Practical Concurrent and Parallel Programming 4

Riko Jacob

IT University of Copenhagen

Friday 2018-09-21

Plan

- Java 8 functional programming
  - Package java.util.function
  - Lambda expressions, method reference expressions
  - Functional interfaces, targeted function type
- Java 8 streams for bulk data
  - Package java.util.stream
- High-level parallel programming
  - Streams: primes, queens
  - Array parallel prefix operations
    - Class java.util.Arrays static methods

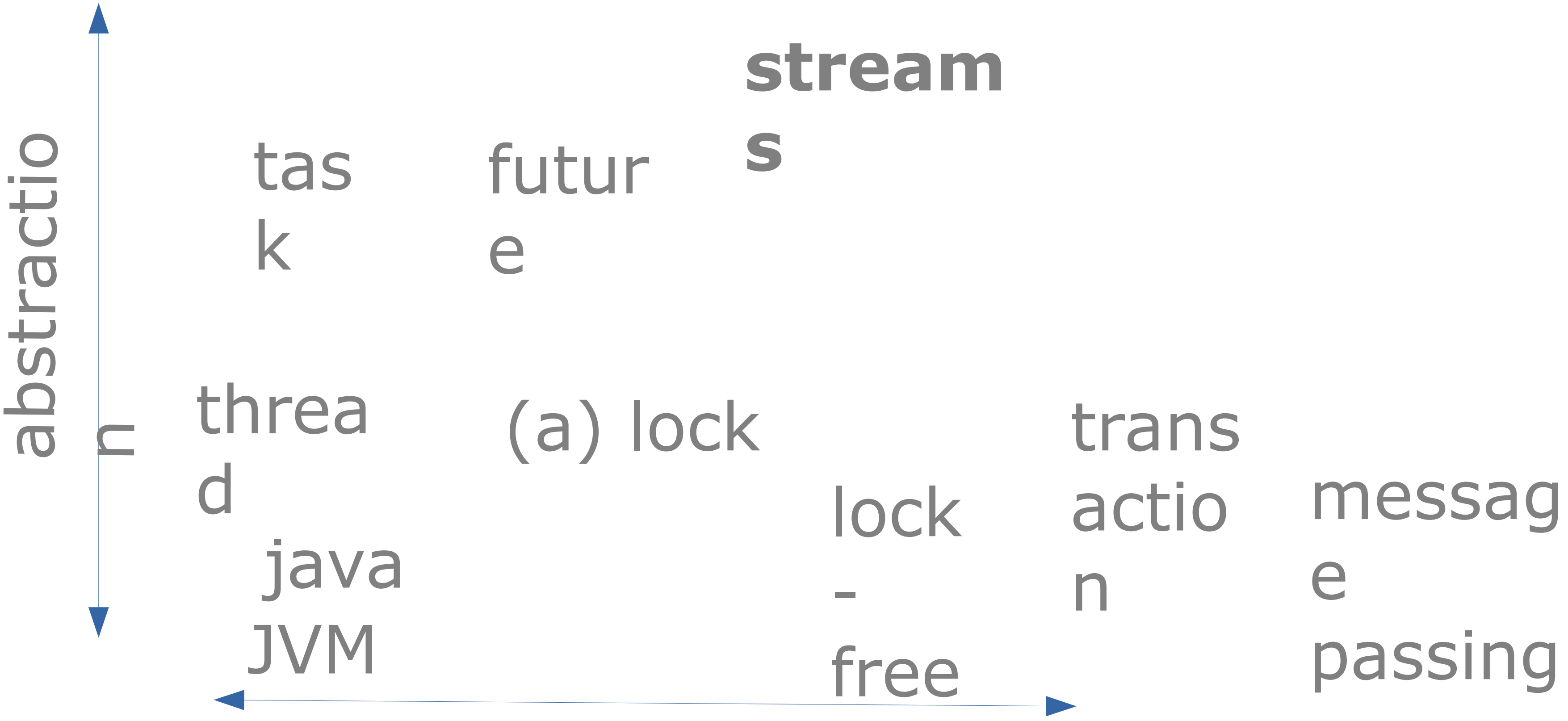
Materials

- *Java Precisely* 3rd edition, MIT Press 2016
  - §11.13: Lambda expressions
  - §11.14: Method reference expressions
  - §23: Functional interfaces
  - §24: Streams for bulk data
  - §25: Class Optional<T>
- Book examples are called Example154.java etc
  - Get them from the book homepage http://www.itu.dk/people/sestoft/javaprecisely/

