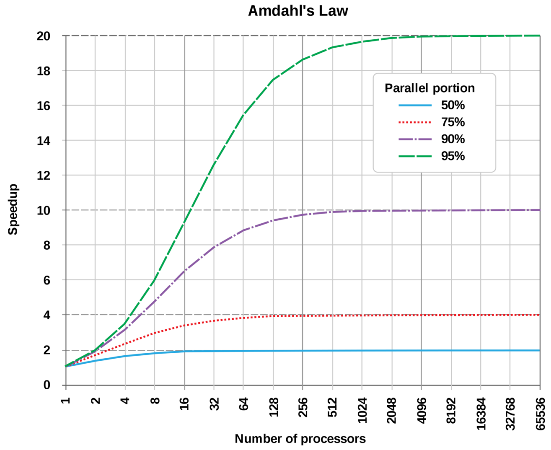
$$Speedup \leq \frac{1}{F + \frac{(1-F)}{N}}$$

$$Utilization = \frac{Speedup}{N}$$

As N approaches infinity; maximum speedup converges to 1/F

- With 50% serial code
  - Maximum speedup is 2
- With 10% serial code
  - Maximum speedup is 10
  - With N= 10
    - Speedup = 5.3 at 53% utilization
  - With N= 100
    - Speedup = 9.2 at 9% utilization

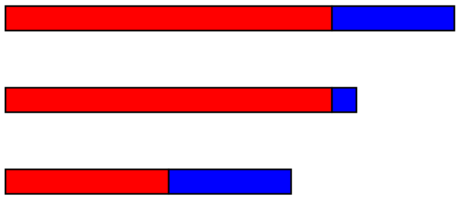
Speedups for different parallelization portions



Source: http://en.wikipedia.org/wiki/Amdahl's_law

Know what to speed up

Two independent parts **A** **B**



Original process

Make **B** 5x faster

Make **A** 2x faster

Image from: http://en.wikipedia.org/wiki/Amdahl's_law

The contents of this slide-set are based on the following references

- *Java Concurrency in Practice. Brian Goetz, Tim Peierls, Joshua Bloch, Joseph Bowbeer, David Holmes, and Doug Lea. Addison-Wesley Professional. ISBN: 0321349601/978-0321349606.   [Chapters 1, 2, 3 and 4]*
- https://www.javaspecialists.eu/archive/Issue192b.html