Principles of Software Construction

Concurrency, part 4: In the trenches of parallelism

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institute for SOFTWARE RESEARCH

Administrivia

- Homework 5b due tonight
  - Commit by 9 a.m. tomorrow to be considered as a Best Framework
- Do you want to be a software engineer?

The foundations of the Software Engineering minor

- Core computer science fundamentals
- Building good software
- Organizing a software project
  - Development teams, customers, and users
  - Process, requirements, estimation, management, and methods
- The larger context of software
  - Business, society, policy
- Engineering experience
- Communication skills
  - Written and oral

SE minor requirements

- Prerequisite: 15-214
- Two core courses
  - 15-313 Foundations of SE (fall semesters)
  - 15-413 SE Practicum (spring semesters)
- Three electives
  - Technical
  - Engineering
  - Business or policy
- Software engineering internship + reflection
  - 8+ weeks in an industrial setting, then
  - 17-413

To apply to be a Software Engineering minor

- Email clegoues@cs.cmu.edu
  - Your name, Andrew ID, expected grad date, QPA, and minor/majors
  - Why you want to be a SE minor
  - Proposed schedule of coursework

- Spring applications due by Friday, 08 April 2016
  - Only 15 SE minors accepted per graduating class
- More information at:
  - http://isri.cmu.edu/education/undergrad/

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Key concepts from Thursday

`java.util.concurrent (j.u.c)`

I. Atomic vars: `java.util.concurrent.atomic`
   – Support various atomic read-modify-write ops

II. Locks: `java.util.concurrent.locks`
   – Read-write locks, conditions, etc.

III. Synchronizers
   – Semaphores, cyclic barriers, countdown latches, etc.

IV. Concurrent collections
   – Shared maps, sets, lists

V. Data exchange collections summary

- `BlockingQueue`: Supports blocking operations
  - `ArrayBlockingQueue`, `LinkedBlockingQueue`
  - `PriorityBlockingQueue`, `DelayQueue`
  - `SynchronousQueue`
- `BlockingDeque`: Supports blocking operations
  - `LinkedBlockingDeque`
- `TransferQueue`: `BlockingQueue` in which producers may wait for consumers
  - `LinkedTransferQueue`

Summary of `BlockingQueue` methods

	Throws exception	*Special value*	*Blocks*	*Times out*
Insert	`add(e)`	`offer(e)`	`put(e)`	`offer(e, time, unit)`
Remove	`remove()`	`poll()`	`take()`	`poll(time, unit)`
Examine	`element()`	`peek()`	n/a	n/a

Summary of `BlockingDeque` methods

- First element (head) methods

	Throws exception	*Special value*	*Blocks*	*Times out*
Insert	`addFirst(e)`	`offerFirst(e)`	`putFirst(e)`	`offerFirst(e, time, unit)`
Remove	`removeFirst()`	`pollFirst()`	`takeFirst()`	`pollFirst(time, unit)`
Examine	getFirst()	peekFirst()	n/a	n/a

	Throws exception	*Special value*	*Blocks*	*Times out*
Insert	`addLast(e)`	`offerLast(e)`	`putLast(e)`	`offerLast(e, time, unit)`
Remove	`removeLast()`	`pollLast()`	`takeLast()`	`pollLast(time, unit)`
Examine	getLast()	peekLast()	n/a	n/a

Today: In the trenches of parallelism

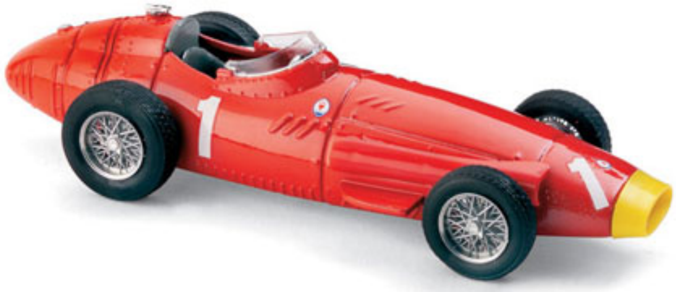
- A high-level view of parallelism
- Concurrent realities
  - …and the j.u.c Executor framework

Puzzler: "Racy Little Number"

```
import org.junit.Test;
import static org.junit.Assert.assertEquals;

public class LittleTest {
   int number;

   @Test
   public void test() throws InterruptedException {
       number = 0;
       Thread t = new Thread(() -> {
          assertEquals(2, number);
       });
       number = 1;
       t.start();
       number++;
       t.join();
   }
}
```



How often does this test pass?

```
import org.junit.Test;
import static org.junit.Assert.assertEquals;

public class LittleTest {
   int number;

   @Test
   public void test() throws InterruptedException {
       number = 0;
       Thread t = new Thread(() -> {
          assertEquals(2, number);
       });
       number = 1;
       t.start();
       number++;
       t.join();
   }
}
```

(a) It always fails

(b) It sometimes passes

(c) It always passes

(d) It always hangs

How often does this test pass?

