Principles of Software Construction: Objects, Design, and Concurrency

Lambdas and streams

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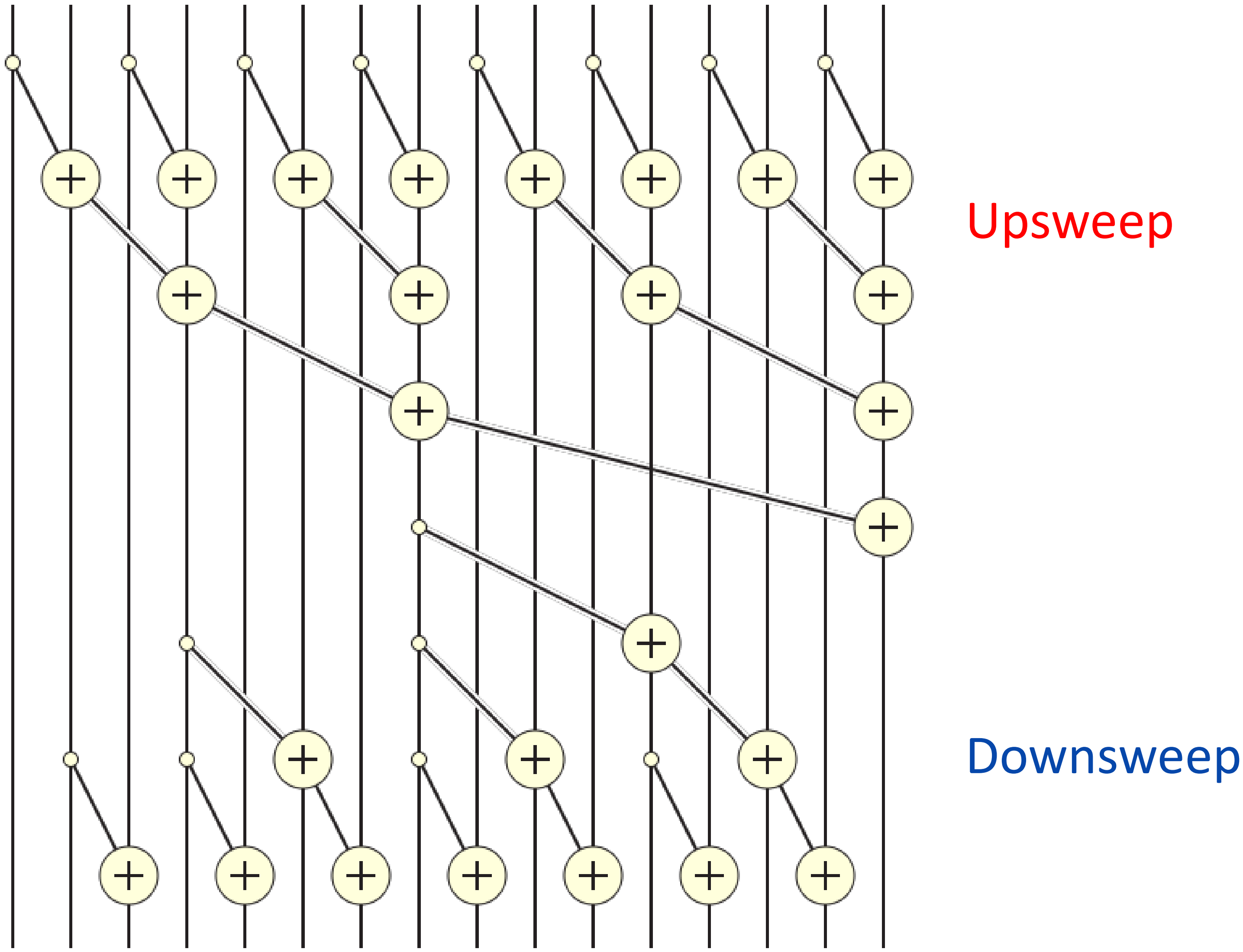
Administrivia

- Homework 5 Best Frameworks available tonight
  - Or early tomorrow
- Plugins for Best Frameworks due Monday 11/19

Unfinished business

Prof. Charlie showed us a fancy parallel prefix algorithm



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

Today's topics

- Two features added in Java 8
  - **Lambdas**: language feature
  - **Streams**: library feature
- Designed to work together

What is a lambda?

