Lecture 27: Safety and Liveness Properties, Java Synchronizers, Dining Philosophers Problem

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Rewrite the transferFunds() method below to use j.u.c. locks with calls to tryLock (see slide 8) instead of synchronized. Your goal is to write a correct implementation that never deadlocks, unlike the buggy version below (which can deadlock). Assume that each Account object already contains a reference to a ReentrantLock object dedicated to that object e.g., from.lock() returns the lock for the from object. Sketch your answer below using pseudocode.

1. public void transferFunds(Account from, Account to, int amount) {
2.     while (true) {
3.         // assume that trylock() does not throw an exception
4.         boolean fromFlag = from.lock().tryLock();
5.         if (!fromFlag) continue;
6.         boolean toFlag = to.lock().tryLock();
7.         if (!toFlag) { from.lock().unlock(); continue; }
8.         try {
9.             from.subtractFromBalance(amount);
10.            to.addToBalance(amount); break;
11.         } finally {
12.             from.lock().unlock(); to.lock().unlock();
13.         } // while
14.     } // while
15. }
**Worksheet #26b solution:**
Linearizability of method calls on a concurrent object

**Is this a linearizable execution for a FIFO queue, q?**

<table>
<thead>
<tr>
<th>Time</th>
<th>Task A</th>
<th>Task B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Invoke q.enq(x)</td>
<td>Invoke q.enq(y)</td>
</tr>
<tr>
<td>1</td>
<td>Return from q.enq(x)</td>
<td>Work on q.enq(y)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Return from q.enq(y)</td>
</tr>
<tr>
<td>3</td>
<td>Invoke q.deq()</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Work on q.deq()</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Return y from q.deq()</td>
<td></td>
</tr>
</tbody>
</table>

No! q.enq(x) must precede q.enq(y) in all linear sequences of method calls invoked on q. It is illegal for the q.deq() operation to return y.
Outline

- Safety and Liveness
- Java Synchronizers: Semaphores
- Dining Philosophers Problem
Safety vs. Liveness

- In a concurrent setting, we need to specify both the safety and the liveness properties of an object.
- Need a way to define:
  - Safety: when an implementation is functionally correct (does not produce a wrong answer).
  - Liveness: the conditions under which it guarantees progress (completes execution successfully).

Examples of safety:
- Data race freedom is a desirable safety property for parallel programs (Module 1).
- Linearizability is a desirable safety property for concurrent objects (Module 2).
Liveness

• Liveness = a program’s ability to make progress in a timely manner

• Termination (“no infinite loop”) is not necessarily a requirement for liveness
  • some applications are designed to be non-terminating

• Different levels of liveness guarantees (from weaker to stronger) for tasks/threads in a concurrent program
  1. Deadlock freedom
  2. Livelock freedom
  3. Starvation freedom
  4. Bounded wait
1. Deadlock-Free Parallel Program Executions

- A parallel program execution is *deadlock-free* if no task’s execution remains incomplete due to it being blocked awaiting some condition.

- Example of a program with a deadlocking execution

  ```java
  // Thread T1
  public void leftHand() {
    synchronized(obj1) {
      synchronized(obj2) {
        // work with obj1 & obj2
        ...
      }
    }
  }
  
  // Thread T2
  public void leftHand() {
    synchronized(obj2) {
      synchronized(obj1) {
        // work with obj2 & obj1
        ...
      }
    }
  }
  ```

- In this case, Task1 and Task2 are in a deadlock cycle.
  - Three constructs that can lead to deadlock in HJlib: async await, finish w/ actors, explicit phaser wait (instead of next)
  - There are many constructs that can lead to deadlock cycles in other programming models (e.g., thread join, synchronized, locks in Java)
2. Livelock-Free Parallel Program Executions

- A parallel program execution exhibits *livelock* if two or more tasks repeat the same interactions without making any progress (special case of nontermination).

- Livelock example:

```java
// Task T1
incrToTwo(AtomicInteger ai) {
    // increment ai till it reaches 2
    while (ai.incrementAndGet() < 2);
}

// Task T2
decrToNegTwo(AtomicInteger ai) {
    // decrement ai till it reaches -2
    while (a.decrementAndGet() > -2);
}
```

- Many well-intended approaches to avoid deadlock result in livelock instead.

- Any HJlib program that uses only Module 1 features, and is data-race-free, is guaranteed to be livelock-free (may be nonterminating in a single task, however).
3. Starvation-Free Parallel Program Executions

- A parallel program execution exhibits *starvation* if some task is repeatedly denied the opportunity to make progress
  - Starvation-freedom is sometimes referred to as “lock-out freedom”
  - Starvation is possible in HJ programs, since all tasks in the same program are assumed to be cooperating, rather than competing
    - If starvation occurs in a deadlock-free HJ program, the “equivalent” sequential program must be non-terminating (infinite loop)

- Classic source of starvation for OS threads: “Priority Inversion”
  - Thread A is at high priority, waiting for result or resource from Thread C at low priority
  - Thread B at intermediate priority is CPU-bound
  - Thread C never runs (because its priority is lower than B’s priority), hence thread A never runs
  - Fix: when a high priority thread waits for a low priority thread, boost the priority of the low-priority thread
4. Bounded Wait

- A parallel program execution exhibits bounded wait if each task requesting a resource should only have to wait for a bounded number of other tasks to “cut in line” i.e., to gain access to the resource after its request has been registered.

- If bound = 0, then the program execution is fair
Outline

• Safety and Liveness

• **Java Synchronizers: Semaphores**

• Dining Philosophers Problem
Key Functional Groups in java.util.concurrent (j.u.c.)

