Principles of Software Construction: Objects, Design, and Concurrency

Introduction to concurrency, part 4

In the trenches of parallelism

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Administrivia

- Homework 5b due Wednesday night
  - Turn in by 9 a.m. Thursday to be considered for Best Framework award
  - Homework 5 Best Frameworks available Friday
- Homework 5c due Tuesday, 11:59 p.m.

Key concepts from last Thursday

Policies for thread safety

1. **Thread-confined state** – mutate but don't share
2. **Shared read-only state** – share but don't mutate
3. **Shared thread-safe** – object synchronizes itself internally
4. **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

3. Shared thread-safe state

- Thread-safe objects that perform internal synchronization
- You can build your own, but not for the faint of heart
- You're better off using ones from `java.util.concurrent`
- `j.u.c` also provides skeletal implementations

`java.util.concurrent` is BIG (1)

1. Atomic variables: `java.util.concurrent.atomic`
   – Support various atomic read-modify-write ops
2. Concurrent collections
   – Shared maps, sets, lists
3. Data exchange collections
   – Blocking queues, deques, etc.
4. Executor framework
   – Tasks, futures, thread pools, completion service, etc.
5. Synchronizers
   – Semaphores, cyclic barriers, countdown latches, etc.
6. Locks: `java.util.concurrent.locks`
   – Read-write locks, conditions, etc.

`java.util.concurrent` is BIG (2)

- Pre-packaged functionality: `java.util.Arrays`
  - Parallel sort, parallel prefix
- Completable futures
  - Multistage asynchronous concurrent computations
- Flows
  - Publish/subscribe service
- And more
  - It just keeps growing

Today

- j.u.c. Executor framework overview
- Concurrency in practice: In the trenches of parallelism

4. Executor framework overview

- Flexible interface-based task execution facility
- Key abstractions
  - `Runnable` – basic task
  - `Callable<T>` – task that returns a value (and can throw an exception)
  - `Future<T>` – a promise to give you a T
  - `Executor` – machine that executes tasks
  - Executor service – `Executor` on steroids
    - Lets you manage termination
    - Can produce `Future` instances

`Executors` – your one-stop shop for executor services

- `Executors.new`**`SingleThreadExecutor`**`()`
  - A single background thread
- `Executors.new`**`FixedThreadPool`**`(int nThreads)`
  - A fixed number of background threads
- `Executors.new`**`CachedThreadPool`**`()`
  - Grows in response to demand

A very simple (but useful) executor service example

- Background execution in a long-lived worker thread
  - To start the worker thread:

```
ExecutorService executor =
  Executors.newSingleThreadExecutor();
```

  - To submit a task for execution:

```
executor.execute(runnable);
```

  - To terminate gracefully:

```
executor.shutdown(); // Allows tasks to finish
```

Other things you can do with an executor service

- Wait for a task to complete

```
Foo foo = executorSvc.submit(callable).get();
```

- Wait for any or all of a collection of tasks to complete

```
invoke{Any,All}(Collection<Callable<T>> tasks)
```

- Retrieve results as tasks complete

```
ExecutorCompletionService
```

- Schedule tasks for execution at a time in the future

```
ScheduledThreadPoolExecutor
```

- etc., ad infinitum

Today

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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
- 210-esque questions: What is total work? What is span?

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: Partial sums can be efficiently combined to form much larger partial sums. E.g., if we know `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]
```

In-class example for parallel prefix sums

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

In-class example for parallel prefix sums (downsweep)

```
[7,   12,    8, -16,   17,   19,   21,   42]
```

In-class example for parallel prefix sums (downsweep)