- Term comes from λ-Calculus
  - Formal logic introduced by Alonzo Church in the 1930's
  - Everything is a function!
- **A lambda (λ) is simply an *anonymous* function**
  - A function without a corresponding identifier (name)

Does Java have lambdas?

A. Yes, it’s had them since the beginning

B. Yes, it’s had them since anonymous classes were added (JDK 1.1, 1997)

C. Yes, it’s had them since Java 8 (2014) – the spec says so

D. No, never had ’em, never will

Function objects in Java 1.0 (1996)

```
class StringLengthComparator implements Comparator {
    private StringLengthComparator() { }
    public static final StringLengthComparator INSTANCE =
            new StringLengthComparator();

    public int compare(Object o1, Object o2) {
        String s1 = (String) o1, s2 = (String) o2;
        return s1.length() - s2.length();
    }
}

Arrays.sort(words, StringLengthComparator.INSTANCE);
```

Function objects in Java 1.1 (1997)

```
Arrays.sort(words, new Comparator() {
   public int compare(Object o1, Object o2) {
       String s1 = (String) o1, s2 = (String) o2;
       return s1.length() - s2.length();
   }
});
```

Class Instance Creation Expression (CICE)

Function objects in Java 5 (2004)

```
Arrays.sort(words, new Comparator<String>() {
   public int compare(String s1, String s2) {
       return s1.length() - s2.length();
   }
});
```

CICE with generics

Function objects in Java 8 (2014)

```
Arrays.sort(words, (s1, s2) -> s1.length() - s2.length());
```

- They feel like lambdas, and they're called lambdas
  - But they're no more anonymous than 1.1 CICE's!
  - However, method name does not appear in code

Java has no function types, only *functional interfaces*

- **Interfaces with only one explicit abstract method**
  - a.k.a *SAM interface* (Single Abstract Method)
- Optionally annotated with `@FunctionalInterface`
  - Do it, for the same reason you use `@Override`
- A lambda is essentially a functional interface literal
- Some functional interfaces you already know:
  - `Runnable`, `Callable`, `Comparator`, `ActionListener`
- Many, many more in package `java.util.function`

Java has 43 standard functional interfaces

Luckily, there is a fair amount of structure

BiConsumer<T,U>
BiFunction<T,U,R>
BinaryOperator<T>
BiPredicate<T,U>
BooleanSupplier
Consumer<T>
DoubleBinaryOperator
DoubleConsumer
DoubleFunction<R>
DoublePredicate
DoubleSupplier
DoubleToIntFunction
DoubleToLongFunction
DoubleUnaryOperator
Function<T,R>
IntBinaryOperator
IntConsumer
IntFunction<R>
IntPredicate
IntSupplier
IntToDoubleFunction
IntToLongFunction
IntUnaryOperator
LongBinaryOperator
LongConsumer
LongFunction<R>
LongPredicate
LongSupplier
LongToDoubleFunction
LongToIntFunction
LongUnaryOperator
ObjDoubleConsumer<T>
ObjIntConsumer<T>
ObjLongConsumer<T>
Predicate<T>
Supplier<T>
ToDoubleBiFunction<T,U>
ToDoubleFunction<T>
ToIntBiFunction<T,U>
ToIntFunction<T>
ToLongBiFunction<T,U>
ToLongFunction<T>
UnaryOperator<T>

The 6 basic standard functional interfaces

Interface	Function Signature	Example
`UnaryOperator<T>`	`T apply(T t)`	`String::toLowerCase`
`BinaryOperator<T>`	`T apply(T t1, T t2)`	`BigInteger::add`
`Predicate<T>`	`boolean test(T t)`	`Collection::isEmpty`
`Function<T,R>`	`R apply(T t)`	`Arrays::asList`
`Supplier<T>`	`T get()`	`Instant::now`
`Consumer<T>`	`void accept(T t)`	`System.out::println`

Most of the remaining 37 interfaces provide support for primitive types. Use them or pay the price!

