Intro to Concurrency and Concurrency in Java

Read: Scott, Chapter 13.1-13.2

Announcements

- Check your Rainbow grades
  - Exam 1-2, Quiz 1-7, HW 1-5
- Let me know if you see anything amiss

Lecture Outline

- Intro to Concurrency

- Our focus: concurrency in Java
  - Threads
  - Synchronized blocks
  - The **`Executor`** framework
  - What can go wrong with threads?

Concurrency

- Concurrent program
  - Any program is concurrent if it may have more than one active execution context --- more than one “thread of control”
- Concurrency is everywhere
  - A multithreaded web browser
  - An IDE which compiles while we edit
- Significant interest in concurrency in programming languages

Concurrency and Parallelism

- Concurrent characterizes a system in which two or more tasks **may be** underway (at any point of their execution) at the same time

- A concurrent system is parallel if more than one task can be physically active at once
  - This requires more than one processor

Multiprocessor Machines

- Two broad categories of parallel architectures

- Shared-memory machines
  - Those in which processors share common memory

- Non-shared-memory machines
  - Those in which processors must communicate with messages

Aside: What Exactly is a Processor?

- For 30+ years, it used to be the single chip with a CPU, cache and other components

- Now, it can mean a single "device" with multiple chips; each chip can have multiple cores; each core can have multiple hardware threads. Also, subsets of the cores can share different levels of cache

Aside: What Exactly is a Processor?

- OS and programming languages abstract away hardware complexity
- For us, programmers, ”processor” means a task/thread of computation
  - Or the hardware that runs thread of computation
- But as we saw many times in this class, abstraction (i.e., improved programmability) comes at a cost

Fundamentals of Concurrent Programming

- Two programming models for concurrency
  - Shared memory
  - Message passing

Fundamentals of Concurrent Programming

- Shared memory
  - Some program variables are accessible to multiple threads --- threads access shared state
  - Threads communicate (interact) through shared state
- E.g., producer and consumer threads
  - Share buffer in memory
  - “Win” from concurrency
    - Consumer thread operates on data at the same time
    - Producer thread produces next data item

Fundamentals of Concurrent Programming

- Message passing
  - Threads have no shared state
  - One thread performs explicit send to transmit data to another
- Similarly, producer and consumer thread
  - Producer sends data as a message
  - “Win” from concurrency

Fundamentals of Concurrent Programming

- Communication
  - Refers to mechanism that allows one thread to obtain information produced by another thread
  - Explicit in message passing models
  - Implicit in shared memory models

- Synchronization
  - Refers to mechanism that allows the programmer to control the relative order of operations that occur
  - Implicit in message passing models
  - Explicit in shared memory models

Shared Memory Model

- Programming language support for the shared memory model
  - Explicit support for concurrency
    - E.g., Java, C#, Rust: explicit threads, locks, synchronization, etc.
  - Libraries
    - C/C++: The POSIX **#include <pthreads.h>**
    - Many types, macros and routines for threads, locks, other synchronization mechanisms
- We will take a closer look at Java

Lecture Outline

- Intro to Concurrency

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  - The **`Executor`** framework
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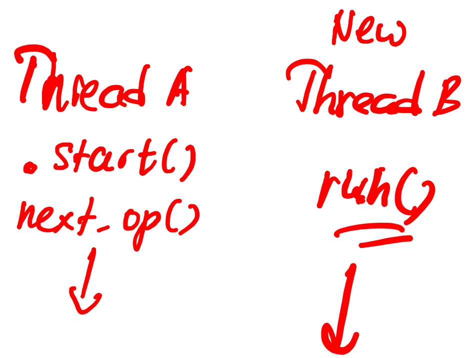
Threads

- Java has explicit support for multiple threads
- Two ways to create new threads:
  - Extend **`java.lang.Thread`**
    - Override "**`run()`**" method
  - Implement **`Runnable`** interface
    - Include a "**`run()`**" method in your class
- Starting a thread
  - **`new MyThread().start();`**
  - **`new Thread(runnable).start();`**
- Abstracted away by **`Executor`** framework



