CMSC 433 – Programming Language Technologies and Paradigms

Thread Safety

Thread Safety

- Scheduler can interleave or overlap threads arbitrarily
- Data can be shared by threads
- Can lead to *interference*
  - Storage corruption
  - Violation of representation invariant
  - Violation of a protocol (e.g., *A* occurs before *B*)

Example

```
public class Example extends Thread {
  private static int count = 0;  // shared state
  public void run() {
    int y = count;
    count = y + 1;
  }
  public static void main(String args[]) {
    Thread t1 = new Example();
    Thread t2 = new Example();
    t1.start();
    t2.start();
  }
}
```

Example

```
static int count = 0;
t1.run() {
  int y = count;
  cnt = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state count = 0

Start: both threads ready to run. Each will increment the global count.

Example

```
static int count = 0;
t1.run() {
  int y = count;
  cnt = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state count = 0

y = 0

T1 executes, grabbing the global counter value into y.

Example

```
static int count = 0;
t1.run() {
  int y = cnt;
  count = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state

count = 1

y = 0

T1 executes again, storing the counter value

Example

```
static int count = 0;
t1.run() {
  int y = count;
  count = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state count = 1

y = 0

y = 1

T1 finishes. T2 executes, grabbing the global
counter value into y.

Example

```
static int count = 0;
t1.run() {
  int y = count;
  count = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state **count = 2**

y = 0

y = 1

T2 executes, storing the incremented count value.

But When I Run it Again?

Example

```
static int count = 0;
t1.run() {
  int y = count;
  cnt = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state count = 0

Start: both threads ready to run. Each will increment the global count.

Example

```
static int count = 0;
t1.run() {
  int y = count;
  count = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state count = 0

y = 0

T1 executes, grabbing the global counter value into y.

Example

```
static int count = 0;
t1.run() {
  int y = count;
  count = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state count = 0

y = 0

y = 0

T1 is pre-empted. T2 executes, grabbing the global counter value into y.

Example

```
static int count = 0;
t1.run() {
  int y = count;
  count = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state **count = 1**

y = 0

y = 0

T2 executes, storing the incremented cnt value.

Example

```
static int count = 0;
t1.run() {
  int y = count;
  count = y + 1;
}
t2.run() {
  int y = count;
  count = y + 1;
}
```

Shared state **count = 1**

y = 0

y = 0

T2 completes. T1 executes again, storing the old counter value (1) rather than the new one (2)!

What Happened?

- The code read the counter value & then increments that value by one
- In the first example, **t1** was preempted after it read the counter but before it stored the new value.
- When t1 resumed, it updated a stale value
- This is an example of a *data race*

Data Races & Race Conditions

- A *data race* occurs when two concurrent threads access a shared variable
  - at least one access is a write and
  - the threads use no explicit mechanism to prevent the accesses from being simultaneous
- A *race condition* occurs when a program's correctness unexpectedly depends on the ordering of events

Question

- If instead of writing

```
int y = cnt;
cnt = y+1;
```

- We had written
  - `cnt++;`
- Would the result be any different?
- Answer: NO!
  - ++ operation is just a syntactic shorthand for the two operations above

Question

- If you run a program with a race condition, will you always get an unexpected result?
  - No! It depends on the scheduler
  - ...i.e., which JVM you're running
  - ...and on the other threads/processes/etc. that are running on the same CPU
- Schedule-driven problems are hard to reproduce

Atomicity

- A particular way in which the execution of two threads is interleaved is called a schedule
- We want to prevent undesirable schedules such as those shown in the counting example

Atomicity

- One way to prevent undesirable schedules is to ensure that the code in the two threads is *atomic*
  - Operations A and B are **atomic** with respect to each other if, from the perspective of the thread executing A, when another thread executes B, either all of B has executed or none of it has.
  - An **atomic operation** is one that is atomic with respect to all operations, including itself, that operate on the same state.

Locks

- Commonly used to enforce atomicity
  - Descends from semaphore construct in OS research & design
- Only one thread can hold a lock
  - Other threads block until they can acquire it
  - The operation of acquiring a lock is atomic
    - Cannot have a race on lock operations themselves!
- In Java every Object has (can act as) a lock
  - Called an *intrinsic lock*

Synchronized Statement

- **synchronized (obj)** { *statements* }
  - Acquires (*locks*) the **obj** intrinsic lock before executing statements in block
  - Releases (*unlocks*) the lock when the statement block completes, whether due to a break, return, exception, etc.

Avoiding Interference: Synchronization