Lambda syntax

Syntax	**Example**
parameter -> *expression*	`x -> x * x`
parameter -> *block*	`s -> { System.out.println(s); }`
(*parameters*) -> *expression*	`(x, y) -> Math.sqrt(x*x + y*y)`
(*parameters*) -> *block*	`(s1, s2) ->` `{ System.out.println(s1 + "," + s2); }`
(*parameter decls*) -> *expression*	`(double x, double y) -> Math.sqrt(x*x + y*y)`
(*parameters decls*) -> *block*	`(List<?> list) ->` `{ Arrays.shuffle(list); Arrays.sort(list); }`

A subtle difference between lambdas & anonymous classes

```
class Enclosing {
    Supplier<Object> lambda() {
        return () -> this;
    }

    Supplier<Object> anon() {
        return new Supplier<Object>() {
            public Object get() { return this; }
        };
    }

    public static void main(String[] args) {
        Enclosing enclosing = new Enclosing();
        Object lambdaThis = enclosing.lambda().get();
        Object anonThis = enclosing.anon().get();
        System.out.println(anonThis == enclosing);   // false
        System.out.println(lambdaThis == enclosing); // true
    }
}
```

Method references – a more succinct alternative to lambdas

- Lambdas are succinct

```
map.merge(key, 1, (count, incr) -> count + incr);
```

- But *method references* can be more so

```
map.merge(key, 1, Integer::sum);
```

- The more parameters, the bigger the win
  - But parameter names *may* provide documentation
  - If you use a lambda, choose parameter names carefully!

Occasionally, lambdas are more succinct

```
service.execute(() -> action());
```

is preferable to

```
service.execute(GoshThisClassNameIsHumongous::action);
```

Know all five kinds of method references

They all have their uses

Type	Example	Lambda Equivalent*
Static	`Integer::parseInt`	`str -> Integer.parseInt(str)`
Bound	`Instant.now()::isAfter`	`Instant then = Instant.now();` `t -> then.isAfter(t)`
Unbound	`String::toLowerCase`	`str -> str.toLowerCase()`
Class Constructor	`TreeMap<K,V>::new`	`() -> new TreeMap<K,V>()`
Array Constructor	`int[]::new`	`len -> new int[len]`

Lambdas vs. method references – the bottom line

- (Almost) anything you can do with a method reference, you can also do with a lambda
- Method references are *usually* more succinct
- But sometimes lambdas are clearer
- Use your best judgment
  - You can always change your mind

What is a stream?

- A bunch of data objects, typically from a collection, array, or input device, for bulk data processing
- Processed by a *pipeline*
  - **A single *stream generator* (data source)**
  - **Zero or more *intermediate stream operations***
  - **A single *terminal stream operation***
- Supports mostly-functional data processing
- Enables painless parallelism
  - Simply replace `stream` with `parallelStream`
  - You may or may not see a performance improvement

Streams are processed *lazily*

- Data is “pulled” by terminal operation, not pushed by source
  - Infinite streams are not a problem
- Intermediate operations can be fused
  - Multiple intermediate operations usually don’t result in multiple traversals
- Intermediate results typically not stored
  - But there are exceptions (e.g., `sorted`)

Simple stream examples – mapping, filtering, sorting, etc.

```
List<String> longStrings = stringList.stream()
    .filter(s -> s.length() > 3)
    .collect(Collectors.toList());

List<String> firstLetters = stringList.stream()
    .map(s -> s.substring(0,1))
    .collect(Collectors.toList());

List<String> firstLettersOfLongStrings = stringList.stream()
    .filter(s -> s.length() > 3)
    .map(s -> s.substring(0,1))
    .collect(Collectors.toList());

List<String> sortedFirstLettersWithoutDups = stringList.stream()
    .map(s -> s.substring(0,1))
    .distinct()
    .sorted()
    .collect(Collectors.toList());
```