Terminology

- Concurrent programming with shared memory is about managing shared mutable state
  - Shared state – memory locations that can be accessed by multiple threads
  - Mutable state – the value of a location could change during its lifetime
- Atomic action – action that executes on the machine as a single indivisible operation
  - E.g., read the value of variable `i` is atomic
  - E.g., write the value of variable `i` is atomic
  - E.g., `i++` is not atomic

What Can Go Wrong?

```
class Account {
  int balance = 0;
  void deposit (int x) {
    this.balance = this.balance + x;
  }
}

class AccountTask implements Runnable {
  public void run() {
    Main.act.deposit(10);
  }
}

public class Main {
  static Account act = new Account();
  public static void main(String args[]) {
    new Thread(new AccountTask()).start();  // Thread A
    new Thread(new AccountTask()).start();  // Thread B
  }
}
```

Account object is shared mutable state.

What Can Go Wrong?

Thread A:

1. `r1 = act.balance`

`r1 += 10`

2. `act.balance = r1`

Thread B:

3. `r2 = act.balance`

`r2 += 10`

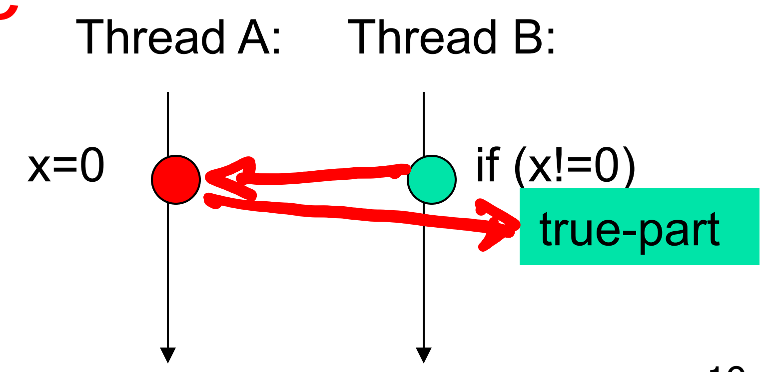
4. `act.balance = r2`

1. → 2. → 3. → 4. ✓ OK

1. → 3. → 2. → 4. ✗ NOT OK.

A Common Bug: Race Condition

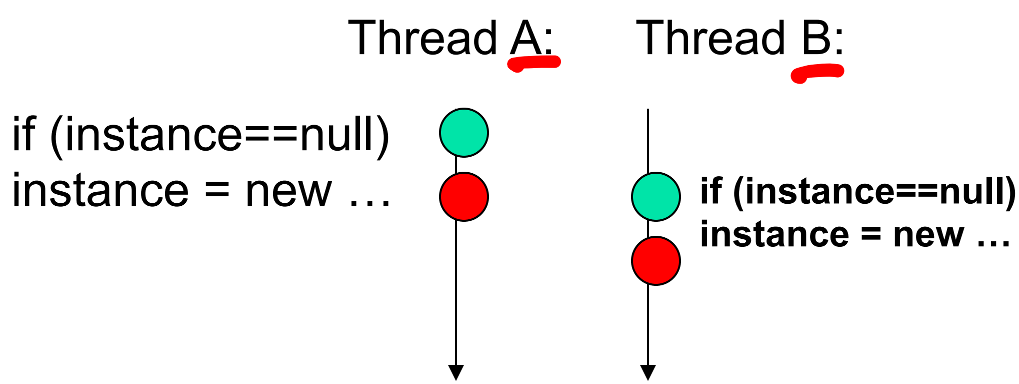
- New types of bugs occur in concurrent programs; race conditions are the most common
- A data race (a type of race condition) occurs when two threads can access the same memory location "simultaneously" and at least one access is a write



A common bug: Race Condition

- Check-and-act data race (common data race)

```
public class LazyInitRace {
    private ExpensiveObject instance = null;
    public ExpensiveObject getInstance() {
      if (instance == null)
        instance = new ExpensiveObject();
      return instance;
    }
}
```