(a) It always fails

(b) It sometimes passes

(c) It always passes – but it tells us nothing

(d) It always hangs

JUnit doesn't see assertion failures in other threads

Another look

```
import org.junit.*;
import static org.junit.Assert.*;

public class LittleTest {
   int number;

   @Test
   public void test() throws InterruptedException {
       number = 0;
       Thread t = new Thread(() -> {
          assertEquals(2, number); // JUnit never sees the exception!
       });
       number = 1;
       t.start();
       number++;
       t.join();
   }
}
```

How do you fix it? (1)

```
// Keep track of assertion failures during test
volatile Exception exception;
volatile Error error;

// Triggers test case failure if any thread asserts failed
@After
public void tearDown() throws Exception {
    if (error != null)
        throw error;
    if (exception != null)
        throw exception;
}
```

How do you fix it? (2)

```
Thread t = new Thread(() -> {
    try {
        assertEquals(2, number);
    } catch(Error e) {
        error = e;
    } catch(Exception e) {
        exception = e;
    }
});
```

Now it sometimes passes*

*YMMV

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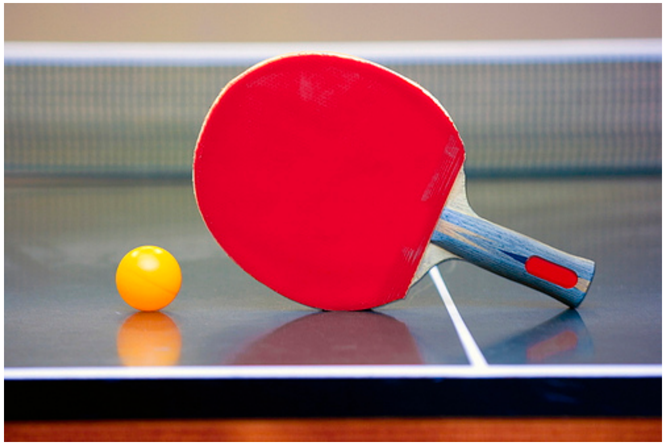
The moral

- JUnit does not support concurrency
- You must provide your own
  - If you don't, you'll get a false sense of security

Puzzler: “Ping Pong”

```
public class PingPong {
    public static synchronized void main(String[] a) {
        Thread t = new Thread(()-> pong() );
        t.run();
        System.out.print("Ping");
    }

    private static synchronized void pong() {
        System.out.print("Pong");
    }
}
```



What does it print?

```
public class PingPong {
    public static synchronized void main(String[] a) {
        Thread t = new Thread(()-> pong() );
        t.run();
        System.out.print("Ping");
    }

    private static synchronized void pong() {
        System.out.print("Pong");
    }
}
```

(a) PingPong

(b) PongPing

(c) It varies

What does it print?

(a) `PingPong`

(b) `PongPing`

(c) It varies

Not a multithreaded program!

Another look

```
public class PingPong {
    public static synchronized void main(String[] a) {
        Thread t = new Thread(()-> pong() );
        t.run();  // An easy typo!
        System.out.print("Ping");
    }

    private static synchronized void pong() {
        System.out.print("Pong");
    }
}
```

How do you fix it?

```
public class PingPong {
    public static synchronized void main(String[] a) {
        Thread t = new Thread(()-> pong() );
        t.start();
        System.out.print("Ping");
    }

    private static synchronized void pong() {
        System.out.print("Pong");
    }
}
```

Now prints PingPong

The moral

- Invoke `Thread.start`, not `Thread.run`
  - Can be very difficult to diagnose
- `java.lang.Thread` should not have implemented `Runnable`
  - …and should not have a public `run` method

Today: In the trenches of parallelism

- A high-level view of parallelism
- Concurrent realities
  - …and the j.u.c Executor framework

Concurrency at the language level

- Consider:

```
Collection<Integer> collection = …;
int sum = 0;
for (int i : collection) {
    sum += i;
}
```

- In python:

```
collection = …
sum = 0
for item in collection:
    sum += item
```

Parallel quicksort in Nesl

```
function quicksort(a) =
  if (#a < 2) then a
  else
   let pivot   = a[#a/2];
       lesser  = {e in a| e < pivot};
       equal   = {e in a| e == pivot};
       greater = {e in a| e > pivot};
       result  = {quicksort(v): v in [lesser,greater]};
   in result[0] ++ equal ++ result[1];
```

- Operations in {} occur in parallel
- 210esque questions: What is the total work? What is the depth?

