CMSC 132: Object-Oriented Programming II

Synchronization in Java

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Multithreading Overview

- Motivation & background
- Threads
  - Creating Java threads
  - Thread states
  - Scheduling
- Synchronization
  - Data races
  - Locks
  - Deadlock
Data Race

Definition

- Concurrent accesses to same shared variable, where at least one access is a write

Properties

- Order of accesses may change result of program
- May cause intermittent errors, very hard to debug

Example

```java
public class DataRace extends Thread {
    static int x;  // shared variable x causing data race
    public void run() { x = x + 1; }  // access to x
}
```
public class DataRace extends Thread {
    static int common = 0;
    public void run() {
        int local = common; // data race
        local = local + 1;
        common = local; // data race
    }
    public static void main(String[] args) throws InterruptedException {
        int max = 3;
        DataRace[] allThreads = new DataRace[max];
        for (int i = 0; i < allThreads.length; i++)
            allThreads[i] = new DataRace();
        for (DataRace t : allThreads)
            t.start();
        for (DataRace t : allThreads)
            t.join();
        System.out.println(common); // may not be 3
    }
}
Data Race Example

Sequential execution output

<table>
<thead>
<tr>
<th>Thread #1</th>
<th>Thread #2</th>
<th>Thread #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>local = common;</td>
<td>local = common;</td>
<td>local = common;</td>
</tr>
<tr>
<td>local = local + 1;</td>
<td>local = local + 1;</td>
<td>local = local + 1;</td>
</tr>
<tr>
<td>common = local;</td>
<td>common = local;</td>
<td>common = local;</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
# Data Race Example

Concurrent execution output (possible case)

<table>
<thead>
<tr>
<th>Thread #1:</th>
<th>local = common;</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thread #2:</td>
<td>local = common;</td>
<td>0</td>
</tr>
<tr>
<td>Thread #3:</td>
<td>local = common;</td>
<td>0</td>
</tr>
<tr>
<td>Thread #1:</td>
<td>local = local + 1;</td>
<td>1</td>
</tr>
<tr>
<td>Thread #2:</td>
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</tr>
<tr>
<td>Thread #1:</td>
<td>common = local;</td>
<td></td>
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<td>common = local;</td>
<td></td>
</tr>
<tr>
<td>Thread #3:</td>
<td>common = local;</td>
<td></td>
</tr>
</tbody>
</table>

Result depends on thread execution order!
Synchronization

Definition

- Coordination of events with respect to time

Properties

- May be needed in multithreaded programs to eliminate data races
- Incurs runtime overhead
- Excessive use can reduce performance
Lock

Definition
- Entity can be held by only one thread at a time

Properties
- A type of synchronization
- Used to enforce mutual exclusion
  - Thread can acquire / release locks
  - Only 1 thread can acquire lock at a time
- Thread will wait to acquire lock (stop execution)
  - If lock held by another thread
- Used to implement monitors
  - Only 1 thread can execute (locked) code at a time
Synchronized Objects in Java

- Java objects provide locks
- To acquire the lock use the `synchronized` keyword
  - Apply `synchronized` keyword to object
    - Will acquire / release lock associated with object
  - Mutual exclusion for code in synchronization block (block defined by `synchronized() { }`)
- Example

```java
Object x = new Object();
synchronized(x) {
    // acquire lock on x on entry
    ...
    // hold lock on x in block
    }
    // release lock on x on exit
```
Fixing Data Race In Our Example

```java
public void run() {
    int local = 0;  // Local storage

    // Add one to common
    local = common;
    local = local + 1;
    common = local;
}
```

Obtain lock for critical section

Release lock

Only one thread can ever be in the critical section
Lock Example

```java
public class DataRace extends Thread {
    static int common = 0;
    static Object o; // all threads use o’s lock
    public void run() {
        synchronized(o) { // single thread at once
            int local = common; // data race eliminated
            local = local + 1;
            common = local;
        }
    }
    public static void main(String[] args) {
        o = new Object();
        ...
    }
}
```

- Keep in mind that lock objects do not need to be static (static is used in the above example to share the lock among all threads)
- How would you solve the data race without using a static lock object?
Locks in Java