The two callers (in thread A and thread B) could receive <u>distinct instances</u> although there should be only one instance

`synchronized` Block

- One mechanism to control the relative order of thread operations and avoid race conditions, is the synchronized block

- Use of **`synchronized`**:

`lock` is a reference to an object

```
synchronized ( lock ) {
   // Read and write of shared state
}
```

Critical section

`synchronized` Method

- One can also declare a method as synchronized:

```
synchronized int m(String x) {
 // blah blah blah
}
```

equivalent to:

```
int m(String x) {
  synchronized ( this ) {
  // blah blah blah
 }
}
```

`synchronized` Blocks

- Every Java object has a built-in intrinsic lock
- A synchronized block has two parts
  - A reference to an object that serves as the lock
  - Block of code to be guarded by this lock
- The lock serves as a mutex (or mutual exclusion lock)
  - Only one thread can hold the lock
  - If thread B attempts to acquire a lock held by thread A, thread B must wait (or block) until thread A releases the lock

How Do We Make Account "Safe"?

```
class Account {
  int balance = 0;
  void deposit (int x) {
    this.balance = this.balance + x;
  }
}
class AccountTask implements Runnable {
  public void run() {
    Main.act.deposit(10);
  }
}
public class Main {
  static Account act = new Account();
  public static void main(String args[]) {
    new Thread(new AccountTask()).start();   // Thread A
    new Thread(new AccountTask()).start();   // Thread B
  }
}
```

Account object is shared mutable state.

Use Synchronized

- To make Account "safe", make **deposit** **synchronized**
  - `synchronized void deposit(int x) { … }`

this refers to global Account object

Thread A:

```
synchronized (this) {
    r1 = balance
    r1 += 10
    balance = r1
}
```

Thread B:

```
synchronized (this) {
    r2 = balance
    r2 += 10
    balance = r2
}
```

Using Synchronized Blocks

- Synchronized blocks help avoid data races

- Granularity of synchronized blocks
  - Synchronized blocks that are too long (i.e., coarse grained locking) sacrifice concurrency and may lead to slowdown
    - Force sequential execution as threads wait for locks
  - Synchronized blocks that are too short (i.e., fine grained locking) may miss data races!
  - Synchronization can cause deadlock!

Question

- In this code example, does `lock` guarantee that no two threads ever execute the critical section “simultaneously”?

```
synchronized ( lock ) {
    // Read and write of shared state
}
```

Thread A
lock
↓
OK ✓

Thread B
lock
↓
OK ✓

Question

- Sequential code:

```
List data = new ArrayList();
if (!data.contains(p)) {
    data.add(p);
}
```

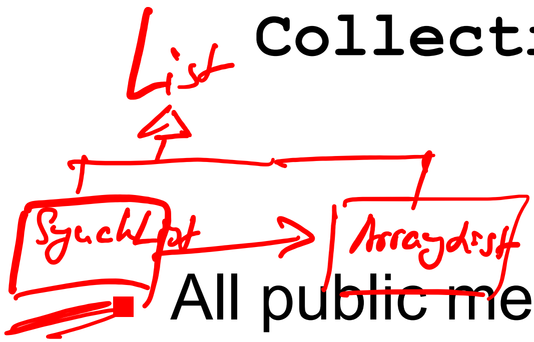
- Concurrent code, **shared mutable state** `data`:

  `List data = new ArrayList()` created in main thread

  - ```
    if (!data.contains(p)) {
        data.add(p);
    }
    ```
    is executed by multiple threads
    ```

Implementing `data` Safely

- One attempt is to use Synchronized Collections (since Java 1.2)
  - Created by **`Collections.synchronizedXYZ`** methods
    - E.g., **`List data = Collections.synchronizedList (new ArrayList());`**



  - All public methods are synchronized on **`this`**
  - Even if `data` is a synchronized List, code still not right. What can go wrong?

Implementing `data` Safely

- Concurrent Collections (since Java 1.5)
  - E.g., `ConcurrentHashMap`
  - Provide additional atomic operations
    - E.g., `putIfAbsent(key, value)`
  - Implement different, more efficient (concurrent) synchronization mechanisms

Lecture Outline

- Intro to Concurrency
- Concurrency in Java
  - Threads
  - Synchronized blocks
  - The `Executor` framework
  - What can go wrong with threads?

Organizing Concurrent Applications

- One way to organize concurrent programs:
  - Organize program into tasks
  - Identify tasks and task boundaries
    - Tasks should be as independent of other tasks as possible
      - Ideally, tasks do not depend on mutable shared state and do not write mutable shared state
      - If there is mutable shared state, tasks should be synchronized appropriately!
    - Each task should be a relatively small portion of the total work

Sequential Task Execution

- Web server

```
public class SingleThreadedWebServer {
 public static void main(String[] args)
                                     throws IOException {
    ServerSocket socket = new ServerSocket(80);
    while (true) {
      Socket connection = socket.accept();
      handleRequest(connection);
    }
 }
}
```

- What problems do you see here?

Explicit Threads for Task Execution

```
public class ThreadPerTaskWebServer {
 public static void main(String[] args)
                                  throws IOException {
   ServerSocket socket = new ServerSocket(80);
   while (true) {
     Socket connection = socket.accept();
     Runnable task = new Runnable() {
        public void run() {
          handleRequest(connection);
        }
      };
     new Thread(task).start();
   }
 }
}
```

The `Executor` Framework

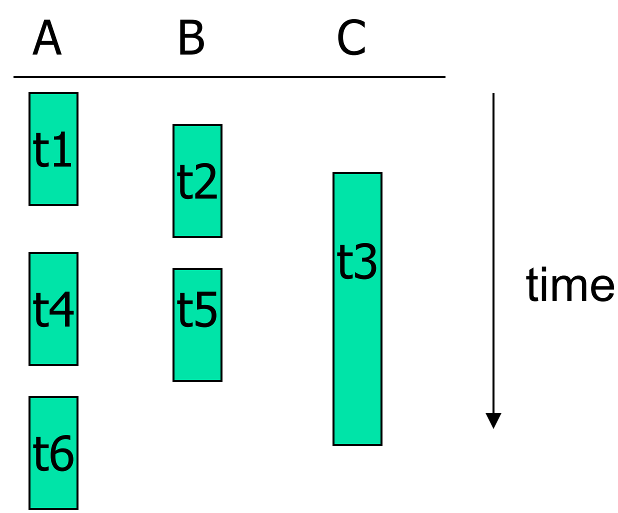
- Part of **`java.util.concurrent`** (Java 1.5)
- Flexible thread pool implementation
  - High-level abstraction: **`Executor`**, not **`Thread`**
  - Decouples task submission from task execution
    - E.g., **`Executor e`** managers a thread pool of 3 threads

e.g., **`Executor e = …`**

```
e.execute(t1);
e.execute(t2);
e.execute(t3);
e.execute(t4);
e.execute(t5);
e.execute(t6);
```

task submission

task execution



Using **Executor** for Task Execution

```
public class TaskExectorWebServer {
 private … Executor e = Excutors.newFixedThreadPool(3);
 public static void main(String[] args)
                             throws IOException {
   ServerSocket socket = new ServerSocket(80);
   while (true) {
      Socket connection = socket.accept();
      Runnable task = new Runnable() {
        public void run() {
            handleRequest(connection);
         }
       };
      e.execute(task); // Task submission,
   }                  // Decoupled from task execution
 }
}
```

So… What Can Go Wrong?

- New types of bugs occur in concurrent programs
  - Race conditions
  - Atomicity violations
  - Deadlocks

- There is nondeterminism in concurrency, which makes reasoning about program behavior extremely difficult

So… What Can Go Wrong?

- Therac 25
- 2003 Northeast blackout:

So… What Can Go Wrong?

- 2003 Northeast blackout:

About eight weeks after the blackout, the bug was unmasked as a particularly subtle incarnation of a common programming error called a "race condition," triggered on August 14th by a perfect storm of events and alarm conditions on the equipment being monitoring. The bug had a window of opportunity measured in milliseconds.

So… What Can Go Wrong?

- 2003 Northeast blackout:

The company did everything it could, says Unum. "We test exhaustively, we test with third parties, and we had in excess of three million online operational hours in which nothing had ever exercised that bug," says Unum. "I'm not sure that more testing would have revealed that. Unfortunately, that's kind of the nature of software...

What Can Go Wrong? Class Vector (Java 1.1's ArrayList)

