CS 455: Introduction to Distributed Systems

[Threads]

Threads block when they can't get that lock
Wanna have your threads stall?
Go ahead, synchronize it all
The antidote to this liveness pitfall?
Keeping the lock scope small

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Topics covered in this lecture

- Data synchronization
- Synchronized blocks
- Lock fairness
- Wait-notify
Heisenbugs

- Term coined by ACM Turing Award winner Jim Gray
  - Pun on the name of Werner Heisenberg
  - Act of observing a system, alters its state!
- Describes a particular class of bugs
  - Those that disappear or change behavior when you try to examine them
- Multithreaded programs are a common source of Heisenbugs

What about regular bugs?

- Sometimes referred to as Bohr bugs
  - Deterministic
  - Generally much easier to diagnose
Two friends plan to meet at Starbucks
But there are two Starbucks on College Avenue

<table>
<thead>
<tr>
<th>Time</th>
<th>@ the First Starbucks Store</th>
<th>@ the Second Starbucks Store</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:10</td>
<td>A is looking for friend B</td>
<td>B is looking for friend A</td>
</tr>
<tr>
<td>12:15</td>
<td>A leaves for the second store</td>
<td>B leaves for the first store</td>
</tr>
<tr>
<td>12:20</td>
<td>B arrives at store</td>
<td>A arrives at store</td>
</tr>
<tr>
<td>12:30</td>
<td>B is Looking for friend A</td>
<td>A is looking for friend B</td>
</tr>
<tr>
<td>12:40</td>
<td>B leaves for the second store</td>
<td>A leaves for the first store</td>
</tr>
</tbody>
</table>

Both friends are now frustrated and undercaffeinated!

DATA SYNCHRONIZATION
Why sharing data between threads is problematic

- **Race conditions**

- Threads attempt to access data more or less *simultaneously*
  - A thread may change the value of data that some other thread is operating on

Example code with race condition

```java
public class MyThread extends Thread {
    private byte[] values;
    private int position;

    public void modifyData(byte[] newValues, int newPosition) {
        ... Modify values and position
    }

    public void utilizeDataAndPerformFunction() {
        ... Use values and position
    }

    public void run() {
        ... Main logic
    }
}
```
In the previous snippet a race condition exists because ...

- The thread that calls `modifyData()` is accessing the same data as the thread that calls `utilizeDataAndPerformFunction()`.
- `utilizeDataAndPerformFunction()` and `modifyData()` are not atomic.
  - It is possible that values and position are changed while they are being used.

What is atomic?

- The code cannot be interrupted during its execution.
  - Accomplished in hardware or simulated in software.
- Code that cannot be found in an intermediate state.
Eliminating the race condition using the synchronized keyword

- If we declared both modifyData() and utilizeDataAndPerformFunction() as synchronized?
  - Only one thread gets to call either method at a time
    - Only one thread accesses data at a time
  - When one thread calls one of these methods, while another is executing one of them?
    - The second thread must wait

Example code with no race conditions by using the synchronized keyword

```java
public class MyThread extends Thread {
    private byte[] values;
    private int position;

    public void synchronized modifyData(byte[] newValues, int newPosition) {
        ... Modify values and position
    }

    public void synchronized utilizeDataAndPerformFunction() {
        ... Use values and position
    }

    public void run() {
        ... Main logic
    }
}
```
Revisiting the mutex lock

- Mutually exclusive lock
- If two threads try to grab a mutex?
  - Only one succeeds
- In Java every object has an associated lock

When a method is declared synchronized ...

- The thread that wants to execute the method must acquire a lock
- Once the thread has acquired the lock?
  - It executes method and releases the lock
- When a method returns, the lock is released
  - Even if the return is because of an exception
Locks and objects

- There is only **one lock per object**
- If two threads call synchronized methods of the same object?
  - Only one can execute immediately
  - The other has to wait until the lock is released

Another code snippet to look at ...

```java
public class MyThread extends Thread {
    private boolean done = false;

    public void run() {
        while (!done) {
            ... Main logic
        }
    }

    public void setDone(boolean isDone) {
        done = isDone;
    }
}
```
Can’t we just synchronize the two methods as we did previously?

- If we synchronized both `run()` and `setDone()`?
  - `setDone()` would never execute!