```
public class Example extends Thread {
  private static int count = 0;
  static Object lock = new Object();
  public void run() {
    synchronized (lock) {
      int y = count;
      count = y + 1;
    }
  }
  …
}
```

***Lock**, for protecting the shared state*

***Acquires** the lock; Only succeeds if not held by another thread*

***Releases** the lock*

Applying Synchronization

```
int cnt = 0;
t1.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
```

Shared state count = 0

T1 acquires the lock

Applying Synchronization

```
int count = 0;
t1.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
```

y = 0

Shared state count = 0

T1 reads count into y

Applying Synchronization

```
int count = 0;
t1.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
```

y = 0

Shared state count = 0

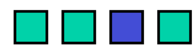
T1 is pre-empted. T2 attempts to acquire the lock but fails because it's held by T1, so it blocks

Applying Synchronization

```
int count = 0;
t1.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
```

y = 0

Shared state **count = 1**



T1 runs, assigning to count

Applying Synchronization

```
int count = 0;
t1.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
```

y = 0

Shared state count = 1

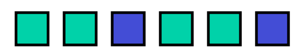
T1 releases the lock and terminates

Applying Synchronization

```
int count = 0;
t1.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
t2.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;
  }
}
```

y = 0

Shared state count = 1

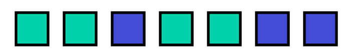


T2 now can acquire the lock.

Applying Synchronization

```
int count = 0;
t1.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;        y = 0
  }
}
t2.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;        y = 1
  }
}
```

Shared state count = 1

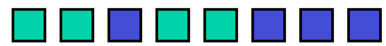


T2 reads count into y.

Applying Synchronization

```
int count = 0;
t1.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;        y = 0
  }
}
t2.run() {
  synchronized(lock) {
    int y = count;
    count = y + 1;        y = 1
  }
}
```

Shared state **count = 2**



T2 assigns count, then releases the lock

More on Locks

- Intrinsic locks are reentrant
  - The thread can reacquire the same lock many times
  - Lock is released when object unlocked the corresponding number of times
- No way to *attempt* to acquire an intrinsic lock
  - Either succeeds, or blocks the thread
  - Java 1.5 java.util.concurrent.locks package added separate locks with more operations (will discuss these later in the semester)

Synchronized Methods

- A method can be synchronized
  - Add **synchronized** modifier before return type
- Obtains the lock on object referenced by **this** before executing method
  - Releases lock when method completes
- For a **static synchronized** method
  - Locks the **Class** object for the class
    - Accessible directly, e.g. **Foo.class**

Synchronization Style

- Internal sync. (class is thread-safe)
  - Have a stateful object synchronize itself (e.g., with synchronized methods). Robust to threaded callers
  - E.g., class Math.Random
- External sync. (class is thread-compatible)
  - Have callers perform synchronization before calling the object
  - If they don't, behavior may be unpredictable

Thread-safe : State

```
public class State {
  private int count = 0;
  public int synchronized incCount(int x) {
    count += x;
  }
  public int synchronized getCount() { return count; }
}
public class MyThread extends Thread {
  State s;
  public MyThread(State s) { this.s = s; }
  public void run() {
    s.incCount(1);
  }
  public void main(String args[]) {
    State s = new State();
    MyThread thread1 = new MyThread(s);
    MyThread thread2 = new MyThread(s);
    thread1.start(); thread2.start();
  }
}
```

Synchronization occurs in State object itself, rather than in its caller.

Thread Compatible: ArrayList