```
class Vector {
   private Object elementData[];
   private int elementCount;

   synchronized void trimToSize() { … }
   synchronized void removeAllElements() {
      elementCount = 0; trimToSize(); }
   synchronized int lastIndexOf(Object elem, int n) {
     for (int i = n; --i > 0;)
        if (elem.equals(elementData[i])) return i;
     return -1;
   }
   int lastIndexOf(Object elem) {
     int n = elementCount;
     return lastIndexOf(elem, n);
   }
…
}
```

A thread can change element count leaving n a stale value.

What Can Go Wrong? Class Vector (Java 1.1)

There is a data race on `elementCount`:

Thread A:

```
removeAllElements
   elementCount=0
   trimToSize
      …elementData=…
```

Thread B:

```
lastIndexOf(elem)
   n=elementCount
```

```
lastIndexOf(elem,n)
   …elementData[i]…
```

↑

Will raise an exception because `elementData` has been reset by thread A.

What Can Go Wrong?

```
ArrayList seen = new ArrayList(); // seen is shared state
    …
void search(Node node) {
    …
    Runnable task = new Runnable() {
       public void run() {
           …
           synchronized (this) { // synchronize access to seen
             if (!seen.contains(node.pos))
               seen.add(node.pos);
             else return;
           }
           // check if current node is a solution
           …
           // compute legal moves, call search(child)
           …
       }
    };
    e.execute(task);
}
```

"this" refers to the Runnable task object. Nothing prevents the thread to obtain the lock of its task.

What Can Go Wrong? java.lang.StringBuffer (Java 1.4)

```
public final class StringBuffer {
  private int count;
  private char[ ] value;
      .      .
  public synchronized StringBuffer append(StringBuffer sb)
  {
      if (sb == null) sb = NULL;
      int len = sb.length();
      int newcount = count + len;
      if (newcount > value.length) expandCapacity(newcount);
      sb.getChars(0, len, value, count);
      count = newcount;
      return this;
  }


  public synchronized int length( ) { return count; }

  public synchronized void getChars(. . .) { . . . }
}
```

Another thread can "interrupt" here changing sb.length. len will be stale.

What Can Go Wrong? java.lang.StringBuffer (Java 1.4)

- Method **`append`** is not "atomic":

Thread A:

Thread B:

`sb.length()`

`sb.delete(…)`

`sb.getChars()`

Will raise an exception because **`sb's value`** array has been updated by thread B.

Atomicity Violation

- Method **`StringBuffer.append`** is not ”atomic”
- Informally, a method is said to be atomic if its “sequential behavior” (i.e., behavior when method is executed in one step), is the same as its “concurrent behavior” (i.e., behavior when method is interrupted by other threads)
  - A method is atomic if it appears to execute in “one step” even in the presence of multiple threads
- Atomicity is a stronger correctness property than race freedom

Using Synchronization

- Lock-based synchronization helps avoid race conditions and atomicity violations
  - But synchronization can cause deadlocks!
- Lock granularity
  - Synchronized blocks that are too long (i.e., coarse grained locking) sacrifice concurrency and may lead to slow down
    - Force sequential execution as threads wait for locks
  - Synchronized blocks that are too short (i.e., fine grained locking) may miss race conditions!

Concurrent Programming is Difficult

- Concurrent programming is about managing shared mutable state
  - Exponential number of interleavings of thread operations

  - OO concurrency: complex shared mutable state
    - Defense: design principles to reduce complexity
    - Defense: immutable classes, objects, or references
    - Defense: avoid representation exposure

The End