Based on slides by
Peter Sestoft

correctness

measure



streams

task

future

abstraction

thread

(a) lock

transaction

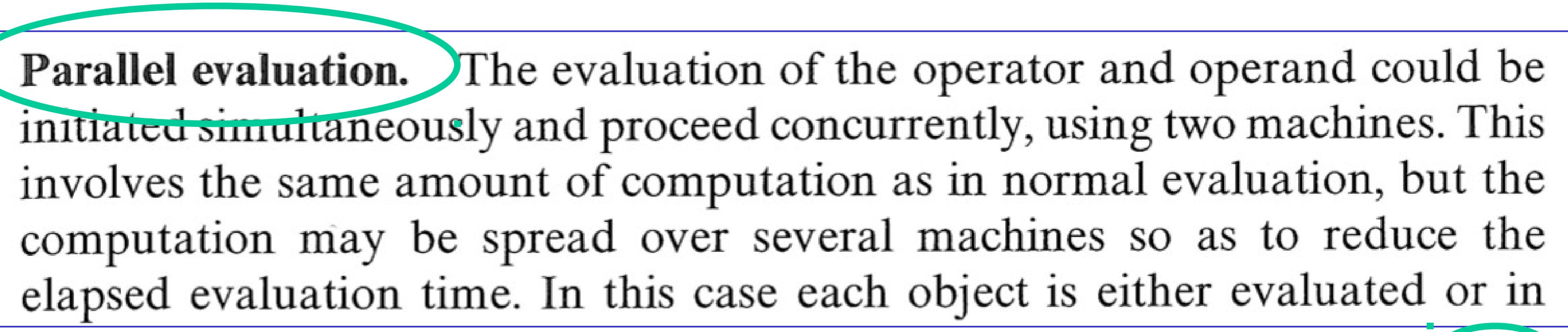
lock-free

message passing

java JVM

model of computation

Parallel functional programming



Parallel evaluation. The evaluation of the operator and operand could be initiated simultaneously and proceed concurrently, using two machines. This involves the same amount of computation as in normal evaluation, but the computation may be spread over several machines so as to reduce the elapsed evaluation time. In this case each object is either evaluated or in

Burge: Recursive programming techniques, 1975

- 1980’es: Language-driven parallel functional programming: dataflow, Peyton Jones, Roe, ...
- Now: Technology-driven, “free lunch is over”: Multicore chips => Java needs parallelism => Java needs (parallelizable) streams => Java needs functional programming

Easy Parallelism

Many independent (almost identical) tasks

Java Streams can express computation of that type (and more)

– this allows automatic parallelization

Need to express the task *without state!*

= *purely functionally*

New in Java 8

- Lambda expressions

  `(String s) -> s.length`

- Method reference expressions

  `String::length`

- Functional interfaces

  `Function<String,Integer>`

- Streams for bulk data

  `Stream<Integer> iStr = sStr.map(String::length)`

- Parallel streams

  `iStr = sStr.parallel().map(String::length)`

- Parallel array operations

  ```
  Arrays.parallelSetAll(arr, i -> sin(i/PI/100.0))
  Arrays.parallelPrefix(arr, (x, y) -> x+y)
  ```

Functional programming in Java

- *Immutable data* instead of objects with state
- *Recursion* instead of loops
- *Higher-order functions* that either
  - take functions as argument
  - return functions as result

Immutable list of T

```
class FunList<T> {
  final Node<T> first;
  protected static class Node<U> {
    public final U item;
    public final Node<U> next;
    public Node(U item, Node<U> next) { ... }
  }
  ...
}
```

