Principles of Software Construction:
Objects, Design, and Concurrency

Part 42: Concurrency

Introduction to concurrency frameworks

In the trenches of parallelism

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Administrivia

- Homework 5b due 11:59 p.m. tonight
  - Turn in by Wednesday 9 a.m. to be considered as a Best Framework
- Optional reading due today:
  - Java Concurrency in Practice, Chapter 12

Key concepts from last Thursday

Strategies for thread safety

- **Thread-confined state** – mutate but don't share
- **Shared read-only state** – share but don't mutate
- **Shared thread-safe** – object synchronizes itself internally
- **Shared guarded** – client synchronizes object(s) externally

Advice for building thread-safe objects

- Do as little as possible in synchronized region: get in, get out
  - Obtain lock
  - Examine shared data
  - Transform as necessary
  - Drop the lock
- If you must do something slow, move it outside the synchronized region

Shared thread-safe

- Thread-safe objects that perform internal synchronization
- You can build your own, but…
- You're better off using ones from `java.util.concurrent`

Concurrent observer pattern with a subtle bug

This code is prone to liveness and safety failures!

```
private final List<Observer<E>> observers = new ArrayList<>();
public void addObserver(Observer<E> observer) {
   synchronized(observers) { observers.add(observer); }
}
public boolean removeObserver(Observer<E> observer) {
   synchronized(observers) { return observers.remove(observer); }
}
private void notifyOf(E element) {
   synchronized(observers) {
       for (Observer<E> observer : observers)
           observer.notify(this, element);
   }
}
```

Concurrent observer pattern with a subtle bug

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```
private final List<Observer<E>> observers = new ArrayList<>();
public void addObserver(Observer<E> observer) {
   synchronized(observers) { observers.add(observer); }
}
public boolean removeObserver(Observer<E> observer) {
   synchronized(observers) { return observers.remove(observer); }
}
private void notifyOf(E element) {
   synchronized(observers) {
       for (Observer<E> observer : observers)
           observer.notify(this, element);  // Callback while
   }                                        // holding lock!
}
```

One solution: *snapshot iteration*

```
private void notifyOf(E element) {
    List<Observer<E>> snapshot = null;

    synchronized(observers) {
        snapshot = new ArrayList<>(observers);
    }

    for (Observer<E> observer : snapshot) {
        observer.notify(this, element); // Safe
    }
}
```

A better solution: `CopyOnWriteArrayList`

```
private final List<Observer<E>> observers =
       new CopyOnWriteArrayList<>();

public void addObserver(Observer<E> observer) {
   observers.add(observer);
}
public boolean removeObserver(Observer<E> observer) {
   return observers.remove(observer);
}
private void notifyOf(E element) {
   for (Observer<E> observer : observers)
       observer.notify(this, element);
}
```

Today

- Concurrency in practice: In the trenches of parallelism

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 (It's a race condition)

The moral

- JUnit does not well-support concurrent tests
  - You might get a false sense of security
- Concurrent clients beware…

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

(d) None of the above

What does it print?

(a) `PingPong`

(b) `PongPing`

(c) It varies

(d) None of the above

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`
- `java.lang.Thread` should not have implemented `Runnable`

Today

- Concurrency in practice: In the trenches of parallelism

Concurrency at the language level

- Consider:

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

- In python:

```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
- 210-esque questions: What is total work? What is depth?

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

Compute 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

Compute 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

Compute 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 unwind 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

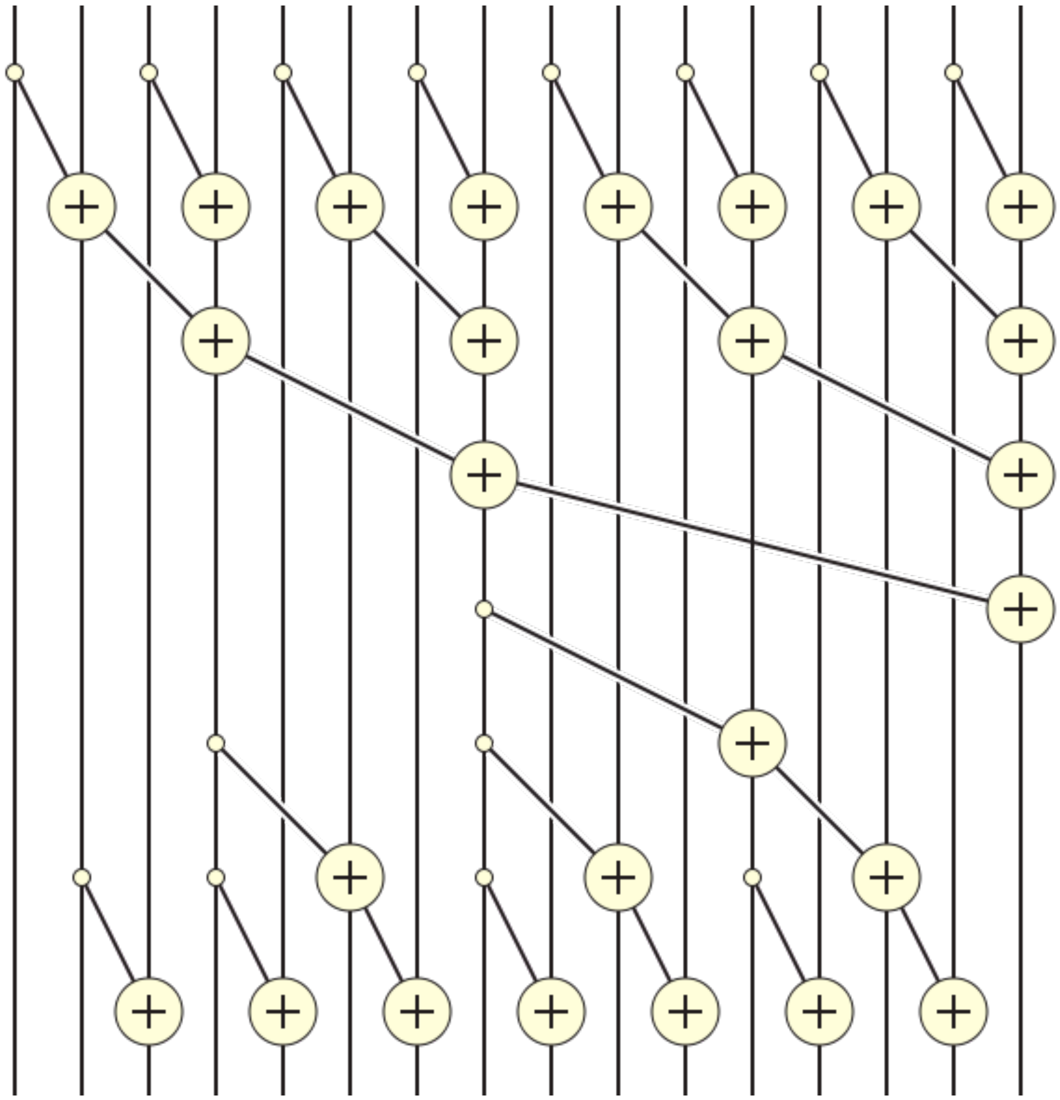
Now unwind to calculate the other sums

```
[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]
```

Doubling array size adds two more levels



Upsweep

Downsweep

Parallel prefix sums

pseudocode

```
// Upsweep
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]

// Downsweep
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]
```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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 from Thursday: Fork/join in Java

- 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`
- 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 `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(…),  // subtasks
                  …);                  // …
    }
}
```

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

In-class example for parallel prefix sums

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