Prefix sums (a.k.a. inclusive scan)

- Goal: given array `x[0…n-1]`, compute array of the sum of each prefix of x

```
[ sum(x[0…0]),
  sum(x[0…1]),
  sum(x[0…2]),
  …
  sum(x[0…n-1]) ]
```

- e.g., `x =` `[13,  9, -4, 19, -6,  2,  6,  3]`

  prefix sums: `[13, 22, 18, 37, 31, 33, 39, 42]`

Parallel prefix sums

- Intuition: If we have already computed the partial sums `sum(x[0…3])` and `sum(x[4…7])`, then we can easily compute `sum(x[0…7])`
- e.g., `x =     [13,  9, -4, 19, -6,  2,  6,  3]`

Parallel prefix sums algorithm, upsweep

- Computes the partial sums in a more useful manner

```
[13,    9,   -4,   19,   -6,    2,    6,    3]

[13,   22,   -4,   15,   -6,   -4,    6,    9]
```

Parallel prefix sums algorithm, upsweep

- Computes the partial sums in a more useful manner

```
[13,  9, -4, 19, -6,  2, 6, 3]

[13, 22, -4, 15, -6, -4, 6, 9]

[13, 22, -4, 37, -6, -4, 6, 5]
```

Parallel prefix sums algorithm, upsweep

- Computes the partial sums in a more useful manner

```
[13,   9,  -4,  19,  -6,   2,   6,   3]

[13,  22,  -4,  15,  -6,  -4,   6,   9]

[13,  22,  -4,  37,  -6,  -4,   6,   5]

[13,  22,  -4,  37,  -6,  -4,   6,  42]
```

⋮

Parallel prefix sums algorithm, downsweep

- Now unwinds to calculate the other sums

```
[13,   22,   -4,   37,   -6,   -4,    6,   42]

[13,   22,   -4,   37,   -6,   33,    6,   42]
```

Parallel prefix sums algorithm, downsweep

- Now unwinds to calculate the other sums

```
[13,   22,   -4,   37,   -6,   -4,    6,   42]

[13,   22,   -4,   37,   -6,   33,    6,   42]

[13,   22,   18,   37,   31,   33,   39,   42]
```

- Recall, we started with:

```
[13,    9,   -4,   19,   -6,    2,    6,    3]
```

Parallel prefix sums

- Intuition: If we have already computed the partial sums `sum(x[0…3])` and `sum(x[4…7])`, then we can easily compute `sum(x[0…7])`
- e.g., `x = [13, 9, -4, 19, -6, 2, 6, 3]`
- Pseudocode:

```
prefix_sums(x):
  for d in 0 to (lg n)-1:         // d is depth
    parallelfor i in 2^d-1 to n-1, by 2^(d+1):
      x[i+2^d] = x[i] + x[i+2^d]

  for d in (lg n)-1 to 0:
    parallelfor i in 2^d-1 to n-1-2^d, by 2^(d+1):
      if (i-2^d >= 0):
        x[i] = x[i] + x[i-2^d]
```

Parallel prefix sums algorithm, in code

- An iterative Java-esque implementation:

```
void iterativePrefixSums(long[] a) {
  int gap = 1;
  for ( ; gap < a.length; gap *= 2) {
    parfor(int i=gap-1; i+gap<a.length; i += 2*gap) {
      a[i+gap] = a[i] + a[i+gap];
    }
  }
  for ( ; gap > 0; gap /= 2) {
    parfor(int i=gap-1; i<a.length; i += 2*gap) {
      a[i] = a[i] + ((i-gap >= 0) ? a[i-gap] : 0);
    }
  }
```

Parallel prefix sums algorithm, in code

- A recursive Java-esque implementation:

```
void recursivePrefixSums(long[] a, int gap) {
  if (2*gap – 1 >= a.length) {
    return;
  }

  parfor(int i=gap-1; i+gap<a.length; i += 2*gap) {
    a[i+gap] = a[i] + a[i+gap];
  }

  recursivePrefixSums(a, gap*2);

  parfor(int i=gap-1; i<a.length; i += 2*gap) {
    a[i] = a[i] + ((i-gap >= 0) ? a[i-gap] : 0);
  }
}
```

Parallel prefix sums algorithm

- How good is this?