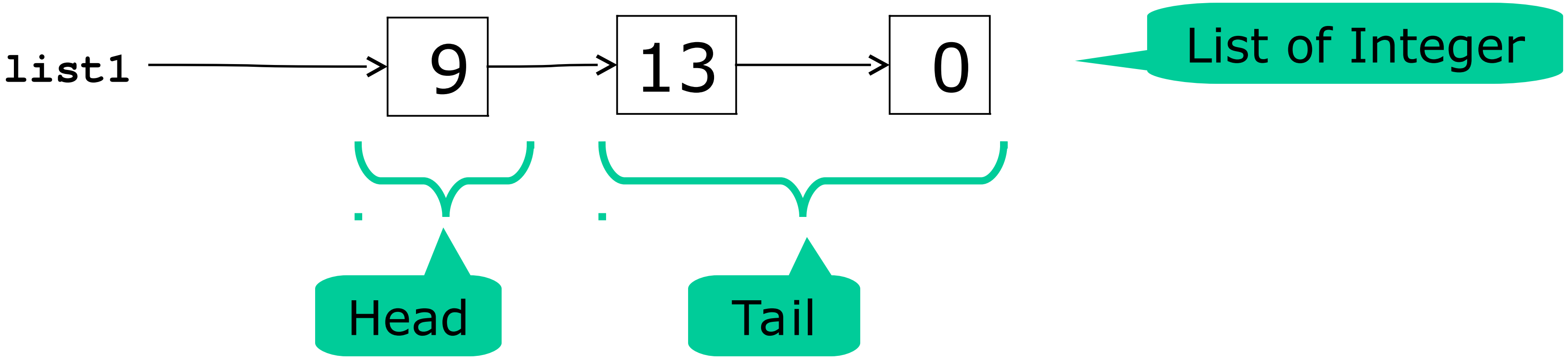
Example154.java

Immutable data

- FunList<T>, linked lists of nodes

```
class FunList<T> {
  final Node<T> first;
  protected static class Node<U> {
    public final U item;
    public final Node<U> next;
    public Node(U item, Node<U> next) { ... }
  }
  static <T> FunList<T> cons(T item, FunList<T> list) {
    return new Node(item, list.first);
  }
```

