Parallel Programming

Recitation Session 8

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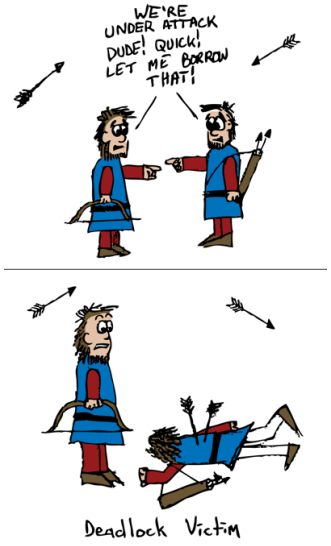
April 29, 2010

Executive Summary

- Some remarks regarding mutual exclusion proofs
- Repeat Read/Write locks
- Classroom exercise: Equivalence of Semaphores and Monitors
- Classroom exercise: Lock proof
- Implement MergeSort and Dining Philosophers with Communicating Sequential Processes



Source: http://dbwhisperer.blogspot.com/2009/07/deadlocks-explained.html

Outline

Notation

```
public void run() {
  while (true) {
    mysignal.request();
    while (true) {
      if (othersignal.read() == 1) break;
      mysignal.free();
      mysignal.request();
    }
    // critical section
    mysignal.free();
  }
}
```

Notation

```
A1 // non-critical section
A2 turn0.flag = 0;
A3 while(true)
     if(turn1.flag == 1)
       break;
A4   turn0.flag = 1;
A5   turn0.flag = 0;
   }
A6 // critical section
A7 turn0.flag = 1;
```

```
B1 // non-critical section
B2 turn1.flag = 0;
B3 while(true) {
     if(turn0.flag == 1)
       break;
B4   turn1.flag = 1;
B5   turn1.flag = 0;
   }
B6 // critical section
B7 turn1.flag = 1;
```


Implication

1. at(A6) $\rightarrow$ turn0.flag == 0

```
A1 // non-critical section
A2 turn0.flag = 0;
A3 while(true)
     if(turn1.flag == 1)
       break;
A4   turn0.flag = 1;
A5   turn0.flag = 0;
   }
A6 // critical section
A7 turn0.flag = 1;
```

Why is invariant (1) true at(A1), at(A2), at(A3), at(A4), at(A5), at(A7)?

Implication: Truth Table

$$A \rightarrow B$$

$\rightarrow$	1	0
1	1	0
0	1	1

1. at(A6) $\rightarrow$ turn0.flag == 0

- at(A1): $0 \rightarrow x = 1$
- at(A2): $0 \rightarrow x = 1$
- at(A3): $0 \rightarrow x = 1$
- at(A4): $0 \rightarrow x = 1$
- at(A5): $0 \rightarrow x = 1$
- at(A7): $0 \rightarrow x = 1$

Equivalence

1. turn0.flag == 0 $\leftrightarrow$ (at(A3) $\vee$ at(A4) $\vee$ at(A6) $\vee$ at(A7))

```
A1 // non-critical section
A2 turn0.flag = 0;
A3 while(true)
     if(turn1.flag == 1)
       break;
A4   turn0.flag = 1;
A5   turn0.flag = 0;
   }
A6 // critical section
A7 turn0.flag = 1;
```

A4 $\rightarrow$ A5 and A7 $\rightarrow$ A1: turn0.flag == 1, why does invariant (1) still hold?

Equivalence: Truth Table

$$A \leftrightarrow B$$

$\leftrightarrow$	1	0
1	1	0
0	0	1

1. `turn0.flag == 0` $\leftrightarrow$ `(at(A3)`$\vee$`at(A4)`$\vee$`at(A6)`$\vee$`at(A7))`

- `A4`$\rightarrow$`A5` == `at(A5)`: $0 \leftrightarrow 0 = 1$
- `A7`$\rightarrow$`A1` == `at(A1)`: $0 \leftrightarrow 0 = 1$

Outline

Read/Write Lock

- Many shared objects have the property that most method calls return information about the object's state without modifying the object (**readers**) while only a small number of calls actually modify the object (**writers**)
- There is no need for readers to synchronize with one another
  - It is perfectly safe for them to access the object concurrently
- Writers, on the other hand, must lock out readers as well as other writers
- A Read/Write Lock allows multiple readers or a single writer to enter the critical section concurrently

Assignment 7

- Implement a Read/Write Lock
- At most four threads
- At most two reader threads (shared access is allowed) and one writer thread
- A thread that executes `read()` is a reader
  - At a later time it can be a writer...

