

Parallel Programming

Recitation Session 8

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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

- 1 **Mutual Exclusion Proofs**
- 2 Read/Write Lock
- 3 Equivalence of Semaphores and Monitors
- 4 Lock Proof
- 5 JCSP: Semaphores
- 6 JCSP: MergeSort
- 7 JCSP: Dining Philosophers

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 $\text{at}(A6) \rightarrow \text{turn0.flag} == 0$

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

```

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: $\text{turn0.flag} == 1$, why does invariant (1) still hold?

Equivalence: Truth Table

$$A \leftrightarrow B$$

\leftrightarrow	1	0
1	1	0
0	0	1

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

■ $A4 \rightarrow A5 == \text{at}(A5): 0 \leftrightarrow 0 = 1$

■ $A7 \rightarrow A1 == \text{at}(A1): 0 \leftrightarrow 0 = 1$

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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()

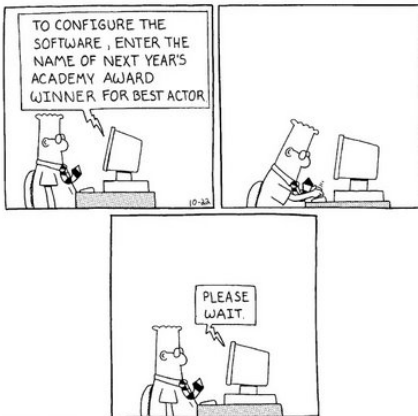
```
public synchronized void writeUnlock() {  
    writing = false;  
    writers--;  
    System.out.println("WRITE LOCK RELEASED " +  
                        writers);  
    notifyAll();  
}
```

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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()`?



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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();
}
```


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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 $\neq 0$: 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 // by 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

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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

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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

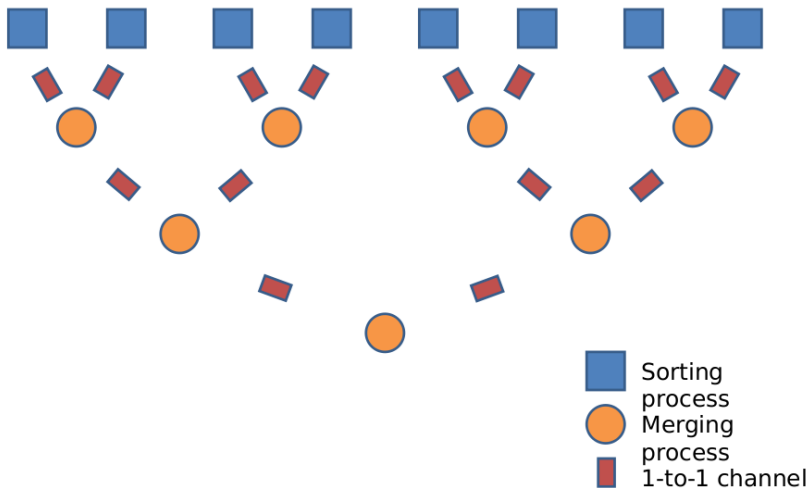
Entities Description

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 CSPProcess {
    // 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 CSPProcess {
    // 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
    }
}
```

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Dining Philosophers



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

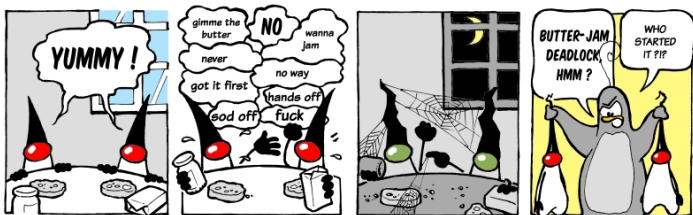
Dining Philosophers

- 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)

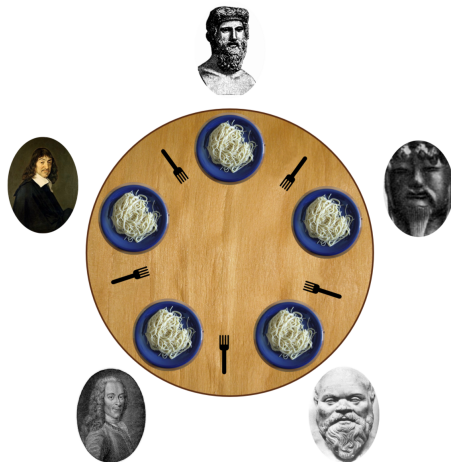


Starvation

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