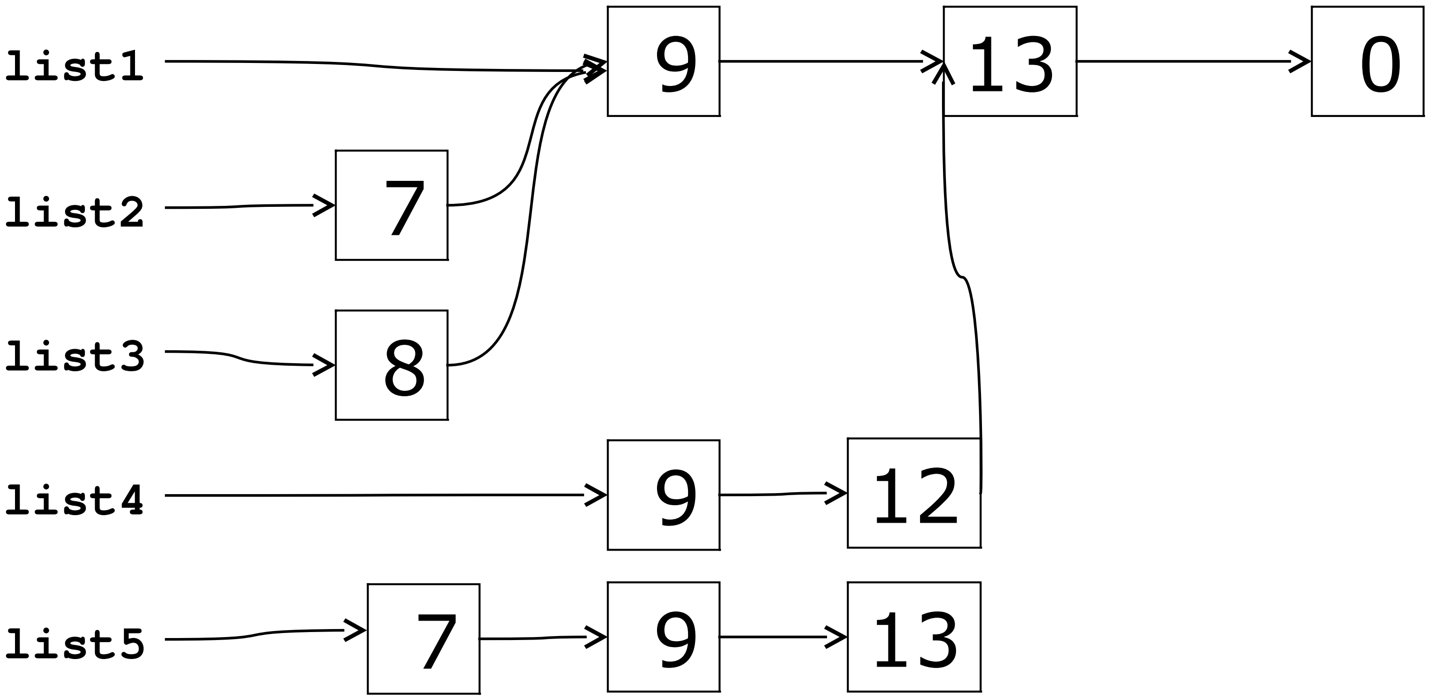
Example154.java



Full Persistence:
Existing data do not change

```
FunList<Integer> empty = new FunList<>(null),
  list1 = cons(9, cons(13, cons(0, empty))),
  list2 = cons(7, list1),
  list3 = cons(8, list1),
  list4 = list1.insert(1, 12),
  list5 = list2.removeAt(3);
```

Example154.java



Recursion in insert

Example154.java

```
public FunList<T> insert(int i, T item) {
  return new FunList<T>(insert(i, item, this.first));
}

static <T> Node<T> insert(int i, T item, Node<T> xs) {
  return i == 0 ? new Node<T>(item, xs)
       : new Node<T>(xs.item, insert(i-1, item, xs.next));
}
```

- “If **`i`** is zero, put **`item`** in a new node, and let its tail be the old list **`xs`**”
- “Otherwise, put the first element of **`xs`** in a new node, and let its tail be the result of inserting **`item`** in position **`i-1`** of the tail of **`xs`**”

Immutable data: Bad and good

- Immutability leads to *more* allocation
  - Takes time and space
  - But today allocators and garbage collectors are fast
- Immutable data structures are automatically persistent
- Immutable data can be safely shared
  - May actually lead to *less* allocation
- Immutable data are automatically threadsafe
  - No (other) thread can change the data
  - And also due to visibility effects of **`final`** modifier

Subtle point

Lambda expressions 1

Example64.java

- One argument lambda expressions:

`string -> int`

```
Function<String,Integer>
  fsi1 = s -> Integer.parseInt(s);

... fsi1.apply("004711") ...
```

Function that takes a string s and parses it as an integer

Calling the function

Same, written in other ways

```
Function<String,Integer>
  fsi2 = s -> { return Integer.parseInt(s); },
  fsi3 = (String s) -> Integer.parseInt(s);
```

- Two-argument lambda expressions:

`string * int -> string`

```
BiFunction<String,Integer,String>
  fsis1 = (s, i) -> s.substring(i, Math.min(i+3, s.length()));
```

Lambda expressions 2

Example64.java

- Zero-argument lambda expression:

`unit -> string`

```
Supplier<String>
  now = () -> new java.util.Date().toString();
```

- One-argument result-less lambda (“void”):

`string -> unit`

```
Consumer<String>
  show1 = s -> System.out.println(">>>" + s + "<<<”);

Consumer<String>
  show2 = s -> { System.out.println(">>>" + s + "<<<"); };
```

Method reference expressions

Example67.java

```
BiFunction<String,Integer,Character> charat
  = String::charAt;
```

Same as (s,i) -> s.charAt(i)

```
System.out.println(charat.apply("ABCDEF", 1));
```

```
Function<String,Integer> parseint = Integer::parseInt;
```

Same as fsi1, fs2 and fs3

```
Function<Integer,Character> hex1
  = "0123456789ABCDEF"::charAt;
```

Conversion to hex digit

Class and array constructors / Factory

```
Function<Integer,C> makeC = C::new; // (i)-> new C(i)
Function<Integer,Double[]> make1DArray = Double[]::new;
```

Targeted function type (TFT)

- A lambda expression or method reference expression does not have a type in itself
- Therefore must have a *targeted function type*
- Lambda or method reference must appear as
  - Assignment right hand side:
    - `Function<String,Integer> f = Integer::parseInt;`