Monitor

```
public class Monitor {
  final int MAX_THREADS;
  final int MAX_READERS = 2;
  FIFOQueue waitList;
  int readers = 0;
  int writers = 0;
  boolean writing = false;

  public Monitor(int maxThreads) {
    MAX_THREADS = maxThreads;
    waitList = new FIFOQueue(maxThreads);
  }

  public void readLock()    { /* ... */ }
  public void readUnlock()  { /* ... */ }
  public void writeLock()   { /* ... */ }
  public void writeUnlock() { /* ... */ }
}
```


readLock()

```
public synchronized void readLock() {
  if (readers >= MAX_READERS || writing || !waitList.isEmpty()) {
    waitList.enq(Thread.currentThread().getId());

    while (true) {
      try {
        wait();
      } catch (InterruptedException e) {
        e.printStackTrace();
      }

      if (waitList.getFirstItem() == Thread.currentThread().getId()
          && !writing && readers < MAX_READERS) {
        waitList.deq();
        break;
      }
    }
  }

  readers++;
  if (readers < MAX_READERS)
    notifyAll();
  System.out.println("READ LOCK ACQUIRED " + readers);
}
```


readUnlock()

```
public synchronized void readUnlock() {
  readers--;
  System.out.println("READ LOCK RELEASED " +
                     readers);
  notifyAll();
}
```


writeLock()

```
public synchronized void writeLock() {
  if (readers > 0 || writers > 0 || !waitList.isEmpty()) {
    waitList.enq(Thread.currentThread().getId());
    while (true) {
      try {
        wait();
      } catch (InterruptedException e) {
        System.out.println(e.getMessage());
      }

      if (waitList.getFirstItem() == Thread.currentThread().getId()
          && !writing && readers == 0) {
        waitList.deq();
        break;
      }
    }
  }

  writers++;
  writing = true;
  System.out.println("WRITE LOCK ACQUIRED " + writers);
}
```

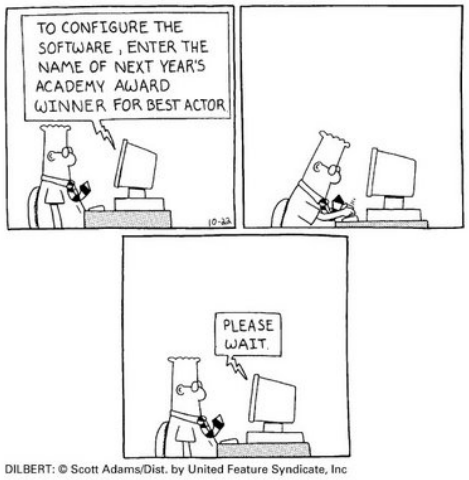
writeUnlock()

```
public synchronized void writeUnlock() {
  writing = false;
  writers--;
  System.out.println("WRITE LOCK RELEASED " +
                     writers);
  notifyAll();
}
```


Outline

Classroom Exercise

- Are semaphores and monitors equivalent?
- How can you implement semaphores with monitors?
- How can you implement monitors with semaphores?
  - What about `wait()` and `notifyAll()`?



Semaphores and Monitors

- Monitor: model for synchronized methods in Java
- Both constructs are equivalent
- One can be used to implement the other

Semaphore Implementation

```
public class Semaphore {
  private int value;
  public Semaphore() {
    value = 0;
  }
  public Semaphore(int k) {
    value = k;
  }
  public synchronized void acquire() {
    /* see later */
  }
  public synchronized void release() {
    /* see later */
  }
}
```


Semaphore Implementation: `acquire()`

```
public synchronized void acquire() {
  while (value == 0) {
    try {
      wait();
    }
    catch (InterruptedException e) {
    }
  }
  value--;
}
```


Semaphore Implementation: `release()`

```
public synchronized void release() {
  ++value;
  notifyAll();
}
```


Monitor with Semaphores

We need 2 semaphores:

- One to make sure that only one synchronized method executes at any given time
  - call this the "access semaphore" `access`
  - binary semaphore
- One semaphore to line up threads that are waiting for some condition
  - call this the "condition semaphore" `cond`
  - counting (general) semaphore
  - threads that wait must do an "acquire"

For convenience

Counter `waitThread` to count number of waiting threads i.e., threads in queue for `cond`

Monitor with Semaphores

1. Frame all synchronized methods with `access.acquire()` and `access.release()`
   - This ensures that only one thread executes a synchronized method at any point in time
   - Recall: `access` is binary.
2. Translate `wait()` and `notifyAll()` to give threads waiting in line a chance to progress (these threads use `cond`)

