CMSC 132:
Object-Oriented Programming II

Synchronization in Java

Department of Computer Science
University of Maryland, College Park

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**

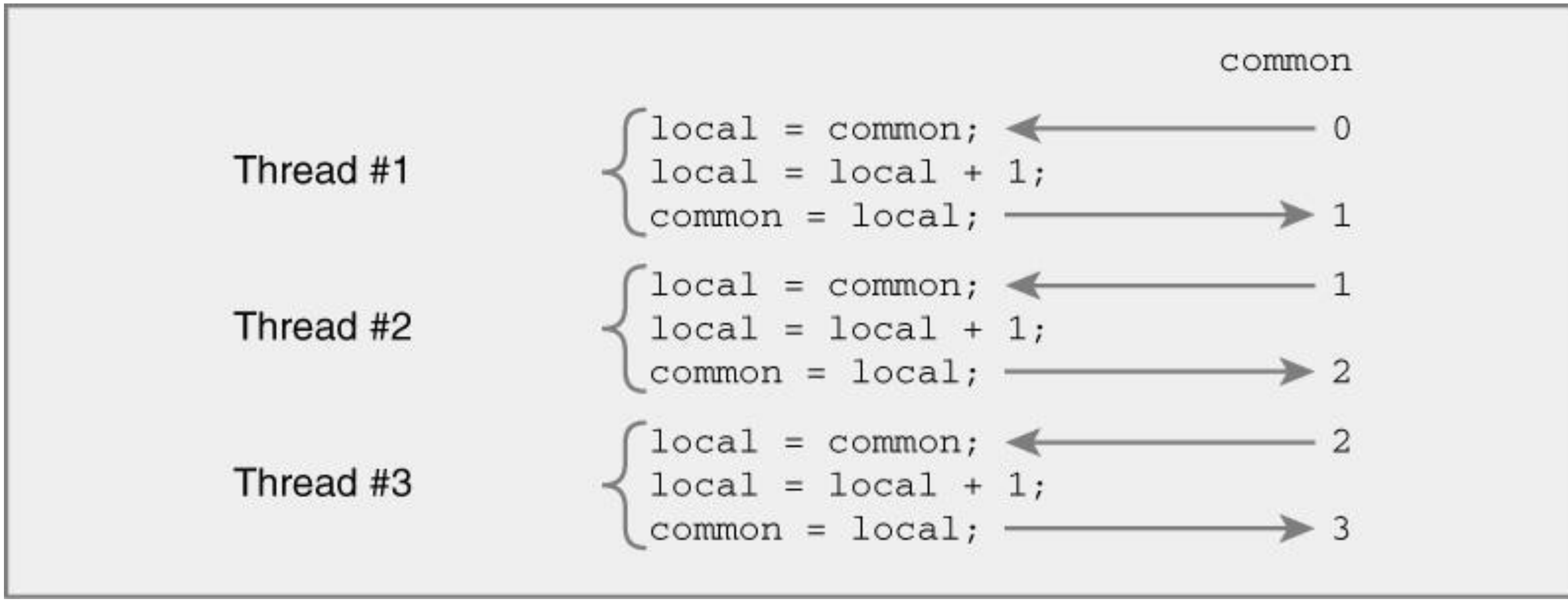
```
public class DataRace extends Thread {
    static int x;    // shared variable x causing data race
    public void run() { x = x + 1; }  // access to x
}
```

Data Race Example

```
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
    }
}
```