TFT

  - Argument to call:
    - `stringList.map(Integer::parseInt)`

`map`'s argument type is TFT

  - In a cast:
    - `(Function<String,Integer>)Integer::parseInt`

TFT

  - Argument to **`return`** statement:
    - `return Integer::parseInt;`

Enclosing method's return type is TFT

Functions as arguments: map

```
public <U> FunList<U> map(Function<T,U> f) {
  return new FunList<U>(map(f, first));
}
static <T,U> Node<U> map(Function<T,U> f, Node<T> xs) {
  return xs == null ? null
       : new Node<U>(f.apply(xs.item), map(f, xs.next));
}
```

Example154.java

- Function **`map`** encodes general behavior
  - Transform each list element to make a new list
  - Argument **`f`** expresses the specific transformation
- Same effect as OO “template method pattern”

Calling map

`7 9 13`

```
FunList<Double> list8 = list5.map(i -> 2.5 * i);
```

`17.5 22.5 32.5`

```
FunList<Boolean> list9 = list5.map(i -> i < 10);
```

`true true false`

Functions as arguments: reduce

```
static <T,U> U reduce(U x0, BiFunction<U,T,U> op, Node<T> xs) {
  return xs == null ? x0
       : reduce(op.apply(x0, xs.item), op, xs.next);
}
```

- `list.reduce(x0, op)`
  `= x0❖x1❖...❖xn`
  if we write `op.apply(x,y)` as `x❖y`

- Example: `list.reduce(0, (x,y) -> x+y)`
  `= 0+x1+...+xn`

Example154.java

Calling reduce

Example154.java

17.5 22.5 32.5

```
double sum = list8.reduce(0.0, (res, item) -> res + item);
```

72.5

```
double product = list8.reduce(1.0, (res, item) -> res * item);
```

12796.875

```
boolean allBig
        = list8.reduce(true, (res, item) -> res && item > 10);
```

true

Tail recursion and loops

```
static <T,U> U reduce(U x0, BiFunction<U,T,U> op, Node<T> xs) {
  return xs == null ? x0
       : reduce(op.apply(x0, xs.item), op, xs.next);
}
```

Tail call

- A call that is the func’s last action is a tail call
- A tail-recursive func can be replaced by a loop

```
static <T,U> U reduce(U x0, BiFunction<U,T,U> op, Node<T> xs) {
  while (xs != null) {
    x0 = op.apply(x0, xs.item);
    xs = xs.next;
  }
  return x0;
}
```

Loop version of reduce

Example154.java

  - The Java compiler does *not* do that automatically

Java 8 functional interfaces

- A *functional interface* has exactly one abstract method

```
interface Function<T,R> {
  R apply(T x);
}
```