Monitor with Semaphores: Auxiliary Fields

```
class FooBar {
  private Semaphore access;
  private Semaphore cond;
  private int waitThread = 0;

  public FooBar() {
    access = new Semaphore(1);
    cond = new Semaphore(0);
  }

  // continued
}
```


(1) Framing all methods

```
public void qux() {
  // Ensure mutual exclusion
  access.acquire();

  // Critical section

  access.release();
}
```

is equivalent to

```
public synchronized void qux() {
  // Critical section
}
```


(2) Translate `wait()`

```
waitThread++;

// other threads can execute
// synchronized methods
access.release();

// wait till condition changes
cond.acquire();
access.acquire();

waitThread--;
```

(2) Translate `notifyAll()`

```
if (waitThread > 0) {
  for (int i=0; i < waitThread; i++) {
    cond.release();
  }
}
```

- All threads waiting are released and will compete to (re)acquire `access`
- They decrement `waitThread` after they leave `cond.acquire()`
- Note that to enter the line (i.e., increment `waitThread`) the thread must hold the access semaphore `access`

(2) Translate `wait()` and `notifyAll()`

- Recall that `access.release()` is done at the end of the synchronized method
- So all the threads that had lined up waiting for `cond` compete to get access to `access`
- No thread can line up while the `cond.release()` operations are done since this thread holds `access`

Note

- We wake up all threads – they might not be able to enter their critical section if the condition they waited for does not hold, but all threads get a chance.
- `notifyAll()` calls `cond.release()` `waitThread`-times
  - If 3 threads were waiting, `cond.value` is set to 3.
  - Now one of the threads wakes up, decrements `waitThreads`, runs to the end and again calls `cond.release()` 2 times → `cond.value` will now be 4 even though only 2 threads are in the wait section of the code
  - A thread may awake a few times and not find that the condition has changed. As long as all the `wait()` are in `while (some_condition)` loop there will be no harm

`wait()` in while-loop

```
public void insert(Object o)
  throws InterruptedException {
  access.acquire();
  while (isFull()) {
    waitThread++;
    access.release(); // let other thread access object
    cond.acquire(); // wait for change of state
    access.acquire()
    waitThread--;
  }
  doInsert(o);
  if (waitThread > 0) {
    for (int i; i < waitThread; i++) {
      cond.release();
    }
  }
  access.release();
}
```

Outline

Classroom Exercise

```
class MyLock implements Lock {
  private int turn;
  private boolean busy = false;

  public void lock() {
    int me = ThreadID.get();
    while (turn != me) {
      while (busy) {
        turn = me;
      }
      busy = true;
    }
  }

  public void unlock() {
    busy = false;
  }
}
```

- Does this protocol satisfy mutual exclusion?
- Is this protocol starvation-free?
- Is this protocol deadlock-free?

Lock

```
class MyLock implements Lock {
  private int turn;
  private boolean busy = false;

  public void lock() {
/* S1 */    int me = ThreadID.get();
/* S2 */    while (turn != me) {
/* S3 */      while (busy) {
/* S4 */        turn = me;
            }
/* S5 */      busy = true;
          }
  }

  public void unlock() {
/* S6 */    busy = false;
  }
}
```


Mutual Exclusion

Protocol does not satisfy mutual exclusion:

- Assume `ThreadIDs` start with a value `!= 0`: `ThreadIDs` don't start with 0 $\rightarrow$ they start with 1 in Java
- No thread can enter critical section (could argue this is mutual exclusion but you have to clarify your answer)
- `turn` is initialized to 0 $\rightarrow$ one aspect of the broken protocol

Mutual Exclusion

T0 attempts to enter the critical section:

```
/* S2 */ → true // me != 0
/* S3 */ false
/* S5 */ busy = true
/* S2 */ true
/* S3 */ true // bye virtue of S5,
              // previous iteration
/* S4 */ turn = me
/* S3 */ true // no exit from loop
```

If another thread attempts to enter the critical section then it will experience the same sequence

Mutual Exclusion

- Assume that ThreadIDs start at 0 or turn is initialized to the ThreadID of the first thread (i.e. 1) to enter the critical section
- This thread succeeds but does not set busy to true:

```
/* S1 */   me = 0 // by assumption
/* S2 */   → false
```

Loop exits but busy unchanged (false)

Starvation

- Protocol is not starvation-free
- Assume there are two threads:
  - If turn is not initialized to the ThreadID of the first thread to acquire the lock, then this thread will be not able to enter its critical section
  - If turn is initialized then the second thread never enters its critical section if the first thread leaves its critical section (with unlock()) before the second thread attempts to enter its critical section