- The `run()` method does not exit until the done flag is set
  - But the done flag cannot be set because `setDone()` cannot execute till `run()` completes

- Uh oh …

The problem stems from the scope of the lock

- **Scope of a lock**
  - Period between grabbing and releasing a lock

- Scope of the `run()` method is too large!
  - Lock is grabbed and never released

- We will look at techniques to *shrink the scope* of the lock

- But let’s look at another solution for now
Let’s look at operations performed on the data item (done)

- The `setDone()` method stores a value into the flag
- The `run()` method reads the value

In our previous example:
- Threads were accessing *multiple* pieces of data
- No way to update multiple data items *atomically* without the synchronized keyword

But Java specifies that the loading and storing of variables is atomic

- Except for long and double variables
- The `setDone()` should be atomic
  - The `run()` method has only one read operation of the data item
- The race condition should *not* exist
  - But why is it there?
Threads are allowed to hold values of variables in registers

- When one thread changes the value of the variable?
  - Another thread may not see the changed variable

- This is particularly true in loops controlled by a variable
  - Looping thread loads value of variable in register and does not notice when value is changed by another thread

Two approaches to solving this

- Providing setter and getter methods for variable and using the synchronized keyword
  - When lock is acquired, temporary values stored in registers are flushed to main memory

- The volatile keyword
  - Much cleaner solution
If a variable is marked as volatile

- Every time it is used?
  - Must be read from main memory
- Every time it is written?
  - Must be written to main memory
- Load and store operations are atomic
  - Even for long and double variables

Some more about volatile variables

- Prior to JDK 1.2 variables were always read from main memory
  - Using volatile variables was moot
- Subsequent versions introduced memory models and optimizations
Synchronization and the volatile keyword

- Can be used *only* when operations use a **single load and store**
  - Operations like `++`, `--`?
  - Load-change-store …

- The **volatile** keyword forces the JVM to not make temporary copies of a variable

- Declaring an array **volatile**?
  - The reference becomes volatile
  - The individual elements are not volatile
Synchronizing methods

- **Not possible** to execute the same method in one thread while ...
  - Method is running in another thread

- If two different synchronized methods in an object are called?
  - They both require the lock of the same object

- Two or more synchronized methods of the same object can never run in parallel in separate threads

A lock is based on a specific instance of an object

- Not on a particular method or class

- Suppose we have 2 objects: objectA and objectB with synchronized methods modifyData() and utilizeData()

- One thread can execute objectA.modifyData() while another executes objectB.utilizeData() in parallel
  - Two different locks are grabbed by two different threads
  - No need for threads to wait for each other
How does a synchronized method behave in conjunction with an unsynchronized one?

- Synchronized methods try to grab the object lock
  - Only 1 synchronized method in a object can run at a time ... provides data protection

- Unsynchronized methods
  - Don’t grab the object lock
  - Can execute at any time ... by any thread
    - Regardless of whether a synchronized method is running

For a given object, at any time ... 

- Any number of unsynchronized methods may be executing

- But only 1 synchronized method can execute
Synchronizing static methods

- A lock can be obtained for each class
  - The **class lock**

- The class lock is the **object lock** of the **Class object** that models the class
  - There is only 1 **Class object** per class
  - Allows us to achieve synchronization for static methods

Object locks and class locks

- Are **not operationally related**

- The class lock can be grabbed and released **independently** of the object lock

- If a non-static synchronized method calls a static synchronized method?
  - It acquires both locks
EXPLICIT LOCKING

The synchronized keyword

- Serializes accesses to synchronized methods in an object
- Not suitable for controlling lock scope in certain situations
- Can be too primitive in some cases
Many synchronization schemes in J2SE 5.0 onwards implement the Lock interface

- Two important methods
  - `lock()` and `unlock()`

- Similar to using the synchronized keyword
  - Call `lock()` at the start of the method
  - Call `unlock()` at the end of the method

- Difference: we have an actual object that represents the lock
  - Store, pass around, or discard

Semantics of the using Lock

- If another thread owns the lock
  - Thread that attempts to acquire the lock must wait until the other thread calls `unlock()`

- Once the waiting thread acquires the lock, it returns from the `lock()` method
Using the Lock interface

```java
public class DataOperator {
  private Lock dataLock = new ReentrantLock();
  public void modifyData(byte[] newValues, int newPosition) {
    try {
      dataLock.lock();
      ... Modify values and position
    } finally {
      dataLock.unlock();
    }
  }
  public void utilizeDataAndPerformFunction() {
    try {
      dataLock.lock();
      ... Use values and position
    } finally {
      dataLock.unlock();
    }
  }
}
```

Advantages of using the Lock interface

- Grab and release locks *whenever* we want
- Now possible for *two objects to share the same lock*
  - Lock is no longer attached to the object whose method is being called
- Can be *attached to data, groups of data*, etc.
  - Not objects containing the executing methods
Advantages of explicit locking

- We can move them anywhere to **adjust lock scope**
  - Can span from a line of code to a scope that encompasses multiple methods and objects