- Atomic variables
  - The key to writing lock-free algorithms
- Concurrent Collections:
  - Queues, blocking queues, concurrent hash map, ...
  - Data structures designed for concurrent environments
- Locks and Conditions
  - More flexible synchronization control
  - Read/write locks
- Executors, Thread pools and Futures
  - Execution frameworks for asynchronous tasking
- Synchronizers: Semaphore, Latch, Barrier, Exchanger
  - Ready made tools for thread coordination
Semaphores

• Conceptually serve as “permit” holders
  — Construct with an initial number of permits
  — acquire(): waits for permit to be available, then “takes” one, i.e., decrements the count of available permits
  — release(): “returns” a permit, i.e., increments the count of available permits
  — But no actual permits change hands
    — The semaphore just maintains the current count
    — Thread performing release() can be different from the thread performing acquire()

• “fair” variant hands out permits in FIFO order

• Useful for managing bounded access to a shared resource
Bounded Blocking Concurrent List using Semaphores

1. public class BoundedBlockingList {
2.   final int capacity;
3.   final ConcurrentLinkedList list = new ConcurrentLinkedList();
4.   final Semaphore sem;
5.   public BoundedBlockingList(int capacity) {
6.     this.capacity = capacity;
7.     sem = new Semaphore(capacity);
8.   }
9.   public void addFirst(Object x) throws InterruptedException {
10.      sem.acquire(); // blocks until a permit is available
11.      try { list.addFirst(x); }
12.      catch (Throwable t){ sem.release(); rethrow(t); } // only performed on exception
13.   }
14.   public boolean remove(Object x) {
15.      if (list.remove(x)) { sem.release(); return true; }
16.      return false;
17.   }
18.   ... } // BoundedBlockingList
Outline

• Safety and Liveness

• Java Synchronizers: Semaphores

• Dining Philosophers Problem
  — Acknowledgments
    – CMSC 330 course notes, U. Maryland
    – Dave Johnson (COMP 421 instructor)
The Dining Philosophers Problem

Constraints
- Five philosophers either eat or think
- They must have two forks to eat (chopsticks are a better motivation!)
- Can only use forks on either side of their plate
- No talking permitted

Goals
- Progress guarantees
  - Deadlock freedom
  - Livelock freedom
  - Starvation freedom
  - Maximum concurrency (no one should starve if there are available forks for them)
General Structure of Dining Philosophers Problem: PseudoCode

1. int numPhilosophers = 5;
2. int numForks = numPhilosophers;
3. Fork[] fork = ... ; // Initialize array of forks
4. forall(point [p] : [0:numPhilosophers-1]) {
5.   while(true) {
6.     Think ;
7.     Acquire forks;
8.     // Left fork = fork[p]
9.     // Right fork = fork[(p-1)%numForks]
10.    Eat ;
11.   } // while
12.} // forall
Solution 1: using Java’s synchronized statement

1. int numPhilosophers = 5;
2. int numForks = numPhilosophers;
3. Fork[] fork = ... // Initialize array of forks
4. forall(point [p] : [0:numPhilosophers-1]) {
5.   while(true) {
6.     Think;
7.     synchronized(fork[p])
8.     synchronized(fork[(p-1)%numForks]) {
9.       Eat;
10.   }
11. }
12. } // while
13.} // forall
Solution 2: using Java’s Lock library

1. int numPhilosophers = 5;
2. int numForks = numPhilosophers;
3. Fork[] fork = ... ; // Initialize array of forks
4. forall(point [p] : [0:numPhilosophers-1]) {
5.   while(true) {
6.     Think ;
7.     if (!fork[p].lock.tryLock()) continue;
8.     if (!fork[(p-1)%numForks].lock.tryLock()) {
9.       fork[p].lock.unlock(); continue;
10.     }
11.     Eat ;
12.     fork[p].lock.unlock();fork[(p-1)%numForks].lock.unlock();
13.   } // while
14.} // forall
Solution 3: using HJ’s isolated statement

1. int numPhilosophers = 5;
2. int numForks = numPhilosophers;
3. Fork[] fork = ... ; // Initialize array of forks
4. forall(point [p] : [0:numPhilosophers-1]) {
5.   while(true) {
6.     Think ;
7.     isolated {
8.       Pick up left and right forks;
9.       Eat ;
10.   }
11. } // while
12.} // forall
Solution 4: using HJ’s object-based isolation

1. `int numPhilosophers = 5;`
2. `int numForks = numPhilosophers;`
3. `Fork[] fork = ... ; // Initialize array of forks`
4. `forall(point [p] : [0:numPhilosophers-1]) {`
5. `while(true) {`
6. `Think ;`
7. `isolated(fork[p], fork[(p-1)%numForks]) {`
8. `Eat ;`
9. `}`
10. `} // while`
11. `} // forall`
Solution 5: using Java’s Semaphores

1. int numPhilosophers = 5;
2. int numForks = numPhilosophers;
3. Fork[] fork = ... ; // Initialize array of forks
4. Semaphore table = new Semaphore(3, true);
5. for (i=0;i<numForks;i++) fork[i].sem = new Semaphore(1, true);
6. forall(point [p] : [0:numPhilosophers-1]) {
   7.   while(true) {
     8.     Think;
     9.     table.acquire(); // At most 3 philosophers at table, assume optimal table assignment
    10.    fork[p].sem.acquire(); // Acquire left fork
    11.    fork[(p-1)%numForks].sem.acquire(); // Acquire right fork
    12.    Eat;
    13.    fork[p].sem.release(); fork[(p-1)%numForks].sem.release();
    14.    table.release();
   15. } // while
   16.} // forall

“true” parameter creates a semaphore that guarantees fairness