Simple stream examples – file input

```
// Prints a file, one line at a time
try (Stream<String> lines = Files.lines(Paths.get(fileName))) {
    lines.forEach(System.out::println);
}

// Prints sorted list of non-empty lines in file (trimmed)
try (Stream<String> lines = Files.lines(Paths.get(fileName))) {
    lines.map(String::trim)
         .filter(s -> !s.isEmpty())
         .sorted()
         .forEach(System.out::println);
}
```

Simple stream examples – bulk predicates

```
boolean allStringHaveLengthThree = stringList.stream()
      .allMatch(s -> s.length() == 3);

boolean anyStringHasLengthThree = stringList.stream()
      .anyMatch(s -> s.length() == 3);
```

Stream example – the first twenty Mersenne Primes

Mersenne number is a number of the form $2^p - 1$

- If *p* is prime, the corresponding Mersenne number *may be* prime
- If it is, it's a **Mersenne prime**

```
static Stream<BigInteger> primes() {
    return Stream.iterate(TWO, BigInteger::nextProbablePrime);
}

public static void main(String[] args) {
    primes().map(p -> TWO.pow(p.intValueExact()).subtract(ONE))
            .filter(mersenne -> mersenne.isProbablePrime(50))
            .limit(20)
            .forEach(System.out::println);
}
```

Iterative program to print large anagram groups in a dictionary

Review: you saw this Collections Framework case study

```
public static void main(String[] args) throws IOException {
    File dictionary = new File(args[0]);
    int minGroupSize = Integer.parseInt(args[1]);

    Map<String, Set<String>> groups = new HashMap<>();
    try (Scanner s = new Scanner(dictionary)) {
        while (s.hasNext()) {
            String word = s.next();
             groups.computeIfAbsent(alphabetize(word),
                 (unused) -> new TreeSet<>()).add(word);
        }
    }

    for (Set<String> group : groups.values())
        if (group.size() >= minGroupSize)
            System.out.println(group.size() + ": " + group);
}
```

Helper function to alphabetize a word

Word nerds call the result an alphagram

```
private static String alphabetize(String s) {
    char[] a = s.toCharArray();
    Arrays.sort(a);
    return new String(a);
}
```

Streams gone crazy

Just because you can doesn't mean you should!

```
public class Anagrams {
  public static void main(String[] args) throws IOException {
    Path dictionary = Paths.get(args[0]);
    int minGroupSize = Integer.parseInt(args[1]);

    try (Stream<String> words = Files.lines(dictionary)) {
      words.collect(
        groupingBy(word -> word.chars().sorted()
                    .collect(StringBuilder::new,
                      (sb, c) -> sb.append((char) c),
                      StringBuilder::append).toString()))
        .values().stream()
          .filter(group -> group.size() >= minGroupSize)
          .map(group -> group.size() + ": " + group)
          .forEach(System.out::println);
    }
  }
}
```

A happy medium

Tasteful use of streams enhances clarity and conciseness

```
public static void main(String[] args) throws IOException {
  Path dictionary = Paths.get(args[0]);
  int minGroupSize = Integer.parseInt(args[1]);

  try (Stream<String> words = Files.lines(dictionary)) {
    words.collect(groupingBy(word -> alphabetize(word)))
      .values().stream() // Terminal op, then create new stream
        .filter(group -> group.size() >= minGroupSize)
        .forEach(g -> System.out.println(g.size() + ": " + g));
    }
}
```

A minipuzzler - what does this print?

```
"Hello world!".chars()
    .forEach(System.out::print);
```

Puzzler solution

```
"Hello world!".chars()
    .forEach(System.out::print);
```

Prints `721011081081113211911111410810033`

Why does it do this?