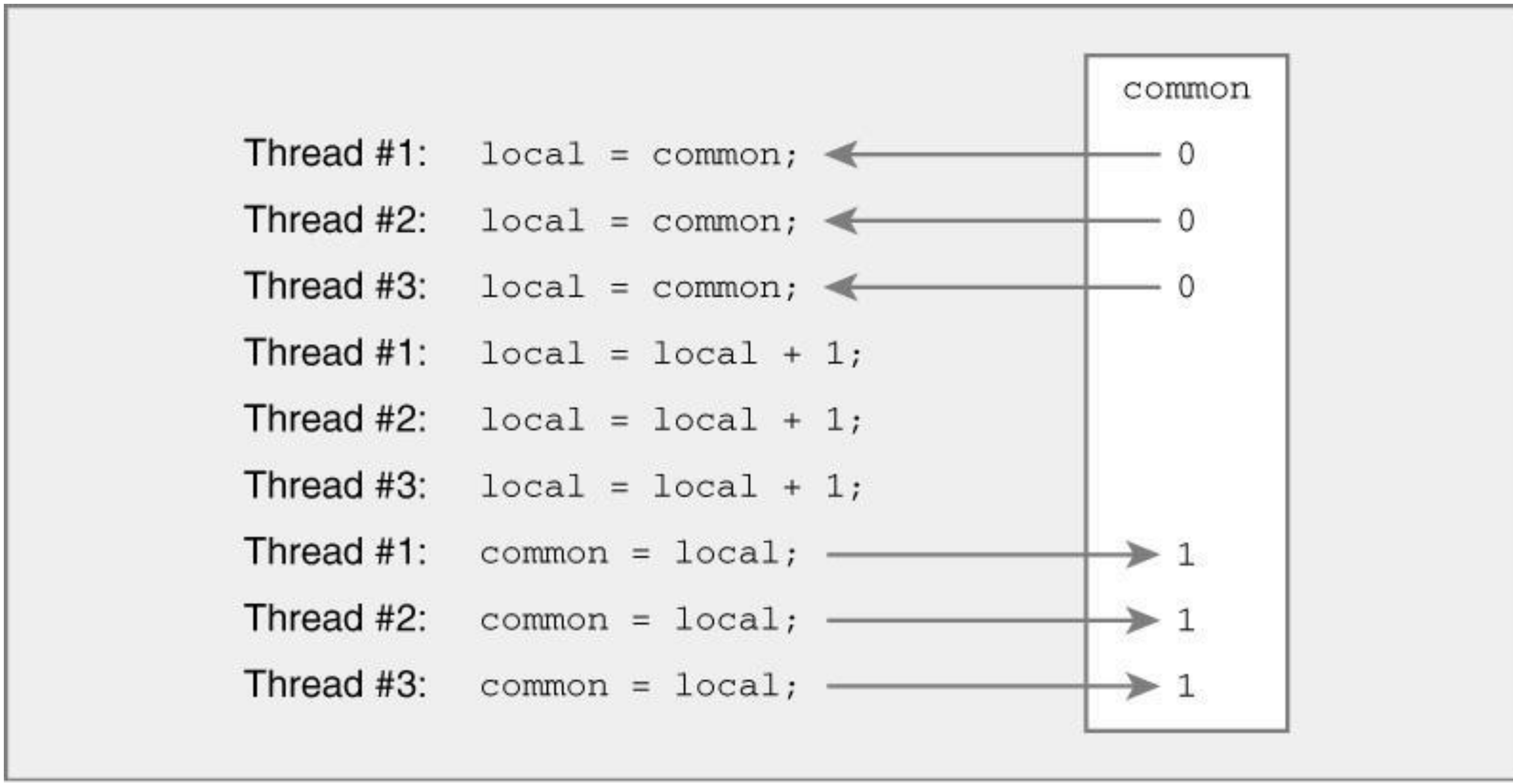
Data Race Example

- **Sequential execution output**



Data Race Example

- **Concurrent execution output (possible case)**



- **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**

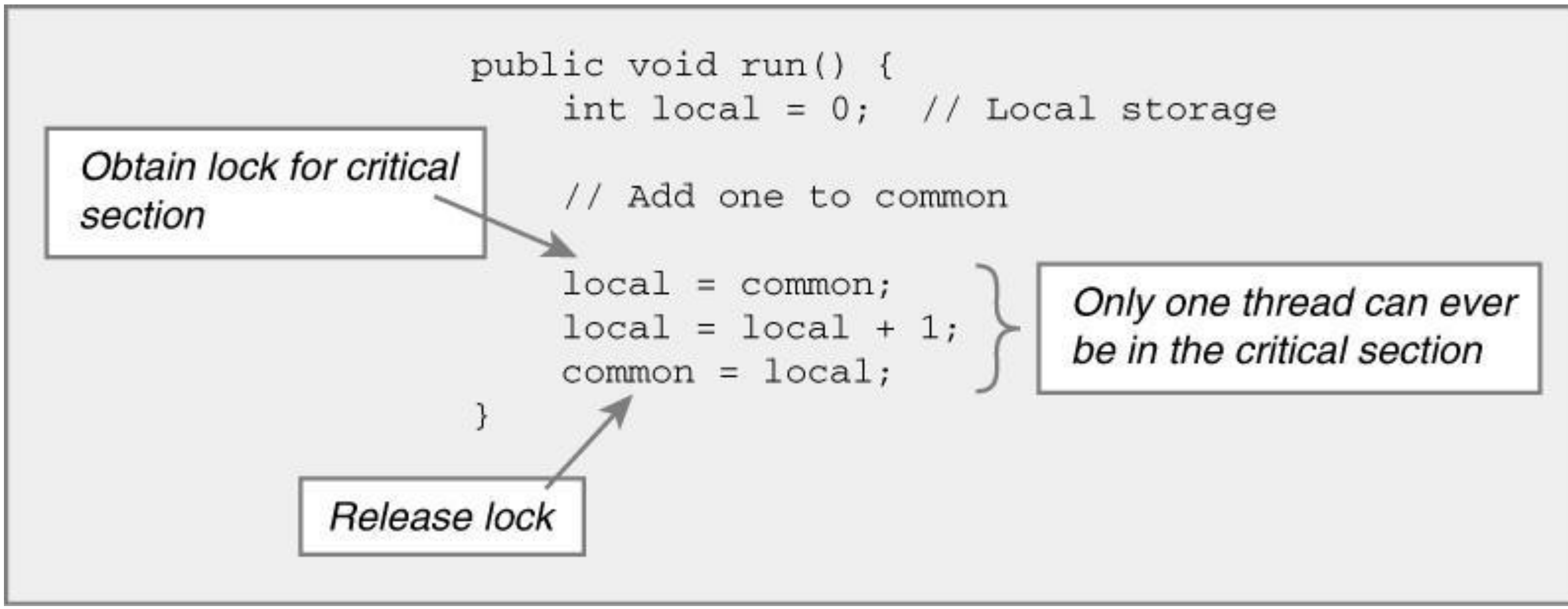
Synchronized Objects in Java

- 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

```
Object x = new Object();
synchronized(x) {      // acquire lock on x on entry
   ...                 // hold lock on x in block
}                      // release lock on x on exit
```

block

Fixing Data Race In Our Example



Lock Example

```
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 $\Rightarrow$ 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

block

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

Synchronized Methods In Java

```
public synchronized void enqueue( Object item ) {

   // Body of method goes here

}
```

Shorthand notation for

```
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
  - Version1 → 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**

