Lecture 30: Safety and Liveness Properties, Java Synchronizers, Dining Philosophers Problem

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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

```
// 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. Lovelock-Free Parallel Program

- 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:

```
// 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

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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

```
public class BoundedBlockingList {
   final int capacity;
   final ConcurrentLinkedList list = new ConcurrentLinkedList();
   final Semaphore sem;
   public BoundedBlockingList(int capacity) {
     this.capacity = capacity;
     sem = new Semaphore(capacity);
  }
  public void addFirst(Object x) throws InterruptedException {
     sem.acquire(); // blocks until a permit is available
     try { list.addFirst(x); }
     catch (Throwable t){ sem.release(); rethrow(t); } // only performed on exception
  }
  public boolean remove(Object x) {
     if (list.remove(x)) {  sem.release(); return true; }
     return false;
  }
  … } // BoundedBlockingList
```

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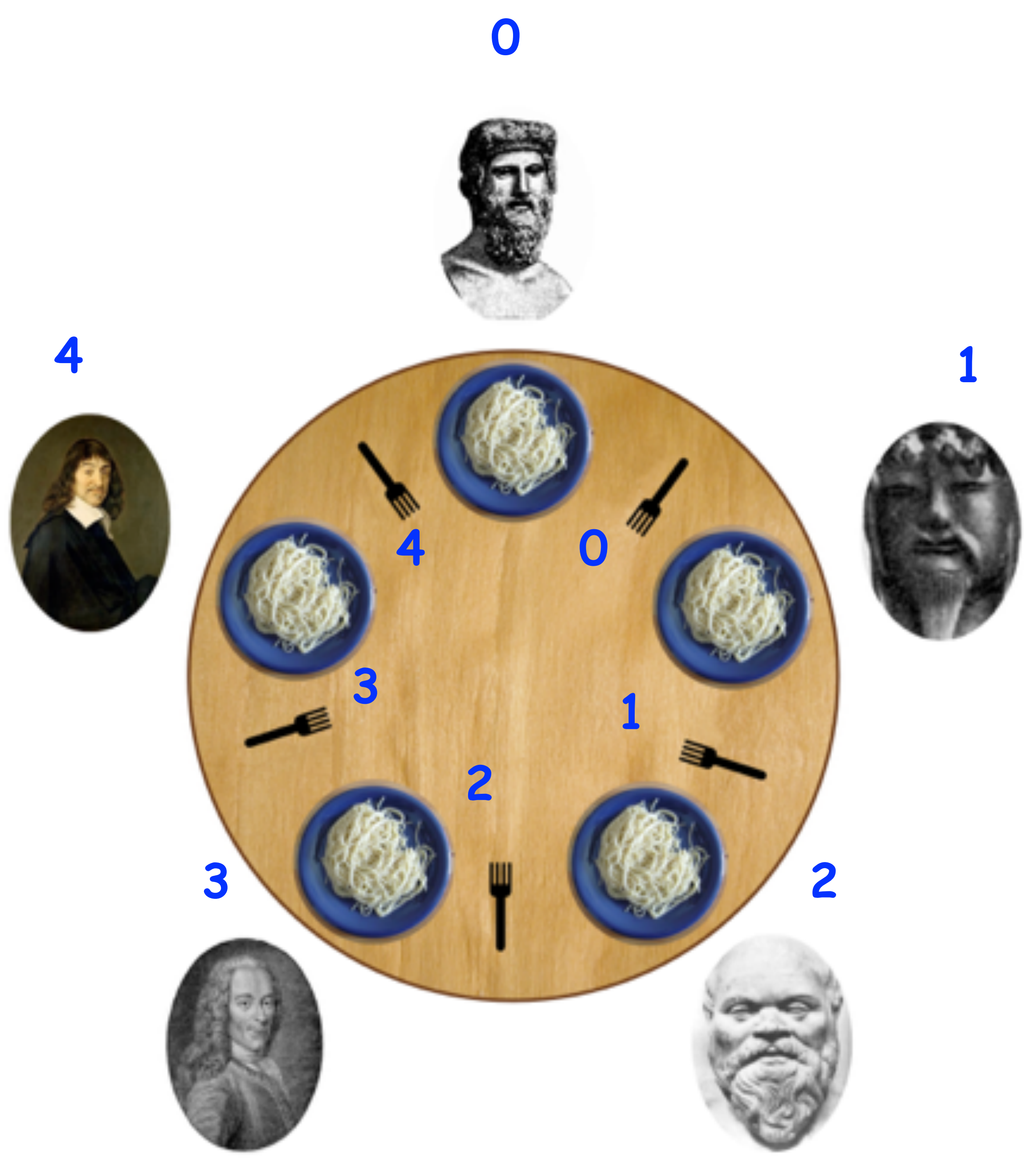
  - Acknowledgments
    - CMSC 330 course notes, U. Maryland
      http://www.cs.umd.edu/~lam/cmsc330/summer2008/lectures/class20-threads_classicprobs.ppt
    - Dave Johnson (COMP 421 instructor)