```
public class MyThread extends Thread {
  static List l = new ArrayList();
  String s; // set in constructor
  void add(String s) {
    synchronized (l) { l.add(s); }}

  boolean check(String s) {
    synchronized (l) {
  return l.contains(s);
}}
  public void run() {
    if (!check(s))add(s);
  }
  public void main(String args[]) {
    MyThread thread1 = new MyThread("hello");
    MyThread thread2 = new MyThread("hello");
    MyThread thread3 = new MyThread("goodbye");
    thread1.start(); thread2.start();thread3.start();
  } }
```

Synchronization occurs in the caller of ArrayList (which is MyThread), not ArrayList itself.

Lack of data races = atomicity?

- For the previous example:
  - Are there any data races?
  - Are there any race conditions?
- What will value will the static variable l have at the end of an execution?

Answer

- There are no data races
  - All accesses are synchronized
- There is a race condition
  - Race condition caused by a violation of atomicity.
  - We expect the output to be { “hello”, “goodbye” }
  - But in fact it could also be { “hello”, “hello”, “goodbye” }

Compound Actions

- This is an example of a compound action
  - A sequence of operations that need to be atomic
- Common examples
  - Read-modify-write
  - Check-then-act

Thread-Compatible class fixed

```
public class MyThread extends Thread {
  static List l = new ArrayList();
  String s;
  public void run() {
    synchronized (l) {
       if (!l.contains(s))
         l.add(s);
    }
  }

  public void main(String args[]) {
    MyThread thread1 = new MyThread("hello");
    MyThread thread2 = new MyThread("hello");
    MyThread thread3 = new MyThread("goodbye");
    thread1.start(); thread2.start();
    thread3.start();
  }
}
```

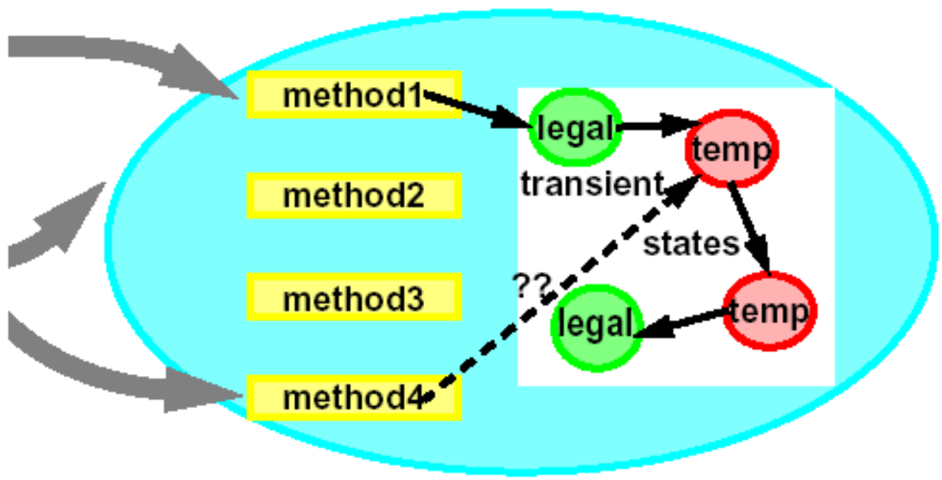
Both contains() and add() are now guarded by a single synchronized block, making them atomic

String class

- Is the String class thread-safe or thread-compatible?
  - Fact: none of its methods are annotated with the keyword “synchronized”
- It’s thread-safe, since callers don’t need to do additional synchronization
- String objects are immutable, so they can be freely shared across threads

Concurrency Rule of Thumb

- Perform actions only when in consistent states
  - Don't want one thread to access an object while another thread is modifying its internal state.



- This boils down to ensuring *object invariants* in the face of concurrent access

A Thread-Safe Multi-Threaded Logging Server

- Logging server
  - Accepts records from client
  - Creates a thread that writes the record to client-specific file
- Organization
  - Utils
    - DataRecord.java
    - LockingMsgHandler.java
  - Client
    - ClientSimulator.java
  - Server
    - LoggingServerCore.java
    - ThreadSafeMultiThreadedServer.java

Let's Look at the Code

- Project
  - SafeMultiThreadedLoggingServer

Ungraded Assignment

- Download the code
- Read and understand how it works
- Run this code and observe its performance
  - Does this code fix the problems you saw in the MultiThreadedServer's behavior?
  - How does this code perform relative to the MultiThreadedServer?
  - What might account for any performance differences?