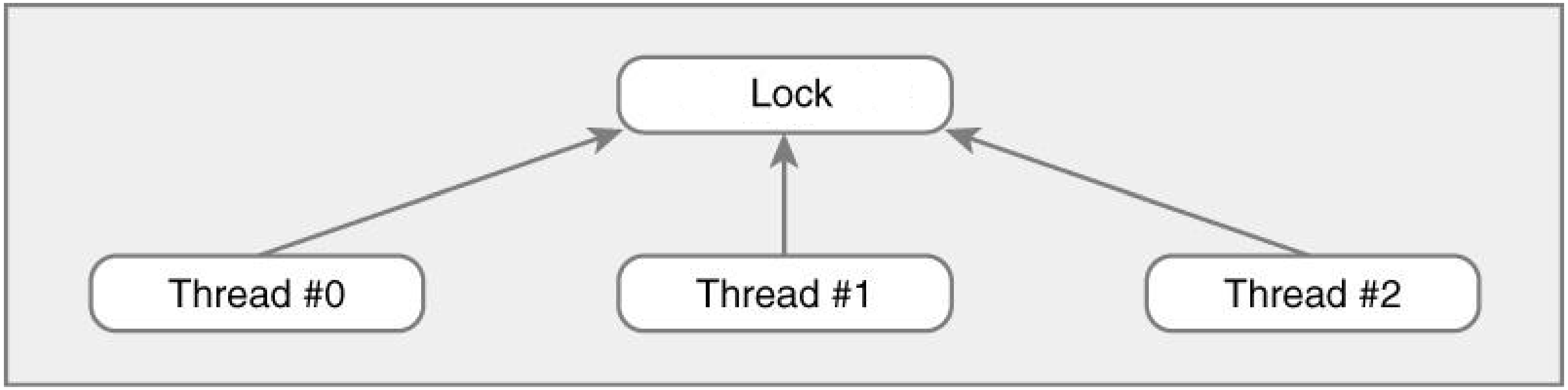
Issue 1) Using Same Lock

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

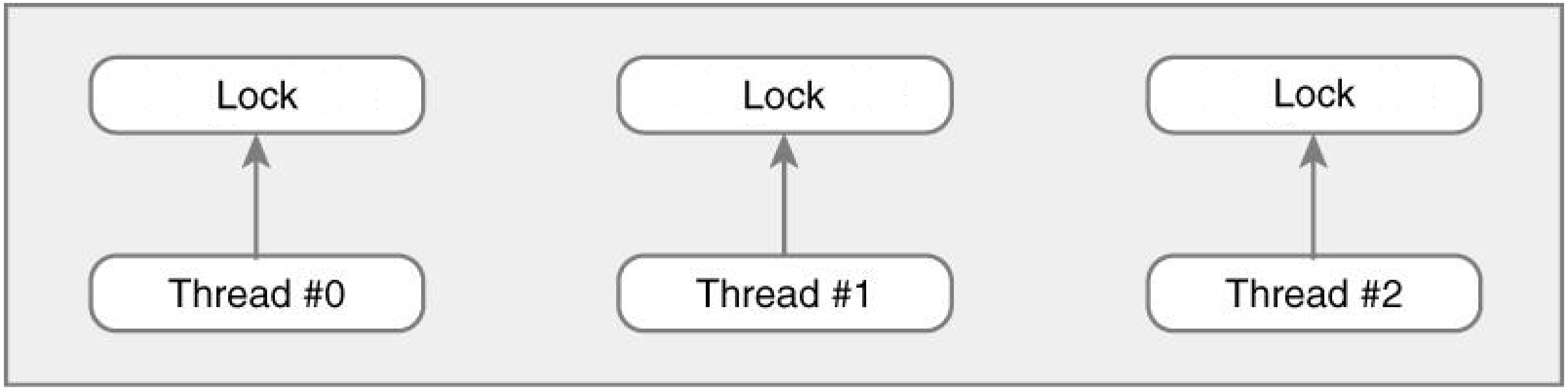
```
foo() {
    Object o = new Object(); // different o per thread
    synchronized(o) {
        … // potential data race
    }
}
```

Locks in Java

- **Single lock for all threads (mutual exclusion)**



- **Separate locks for each thread (no synchronization)**



Lock Example – Incorrect Version

```
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**

```
synchronized(o) {
   int local = common;     // all 3 statements must
   local = local + 1;      // be executed together
   common = local;         // by single thread
}
```

Lock Example – Incorrect Version

```
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;
        }                               // transaction not atomic
        synchronized(o) {               // data race may occur
            local = local + 1;          // even using locks
            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) {
         …
      }
   }
}
```

```
Thread2() {
   synchronized(b) {
      synchronized(a) {
         …
      }
   }
}
```

// Thread1 holds lock for a, waits for b
// Thread2 holds lock for b, waits for a

Deadlock Example 2

```
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^{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