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

```
int numPhilosophers = 5;
int numForks = numPhilosophers;
Fork[] fork = ... ; // Initialize array of forks
forall(point [p] : [0:numPhilosophers-1]) {
  while(true) {
    Think ;
    Acquire forks;
      // Left fork = fork[p]
      // Right fork = fork[(p-1)%numForks]
    Eat ;
  } // while
} // forall
```

Solution 1: using Java's synchronized statement

```
int numPhilosophers = 5;
int numForks = numPhilosophers;
Fork[] fork = ... ; // Initialize array of forks
forall(point [p] : [0:numPhilosophers-1]) {
  while(true) {
    Think ;
    synchronized(fork[p])
      synchronized(fork[(p-1)%numForks]) {
        Eat ;
      }
    }
  } // while
} // forall
```

Solution 2: using Java's Lock library

```
int numPhilosophers = 5;
int numForks = numPhilosophers;
Fork[] fork = ... ; // Initialize array of forks
forall(point [p] : [0:numPhilosophers-1]) {
  while(true) {
    Think ;
    if (!fork[p].lock.tryLock()) continue;
    if (!fork[(p-1)%numForks].lock.tryLock()) {
      fork[p].lock.unLock(); continue;
    }
    Eat ;
    fork[p].lock.unlock();fork[(p-1)%numForks].lock.unlock();
  } // while
} // forall
```

Solution 3: using HJ's isolated statement

```
int numPhilosophers = 5;
int numForks = numPhilosophers;
Fork[] fork = ... ; // Initialize array of forks
forall(point [p] : [0:numPhilosophers-1]) {
  while(true) {
    Think ;
    isolated {
      Pick up left and right forks;
      Eat ;
    }
  } // while
} // forall
```

Solution 4: using HJ's object-based isolation

```
int numPhilosophers = 5;
int numForks = numPhilosophers;
Fork[] fork = ... ; // Initialize array of forks
forall(point [p] : [0:numPhilosophers-1]) {
  while(true) {
    Think ;
    isolated(fork[p], fork[(p-1)%numForks]) {
      Eat ;
    }
  } // while
} // forall
```

Solution 5: using Java’s Semaphores

```
int numPhilosophers = 5;
int numForks = numPhilosophers;
Fork[] fork = ... ; // Initialize array of forks
Semaphore table = new Semaphore(3, true);
for (i=0;i<numForks;i++) fork[i].sem = new Semaphore(1, true);
forall(point [p] : [0:numPhilosophers-1]) {
  while(true) {
    Think ;
    table.acquire(); // At most 3 philosophers at table, assume optimal table assignment
    fork[p].sem.acquire(); // Acquire left fork
    fork[(p-1)%numForks].sem.acquire(); // Acquire right fork
    Eat ;
    fork[p].sem.release(); fork[(p-1)%numForks].sem.release();
    table.release();
  } // while
} // forall
```

“true” parameter creates a semaphore that guarantees fairness

Characterizing Solutions to the Dining Philosophers Problem

For the five solutions studied in today's lecture, indicate in the table below which of the following conditions are possible and why:

1. Deadlock: when all philosopher tasks are blocked (neither thinking nor eating)
2. Livelock: when all philosopher tasks are executing but ALL philosophers are starved
3. Starvation: when one or more philosophers are starved (never get to eat)
4. Non-Concurrency: when more than one philosopher cannot eat at the same time, even when resources are available

Worksheet: Characterizing Solutions to the Dining Philosophers Problem

	Deadlock	Livelock	Starvation	Non-concurrency
Solution 1: synchronized				
Solution 2: tryLock/unLock				
Solution 3: isolated				
Solution 4: object-based isolation				
Solution 5: semaphores				