Properties

- A lock can be held by only one thread at a time
- Locked block of code ⇒ critical section
- Note: critical section should not be confused with the term critical section use for algorithmic complexity analysis
- You must protect the critical section wherever it appears in your code, otherwise several threads may access the critical section simultaneously
  - In other words, protecting the critical section with a lock, in a section(s) of your code, will not automatically protect the critical section everywhere it appears in your code

- Lock is released when block terminates
  - End of block reached
  - Exit block due to return, continue, break
  - Exception thrown
Synchronized Methods In Java

- Apply synchronized keyword to method
  - Mutual exclusion for entire body of method
  - Synchronizes on current object

Example

```java
synchronized foo() { …code… }
// shorthand notation for
foo() {
    synchronized (this) { …code… }
}
```
public synchronized void enqueue( Object item ) {
    // Body of method goes here
}

public void enqueue( Object item ) {
    synchronized ( this ) {
        // Body of method goes here
    }
}
Examples

Code distribution provides an example of an account shared by two kinds of buyers (Normal buyer and Excessive buyer)

Four versions

- Version 1 → Buyers synchronize using the account object as lock object
- Version 2 → deposit/withdrawal/getBalance methods synchronize using a lock object (defined as instance variable of Account object)
- Version 3 → As in Version 2 but lock object is the current object
- Version 4 → deposit/withdrawal/getBalance methods defined as synchronized methods
Synchronization Issues

1. Use same lock to provide mutual exclusion
2. Ensure atomic transactions
3. Avoiding deadlock
Issue 1) Using Same Lock

Potential problem

- Mutual exclusion depends on threads acquiring same lock
- No synchronization if threads have different locks

Example

```java
foo() {
    Object o = new Object(); // different o per thread
    synchronized(o) {
        ... // potential data race
    }
}
```
Locks in Java

- Single lock for all threads (mutual exclusion)

- Separate locks for each thread (no synchronization)
public class DataRace extends Thread {
    static int common = 0;
    public void run() {
        Object o = new Object(); // different o per thread
        synchronized(o) {
            int local = common; // data race
            local = local + 1;
            common = local; // data race
        }
    }

    public static void main(String[] args) {
        ...
    }
}
Issue 2) Atomic Transactions

Potential problem

- Sequence of actions must be performed as single atomic transaction to avoid data race
- Ensure lock is held for duration of transaction

Example

```java
synchronized(o) {
    int local = common;  // all 3 statements must
    local = local + 1;  // be executed together
    common = local;      // by single thread
}
```
public class DataRace extends Thread {
    static int common = 0;
    static Object o; // all threads use o’s lock
    public void run() {
        int local;
        synchronized(o) {
            local = common;
        }
        synchronized(o) {
            local = local + 1;
            common = local;
        }
    }
}
Issue 3) Avoiding Deadlock

Potential problem

- Threads holding lock may be unable to obtain lock held by other thread, and vice versa
- Thread holding lock may be waiting for action performed by other thread waiting for lock
- Program is unable to continue execution (deadlock)
Deadlock Example 1

Object a = new Object()
Object b = new Object()
Thread1() {
    synchronized(a) {
        synchronized(b) {
            ...          synchronized(b) {
            ...            synchronized(a) {
                ...                ...            }
        }
    }
}

// Thread1 holds lock for a, waits for b
// Thread2 holds lock for b, waits for a
void swap(Object a, Object b) {
    Object local;
    synchronized(a) {
        synchronized(b) {
            local = a; a = b; b = local;
        }
    }
}

Thread1() { swap(a, b); }  // holds lock for a, waits for b
Thread2() { swap(b, a); }  // holds lock for b, waits for a
Deadlock

Avoiding deadlock

- In general, avoid holding lock for a long time
- Especially avoid trying to hold two locks
  - May wait a long time trying to get 2\textsuperscript{nd} lock
Thread-safe

- Thread-safe – Code is considered thread-safe if it works correctly when executed by multiple threads simultaneously.

- Example: ArrayList is not thread-safe

From Java API: “Note that this implementation is not synchronized. If multiple threads access an ArrayList instance concurrently, and at least one of the threads modifies the list structurally, it must be synchronized externally.”
Synchronization Summary

- Needed in multithreaded programs
- Can prevents data races
- Java objects support synchronization
- Many other tricky issues
  - To be discussed in future courses