```
[7,    12,     8,  -16,    17,    19,    21,    42]
```

```
[7,    12,    20,  -16,     1,     3,    24,    42]
```

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


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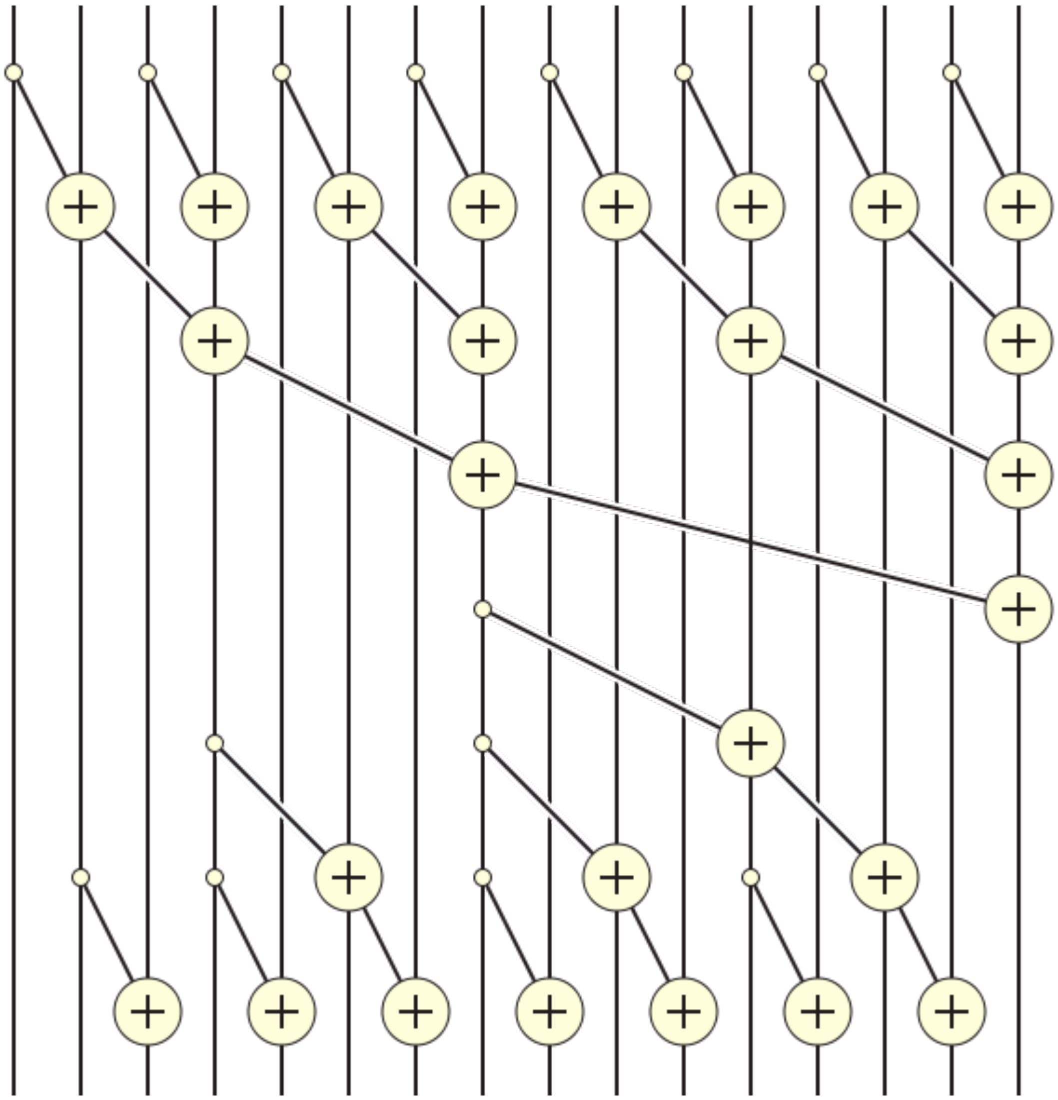
Doubling array size adds two more levels



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]
```

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)
  - Span: O(lg n)
- See `PrefixSums.java`, `PrefixSumsSequentialWithParallelWork.java`

Goal: parallelize the PrefixSums implementation

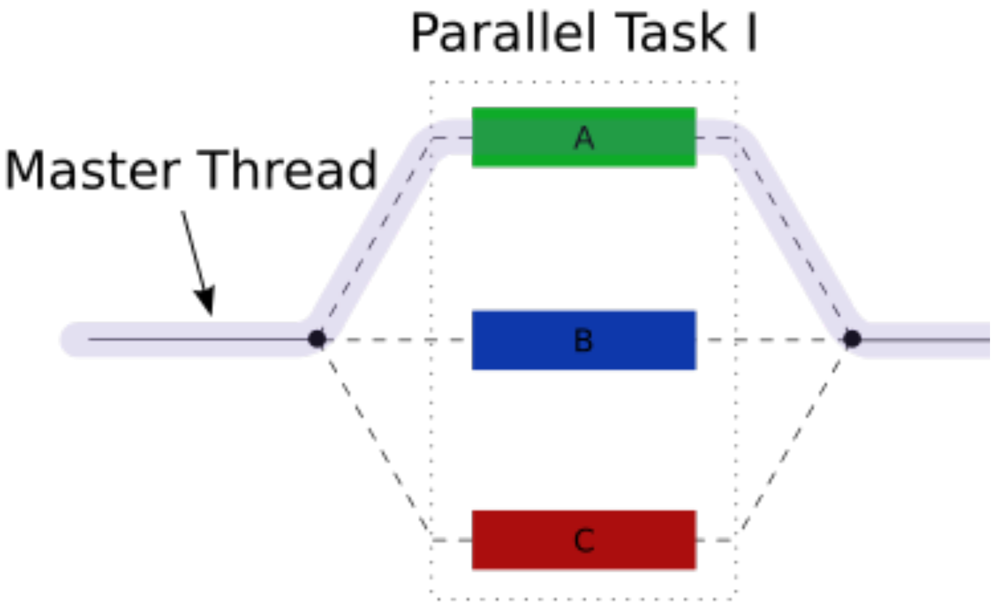
- Specifically, parallelize the parallelizable loops

```
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];
}
```

The fork-join pattern




```
if (my portion of the work is small)
    do the work directly
else
    split my work into pieces
    recursively process the pieces
```

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)
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- See `PrefixSumsParallelArrays.java`

Parallel prefix sums algorithm

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- See `PrefixSumsSequential.java`

Parallel prefix sums algorithm

- How good is this?
  - Work: O(n)
  - Span: 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. Know the libraries
  - Cache and constants matter

In-class example for parallel prefix sums

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

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