Puzzler explanation

```
"Hello world!".chars()
      .forEach(System.out::print);
```

Prints `721011081081113211911111410810033`

String’s `chars` method returns an `IntStream`

How do you fix it?

```
"Hello world!".chars()
      .forEach(x -> System.out.print((char) x));
```

Now prints `Hello world`

Moral

- Streams only for object ref types, `int`, `long`, and `double`
- Minor primitive types are missing
- Type inference can be confusing
- **Avoid using streams for char processing**

Streams – the bottom line

- Streams are great for many things…
  - But they’re not a panacea
- When you first learn streams, you may want to convert all of your loops. Don’t!
  - It may make your code shorter, but not clearer
- Exercise judgment
  - Properly used, streams increase brevity and clarity
  - **Most programs should combine iteration and streams**
- It’s not always clear at the outset
  - If you don’t know, take a guess and start hacking
  - If it doesn’t feel right, try the other approach

Use caution making streams parallel

Remember our Mersenne primes program?

```
static Stream<BigInteger> primes() {
    return Stream.iterate(TWO, BigInteger::nextProbablePrime);
}

public static void main(String[] args) {
    primes().map(p -> TWO.pow(p.intValueExact()).subtract(ONE))
        .filter(mersenne -> mersenne.isProbablePrime(50))
        .limit(20)
        .forEach(System.out::println);
}
```

Runs in 12.5s on my quad-core, 8-thread core i7

How fast do you think *this* program runs?

```
static Stream<BigInteger> primes() {
    return Stream.iterate(TWO, BigInteger::nextProbablePrime);
}

public static void main(String[] args) {
    primes().map(p -> TWO.pow(p.intValueExact()).subtract(ONE))
        .parallel()
        .filter(mersenne -> mersenne.isProbablePrime(50))
        .limit(20)
        .forEach(System.out::println);
}
```

How fast do you think *this* program runs?

```
static Stream<BigInteger> primes() {
    return Stream.iterate(TWO, BigInteger::nextProbablePrime);
}

public static void main(String[] args) {
    primes().map(p -> TWO.pow(p.intValueExact()).subtract(ONE))
        .parallel()
        .filter(mersenne -> mersenne.isProbablePrime(50))
        .limit(20)
        .forEach(System.out::println);
}
```

Very, very slowly. I gave up after half an hour.

Why did the program run so slowly?

- **The streams library has no idea how to parallelize it**
  - **And the heuristics fail miserably**
- In the *best* case, `parallel` is unlikely to help if:
  - Stream source is `Stream.iterate`, **or**
  - Intermediate `limit` operation is used
- This *isn't* the best case
  - Default strategy for **`limit`** computes excess elements
  - Each Mersenne prime takes twice as long to compute as last one
- **Moral: do not parallelize indiscriminately!**

What *does* parallelize well?

- Arrays, `ArrayList`, `HashMap`, `HashSet`, `ConcurrentHashMap`, `int` and `long` ranges…
- What do these sources have in common?
  - Predictably splittable
  - Good *locality of reference*
- Terminal operation also matters
  - Must be quick, or easily parallelizable
  - Best are *reductions*, e.g., `min`, `max`, `count`, `sum`
  - Collectors (AKA *mutable reductions*) not so good
- Intermediate operations matter too
  - Mapping and filtering good, `limit` bad

Example – number of primes ≤ n, $\pi(n)$

```
static long pi(long n) {
    return LongStream.rangeClosed(2, n)
        .mapToObj(BigInteger::valueOf)
        .filter(i -> i.isProbablePrime(50))
        .count();
}
```

Takes 31s to compute $\pi(10^8)$ on my machine

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Example – number of primes ≤ *n*, π(*n*)

```
static long pi(long n) {
    return LongStream.rangeClosed(2, n)
        .parallel()
        .mapToObj(BigInteger::valueOf)
        .filter(i -> i.isProbablePrime(50))
        .count();
}
```

In parallel, it takes 9.2s, which is 3.7 times as fast!

`.parallel()` is merely an optimization

- Optimize Judiciously [EJ Item 67]
- **Don’t parallelize unless you can prove it maintains correctness**
- Don’t parallelize unless you have a good reason to believe it will help
- **Measure performance before and after**

Summary

- When to use a lambda
  - Always, in preference to CICE
- When to use a method reference
  - Almost always, in preference to a lambda
- When to use a stream
  - When it feels and looks right
- When to use a parallel stream
  - When you've demonstrated that it's a performance win