- Lock at scope **specific to problem**
  - Not just the object

**Synchronized Blocks**
Much of what we accomplish with the Lock we can do so with the synchronized keyword

```java
public class DataOperator {
    public void modifyData(byte[] newValues, int newPosition) {
        synchronized(this) {
            ... Modify values and position
        }
    }

    public void utilizeDataAndPerformFunction() {
        synchronized(this) {
            ... Use values and position
        }
    }
}
```

Synchronized methods vs. Synchronized Blocks

- Possible to use only the synchronized block mechanism to synchronize whole method
- You decide when it's best to synchronize a block of code or the whole method
- **RULE:** Establish as small a lock scope as possible
The Lock interface [java.util.concurrent.locks]

```java
class Lock {
    public void lock();
    public void lockInterruptibly()
        throws InterruptedException;
    public boolean tryLock();
    public boolean tryLock(long time, TimeUnit unit)
        throws InterruptedException;
    public void unlock();
    public Condition newCondition();
}
```

Lock Fairness

- ReentrantLock allows locks to be granted **fairly**
  - Locks are granted as close to arrival order as possible
  - Prevents lock starvation from happening

- Possibilities for granting locks
  1. First-come-first-served
  2. Allows servicing the maximum number of requests
  3. Do what's best for the platform
Objects and communications

- Every object has a lock
- Every object also includes mechanisms that allow it to be a waiting area
  - Allows communication between threads
Conditions

- One thread needs a **condition** to exist
  - Assumes another thread will *create* that condition

- When another thread creates the condition?
  - It *notifies* the first thread that has been *waiting* for that condition

```java
public class Object {
    public void wait();
    public void wait(long timeout);
    public void notify();
}
```
wait(), notify() and the Object class

- Wait-and-notify mechanisms are available for every object
  - Accomplished by method invocations
- Synchronized mechanism is handled by using a keyword

Wait-and-notify relate to synchronization, but …

- It is more of a communications mechanism
- Allows one thread to communicate to another that a condition has occurred
  - Does not specify what that specific condition is
Can wait-and-notify replace the synchronized mechanism?

- No
- Does not solve the race condition that the synchronized mechanism solves
- Must be used in conjunction with the synchronized lock
  - Prevents race condition that exists in the wait–notify mechanism itself

A code snippet that uses wait-notify to control the execution of the thread

```java
public class Tester implements Runnable {
    private boolean done = true;

    public synchronized run() {
        while (true) {
            if (done) wait();
            else { /* Logic */ wait(100); }
        }
    }

    public synchronized void setDone(boolean b) {
        done = b;
        if (!done) notify();
    }
}
```
About the `wait()` method

- When `wait()` executes, the synchronization lock is *released*
  - By the JVM

- When a notification is received?
  - The thread needs to *reacquire* the synchronization lock before returning from `wait()`

Integration of `wait-notify` and synchronization

- **Tightly integrated** with the synchronization lock
  - Feature *not directly available to us*
  - Not possible to implement this: native method

- This is typical of approach in other libraries
  - *Condition variables* for Solaris and POSIX threads require that a mutex lock be held
Details of the race condition in the wait-notify mechanism

- The first thread **tests the condition** and confirms that it must wait
- The second thread **sets the condition**
- The second thread calls **notify()**
  - This **goes unheard** because the first thread is not yet waiting
- The first thread calls **wait()**

How does the potential race condition get resolved?

- To call **wait()** or **notify()**
  - Obtain lock for the object on which this is being invoked
- It seems as if the lock has been held for the entire **wait()** invocation, but ...
  1. **wait()** releases lock prior to waiting
  2. Reacquires the lock just before returning from **wait()**
Is there a race condition during the time `wait()` releases and reacquires the lock?

- `wait()` is **tightly integrated** with the lock mechanism
- Object lock is **not freed until** the waiting thread is in a **state in which it can receive notifications**
  - System prevents race conditions from occurring here

If a thread receives a notification is it guaranteed that condition is set?

- No
- **Prior** to calling `wait()`, **test condition** while holding lock
- Upon **returning** from `wait()` **retest** condition to see if you should `wait()` again
What if `notify()` is called and no thread is waiting?

- Wait-and-notify mechanism has no knowledge about the condition about which it notifies.
- If `notify()` is called when no other thread is waiting?
  - The notification is lost.

What happens when more than 1 thread is waiting for a notification?

- Language specification does not define which thread gets the notification.
  - Based on JVM implementation, scheduling and timing issues.
- *No way to determine* which thread will get the notification.
notifyAll()

- All threads that are waiting on an object are notified
- When threads receive this, they must work out
  1. Which thread should continue
  2. Which thread(s) should call `wait()` again
     - All threads wake up, but they **still have to reacquire the object lock**
     - Must wait for the lock to be freed

The contents of this slide-set are based on the following references