Deadlock

- Protocol is not deadlock-free
- Situation for deadlock is similar to the situation for starvation in this case
- The thread will enter the lock method but never exit

Outline

Semaphores

- Special Integer variable with 2 atomic operations
  - `P()`: Passeren, wait/up
  - `V()`: Vrijgeven/Verhogen, signal/down
- Map into JCSP by defining a semaphore process

Semaphores in JCSP

- Semaphore `CSProcess`
- Two channels for `P` and `V`
- Two + Two channels
  - `P` – request/confirm
  - `V` – request/confirm

Outline

Overview

- Thread hierarchy similar to previous mergesort assignment
- Threads are replaced with JCSP processes
- Communication allowed only via JCSP channels – no shared data between processes
- Use the JCSP library provided on the website

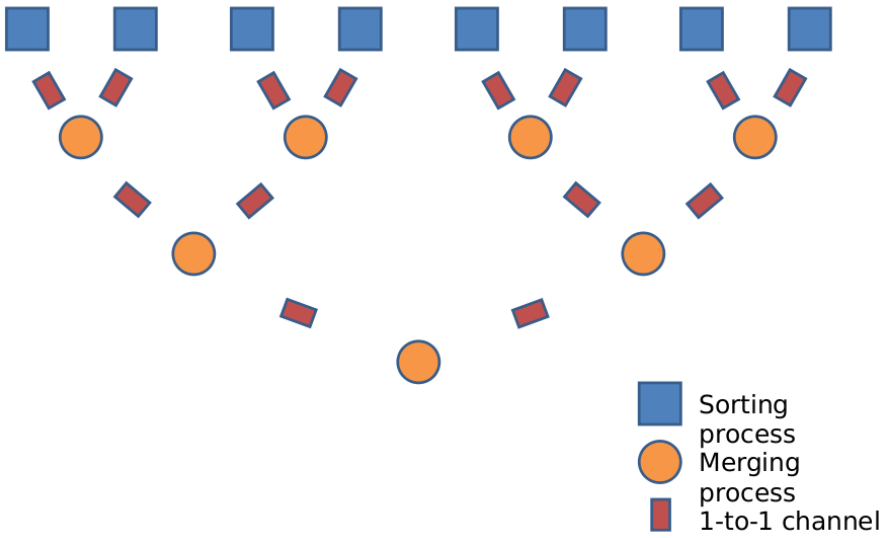
Entities Description

Sorting process: randomly generates a subarray, sorts it sequentially, and then passes the result to its parent merging process

Merging process: takes 2 sorted subarrays from its children, merges and passes the result to its parent merging process

Communication channel: allows data passing between processes

Entities Layout



Reading Policy

How can the data from 2 children be read?

1. Read all data from first child, then read all data from second child
   - Read whole subarray
2. Read data from both children simultaneously
   - Read whole subarray
3. Similar to (2), but read data in pairs and proceed to output current element of the not-yet-fully-sorted subarray
   - Read subarray element-wise

Skeleton

```
import org.jcsp.lang.*;

public class MergeSort {
  // TODO: add possible fields and methods

  public static void main(String[] args) {
    // the total number of JCSP processes that will be run
    // (will be changed, of course, by your code)
    int numberOfProcesses = 0;

    // TODO: add code here

    // create process array
    CSProcess[] allProcesses = new CSProcess[numberOfProcesses];

    // TODO: add code here

    // run all JCSP processes, they should synchronize via the
    // communication channels
    Parallel parallel = new Parallel(allProcesses);
    parallel.run();
  }
}
```


Skeleton: Sorting

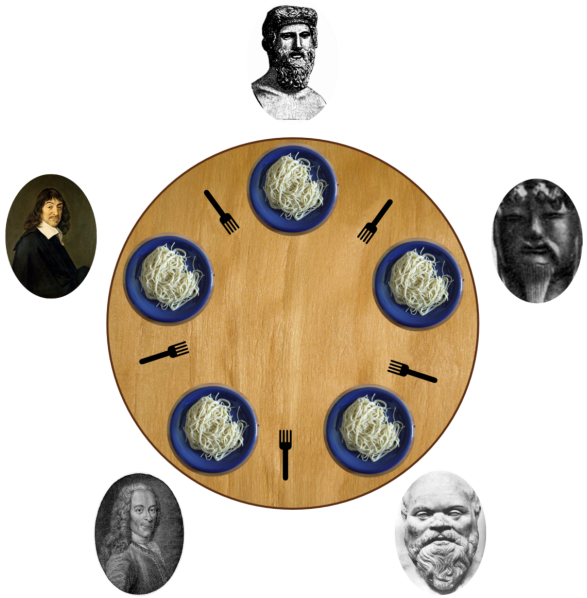
```
import java.util.Random;
import org.jcsp.lang.*;

public class SortingProcess implements CSProcess {
  // TODO: add possible fields/methods

  public SortingProcess() {
    // TODO: add code, change signature if necessary
  }

  public void run() {
    // TODO: initialize random subarray (or do it in
    //       the constructor, alternatively), sort
    //       it sequentially, and write it to parent
   }
}
```


