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; } local = local + 1; } common = local;</td>
<td>{ local = common; } local = local + 1; } common = local;</td>
<td>{ local = common; } local = local + 1; } common = local;</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
Data Race Example

Concurrent execution output (possible case)

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

- Apply `synchronized` keyword to object
  - Will acquire / release lock associated with object
- Mutual exclusion for code in synchronization block

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
    }
```
Synchronized Methods In Java

Java methods also provide locks

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

Example

```java
synchronized foo() {  …code…  }
// shorthand notation for
foo() {
    synchronized (this) {  …code…  }
}
```

block
Synchronized Methods in Java

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

**Shorthand notation for**

```java
public void enqueue( Object item ) {
    synchronized ( this ) {
        // Body of method goes here
    }
}
```
Locks in Java

Properties

- No other thread can get lock on x while in block
- Other threads can still access/modify x!
- Locked block of code \(\Rightarrow\) critical section

- Lock is released when block terminates
  - End of block reached
  - Exit block due to return, continue, break
  - Exception thrown
Synchronization 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*
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();
        ...
    }
}
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;
        } // transaction not atomic
        // data race may occur
        // even using locks
    }
}
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;
Object b;

Thread1() {
    synchronized(a) {
        synchronized(b) {
            synchronized(b) {
                ...
                }
            }
        }
    }

Thread2() {
    synchronized(b) {
        synchronized(a) {
            ...
            }
        }
    }

// Thread1 holds lock for a, waits for b
// Thread2 holds lock for b, waits for a
Deadlock Example 2

```java
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
```
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
Synchronization Summary

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