Parallel prefix sums algorithm

- How good is this?
  - Work: O(n)
  - Depth: O(lg n)
- See `PrefixSums.java`, `PrefixSumsSequentialWithParallelWork.java`

Goal: parallelize the PrefixSums implementation

- Specifically, parallelize the parallelizable loops

```
parfor(int i=gap-1; i+gap<a.length; i += 2*gap) {
  a[i+gap] = a[i] + a[i+gap];
}
```

- Partition into multiple segments, run in different threads

```
for(int i=left+gap-1; i+gap<right; i += 2*gap) {
  a[i+gap] = a[i] + a[i+gap];
}
```

Recall the Java primitive concurrency tools

- The `java.lang.Runnable` interface

```
void           run();
```

- The `java.lang.Thread` class

```
Thread(Runnable r);
void           start();
static void    sleep(long millis);
void           join();
boolean        isAlive();
static Thread currentThread();
```

Recall the Java primitive concurrency tools

- The `java.lang.Runnable` interface

```
void            run();
```

- The `java.lang.Thread` class

```
Thread(Runnable r);
void            start();
static void     sleep(long millis);
void            join();
boolean         isAlive();
static Thread   currentThread();
```

- The `java.util.concurrent.Callable<V>` interface
  - Like `java.lang.Runnable` but can return a value

```
V               call();
```

A framework for asynchronous computation

- The `java.util.concurrent.Future<V>` interface

```
V           get();
V           get(long timeout, TimeUnit unit);
boolean     isDone();
boolean     cancel(boolean mayInterruptIfRunning);
boolean     isCancelled();
```

A framework for asynchronous computation

- The `java.util.concurrent.Future<V>` interface:

```
V           get();
V           get(long timeout, TimeUnit unit);
boolean     isDone();
boolean     cancel(boolean mayInterruptIfRunning);
boolean     isCancelled();
```

- The `java.util.concurrent.ExecutorService` interface:

```
Future<?>   submit(Runnable task);
Future<V>   submit(Callable<V> task);
List<Future<V>>
      invokeAll(Collection<? extends Callable<V>> tasks);
Future<V>
      invokeAny(Collection<? extends Callable<V>> tasks);
void shutdown();
```

`Executors` for common computational patterns

- From the `java.util.concurrent.Executors` class

```
static ExecutorService newSingleThreadExecutor();
static ExecutorService newFixedThreadPool(int n);
static ExecutorService newCachedThreadPool();
static ExecutorService newScheduledThreadPool(int n);
```

- Aside: see NetworkServer.java (later)

Fork/Join: another common computational pattern

- In a long computation:
  - Fork a thread (or more) to do some work
  - Join the thread(s) to obtain the result of the work

Fork/Join: another common computational pattern

- In a long computation:
  - Fork a thread (or more) to do some work
  - Join the thread(s) to obtain the result of the work
- The `java.util.concurrent.ForkJoinPool` class
  - Implements `ExecutorService`
  - Executes `java.util.concurrent.ForkJoinTask<V>` or
    `java.util.concurrent.RecursiveTask<V>` or
    `java.util.concurrent.RecursiveAction`

The `RecursiveAction` abstract class

```
public class MyActionFoo extends RecursiveAction {
    public MyActionFoo(…) {
        store the data fields we need
    }

    @Override
    public void compute() {
        if (the task is small) {
            do the work here;
            return;
        }

        invokeAll(new MyActionFoo(…),  // smaller
                  new MyActionFoo(…),  // tasks
                  …);                  // …
    }
}
```

A ForkJoin example

- See `PrefixSumsParallelForkJoin.java`
- See the processor go, go go!

Parallel prefix sums algorithm

- How good is this?
  - Work: O(n)
  - Depth: O(lg n)
- See `PrefixSumsParallelArrays.java`

Parallel prefix sums algorithm

- How good is this?
  - Work: O(n)
  - Depth: O(lg n)
- See `PrefixSumsParallelArrays.java`
- See `PrefixSumsSequential.java`

Parallel prefix sums algorithm

- How good is this?
  - Work: O(n)
  - Depth: O(lg n)
- See `PrefixSumsParallelArrays.java`
- See `PrefixSumsSequential.java`
  - n-1 additions
  - Memory access is sequential
- For `PrefixSumsSequentialWithParallelWork.java`
  - About 2n useful additions, plus extra additions for the loop indexes
  - Memory access is non-sequential
- The punchline:
  - Don't roll your own
  - Cache and constants matter

Coming Thursday…

- Distributed systems

In-class example for parallel prefix sums

```
[7,    5,    8,  -36,   17,    2,   21,   18]
```