Type of functions from T to R

C#: Func<T,R>

F#: T -> R

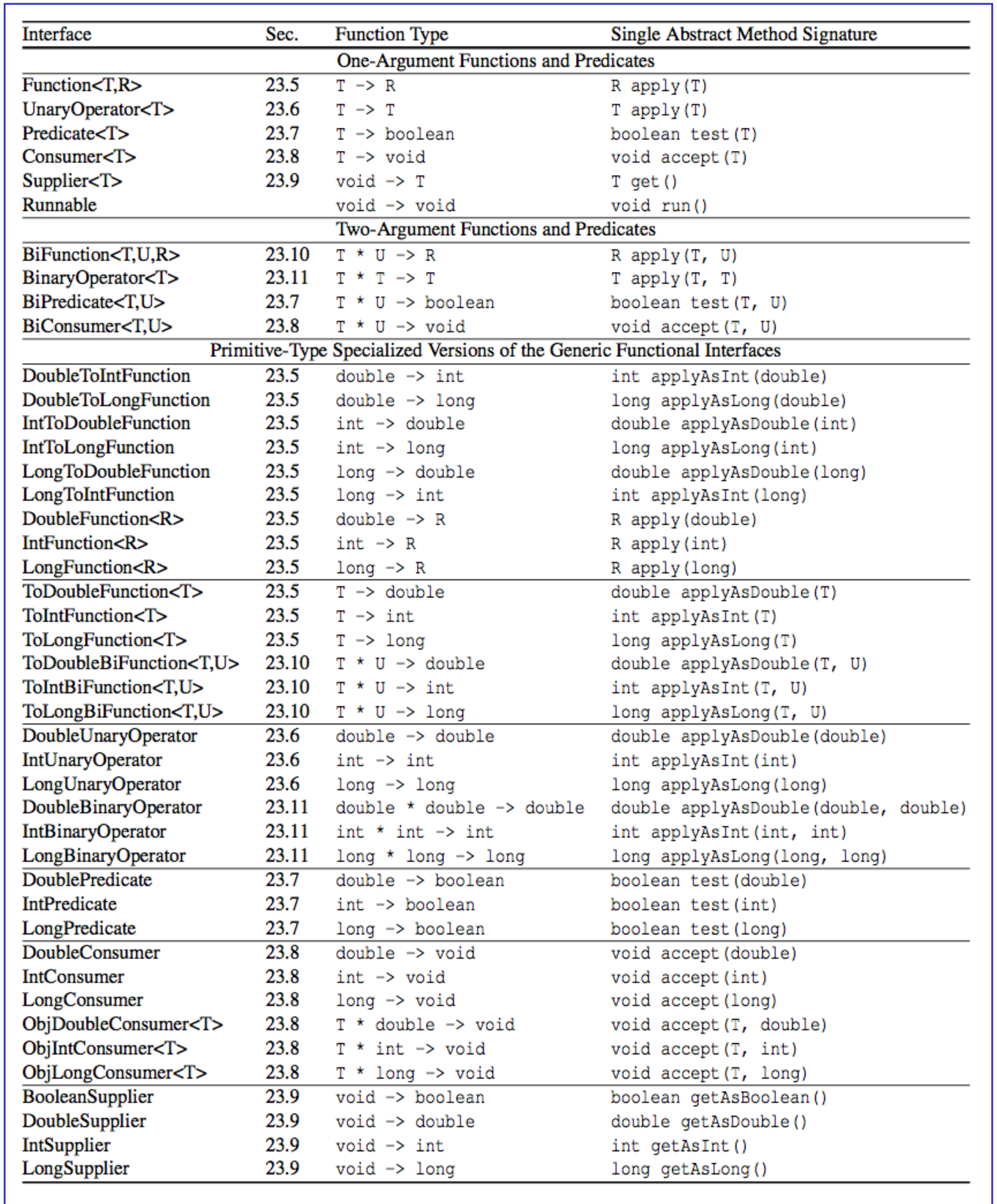
```
interface Consumer<T> {
  void accept(T x);
}
```