Skeleton: Merging

```
import org.jcsp.lang.*;

public class MergingProcess implements CSProcess {
  // TODO: add possible fields/methods

  public MergingProcess() {
    // TODO: add code, change signature if necessary
  }

  // the process' run() method
  public void run() {
    // TODO: read subarrays from children, merge them,
    //       write merged subarray to parent
  }
}
```


Outline

Dining Philosophers



Source: http://en.wikipedia.org/wiki/File:Dining_philosophers.png

Dining Philosophers

- Five philosophers sitting at a table doing one of two things:
  - eating or
  - thinking
- While eating, they are not thinking, and while thinking, they are not eating
- Philosophers sit at a circular table with a large bowl of spaghetti in the center
- Each philosopher has one fork to his left and one fork to his right
- Philosopher must eat with two forks: Can only use the forks on his immediate left and immediate right

Deadlock and Starvation

Deadlock

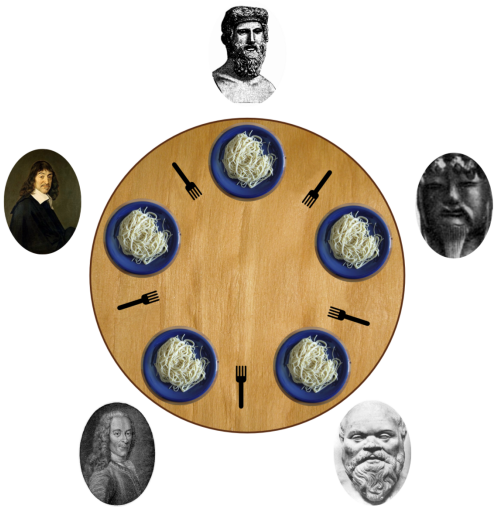
Philosophers never speak to each other: creates a dangerous possibility of deadlock when every philosopher holds a left fork and waits perpetually for a right fork (or vice versa)

Starvation

Starvation – pun intended – might also occur independently of deadlock if a philosopher is unable to acquire both forks because of a timing problem

Strategies to Avoid Deadlock

- Security Guard: limits entry to dining hall
- Asymmetric philosophers: 4 philosophers pick up left fork first, 1 philosopher picks up right fork first
- See http://en.wikipedia.org/wiki/Dining_philosophers_problem#Solutions for other strategies



Source: http://en.wikipedia.org/wiki/File:Dining_philosophers.png

Skeleton: Main

```
import org.jcsp.lang.CSProcess;
import org.jcsp.lang.Parallel;

public class Main implements CSProcess {
  private final static int NUM_PHILOSOPHERS = 5;
  private final CSProcess go;

  public Main() {
    final Philosopher[] philosophers = new Philosopher[NUM_PHILOSOPHERS];
    for (int i = 0; i < philosophers.length; i++) {
      philosophers[i] = new Philosopher(i);
    }
    go = new Parallel(new CSProcess[] {new Parallel(philosophers)});
  }

  @Override
  public void run() {
    go.run();
  }

  public static void main(String[] args) {
    new Main().run();
  }
}
```


Skeleton: Philosopher

```
import org.jcsp.lang.CSProcess;

public class Philosopher implements CSProcess {
  private final int ID;
  public Philosopher(int id) {
    this.ID = id;
  }

  @Override
  public void run() {
    try {
      for (;;) {
        think(); eat();
      }
    } catch (InterruptedException e) {
      e.printStackTrace();
    }
  }
  private void think() throws InterruptedException {
    Thread.sleep((long)(Math.random() * 500));
    System.out.println("Philosopher " + ID + " : Thinking...");
  }
  private void eat() throws InterruptedException {
    Thread.sleep((long)(Math.random() * 500));
    System.out.println("Philosopher " + ID + " : Please, give me two forks!");
  }
}
```


Summary

- Mutual exclusion proofs
- Read/Write locks
- Equivalence of Semaphores and Monitors
- Lock proof
- MergeSort and Dining Philosophers in JCSP