Type of functions from T to void

C#: Action<T>

F#: T -> unit

(Too) many functional interfaces



Interface	Sec.	Function Type	Single Abstract Method Signature
		One-Argument Functions and Predicates	
Function<T,R>	23.5	`T -> R`	`R apply(T)`
UnaryOperator<T>	23.6	`T -> T`	`T apply(T)`
Predicate<T>	23.7	`T -> boolean`	`boolean test(T)`
Consumer<T>	23.8	`T -> void`	`void accept(T)`
Supplier<T>	23.9	`void -> T`	`T get()`
Runnable		`void -> void`	`void run()`
		Two-Argument Functions and Predicates	
BiFunction<T,U,R>	23.10	`T * U -> R`	`R apply(T, U)`
BinaryOperator<T>	23.11	`T * T -> T`	`T apply(T, T)`
BiPredicate<T,U>	23.7	`T * U -> boolean`	`boolean test(T, U)`
BiConsumer<T,U>	23.8	`T * U -> void`	`void accept(T, U)`
		Primitive-Type Specialized Versions of the Generic Functional Interfaces	
DoubleToIntFunction	23.5	`double -> int`	`int applyAsInt(double)`
DoubleToLongFunction	23.5	`double -> long`	`long applyAsLong(double)`
IntToDoubleFunction	23.5	`int -> double`	`double applyAsDouble(int)`
IntToLongFunction	23.5	`int -> long`	`long applyAsLong(int)`
LongToDoubleFunction	23.5	`long -> double`	`double applyAsDouble(long)`
LongToIntFunction	23.5	`long -> int`	`int applyAsInt(long)`
DoubleFunction<R>	23.5	`double -> R`	`R apply(double)`
IntFunction<R>	23.5	`int -> R`	`R apply(int)`
LongFunction<R>	23.5	`long -> R`	`R apply(long)`
ToDoubleFunction<T>	23.5	`T -> double`	`double applyAsDouble(T)`
ToIntFunction<T>	23.5	`T -> int`	`int applyAsInt(T)`
ToLongFunction<T>	23.5	`T -> long`	`long applyAsLong(T)`
ToDoubleBiFunction<T,U>	23.10	`T * U -> double`	`double applyAsDouble(T, U)`
ToIntBiFunction<T,U>	23.10	`T * U -> int`	`int applyAsInt(T, U)`
ToLongBiFunction<T,U>	23.10	`T * U -> long`	`long applyAsLong(T, U)`
DoubleUnaryOperator	23.6	`double -> double`	`double applyAsDouble(double)`
IntUnaryOperator	23.6	`int -> int`	`int applyAsInt(int)`
LongUnaryOperator	23.6	`long -> long`	`long applyAsLong(long)`
DoubleBinaryOperator	23.11	`double * double -> double`	`double applyAsDouble(double, double)`
IntBinaryOperator	23.11	`int * int -> int`	`int applyAsInt(int, int)`
LongBinaryOperator	23.11	`long * long -> long`	`long applyAsLong(long, long)`
DoublePredicate	23.7	`double -> boolean`	`boolean test(double)`
IntPredicate	23.7	`int -> boolean`	`boolean test(int)`
LongPredicate	23.7	`long -> boolean`	`boolean test(long)`
DoubleConsumer	23.8	`double -> void`	`void accept(double)`
IntConsumer	23.8	`int -> void`	`void accept(int)`
LongConsumer	23.8	`long -> void`	`void accept(long)`
ObjDoubleConsumer<T>	23.8	`T * double -> void`	`void accept(T, double)`
ObjIntConsumer<T>	23.8	`T * int -> void`	`void accept(T, int)`
ObjLongConsumer<T>	23.8	`T * long -> void`	`void accept(T, long)`
BooleanSupplier	23.9	`void -> boolean`	`boolean getAsBoolean()`
DoubleSupplier	23.9	`void -> double`	`double getAsDouble()`
IntSupplier	23.9	`void -> int`	`int getAsInt()`
LongSupplier	23.9	`void -> long`	`long getAsLong()`

```
interface IntFunction<R> {
  R apply(int x);
}
```

Use instead of Function<Integer,R> to avoid (un)boxing

Primitive-type specialized interfaces

Java Precisely 3rd ed. page 125

Primitive-type specialized interfaces for int, double, and long

```
interface Function<T,R> {
  R apply(T x);
}
```

```
interface IntFunction<R> {
  R apply(int x);
}
```

Why both?

What difference?

```
Function<Integer,String> f1 = i -> "#" + i;
IntFunction<String> f2 = i -> "#" + i;
```

- Calling **`f1.apply(i)`** will *box* **`i`** as Integer
  - Allocating object in heap, takes time and memory
- Calling **`f2.apply(i)`** avoids boxing, is faster
- Purely a matter of performance

Functions that return functions

- Conversion of n to English numeral, cases

  n < 20 : one, two, ..., nineteen

  n < 100: twenty-three, ...

  n >= 100: two hundred forty-three, ...

  n >= 1000: three thousand two hundred forty-three...

  n >= 1 million: ...

  n >= 1 billion: ...

Same pattern

Convert n < 100

```
private static String less100(long n) {
  return n<20 ? ones[(int)n]
           : tens[(int)n/10-2] + after("-", ones[(int)n%10]);
}
static LongFunction<String> less(long limit, String unit,
                                 LongFunction<String> conv) {
  return n -> n<limit ? conv.apply(n)
                      : conv.apply(n/limit) + " " + unit
                        + after(" ", conv.apply(n%limit));
}
```

Example158.ja

Functions that return functions

- Using the general higher-order function

```
static final LongFunction<String>
  less1K = less(          100, "hundred",  Example158::less100),
  less1M = less(        1_000, "thousand", less1K),
  less1B = less(    1_000_000, "million",  less1M),
  less1G = less(1_000_000_000, "billion",  less1B);
```

Example158.java

- Converting to English numerals:

```
public static String toEnglish(long n) {
  return n==0 ? "zero" : n<0 ? "minus " + less1G.apply(-n)
                             : less1G.apply(n);
}
```

`toEnglish(2147483647)`

```
two billion one hundred forty-seven million
four hundred eighty-three thousand six hundred forty-seven
```

Streams for bulk data

- Stream<T> is a finite or infinite sequence of T
  - Possibly lazily generated
  - Possibly parallel
- Stream methods
  - **`map`**, **`flatMap`**, **`reduce`**, **`filter`**, ...
  - These take functions as arguments
  - Can be combined into pipelines
  - Java optimizes (and parallelizes) the pipelines well
- Similar to
  - Iterators, but very different implementation
  - The extension methods underlying .NET Linq

Some stream operations

- `Stream<Integer> s = Stream.of(2, 3, 5)`
- `s.filter(p)` = the `x` where `p.test(x)` holds

  `s.filter(x -> x%2==0)` gives 2
- `s.map(f)` = results of `f.apply(x)` for `x` in `s`

  `s.map(x -> 3*x)` gives 6, 9, 15
- `s.flatMap(f)` = a flattening of the streams created by `f.apply(x)` for `x` in `s`

  `s.flatMap(x -> Stream.of(x,x+1))` gives 2,3,3,4,5,6
- `s.findAny()` = some element of `s`, if any, or else the absent Option<T> value

  `s.findAny()` gives 2 or 3 or 5
- `s.reduce(x0, op)` = `x0❖s0❖...❖sn` if we write `op.apply(x,y)` as `x❖y`

  `s.reduce(1, (x,y)->x*y)` gives 1*2*3*5 = 30

Similar functions are everywhere

- Java stream **`map`** is called
  - **`map`** in Haskell, Scala, F#, Clojure
  - **`Select`** in C#
- Java stream **`flatMap`** is called
  - **`flatMap`** in Haskell, Scala
  - **`collect`** in F#
  - **`SelectMany`** in C#
  - **`mapcat`** in Clojure
- Java **`reduce`** is a special (assoc. op.) case of
  - **`foldl`** in Haskell
  - **`foldLeft`** in Scala
  - **`fold`** in F#
  - **`Aggregate`** in C#
  - **`reduce`** in Clojure

Counting primes on Java 8 streams

- Our old standard Java for loop:

```
int count = 0;
for (int i=0; i<range; i++)
  if (isPrime(i))
    count++;
```

Classical efficient imperative loop

- Sequential Java 8 stream:

```
IntStream.range(0, range)
.filter(i -> isPrime(i))
.count()
```

Pure functional programming …

- Parallel Java 8 stream:

```
IntStream.range(0, range)
.parallel()
.filter(i -> isPrime(i))
.count()
```

… and thus parallelizable and thread-safe

Performance results (!!)

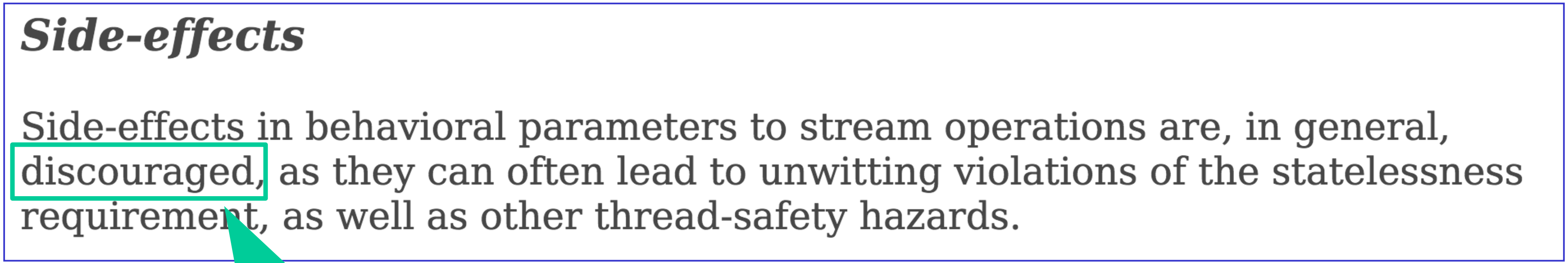
- Counting the primes in 0 ...99,999

Method	Intel i7 (ms)	AMD Opteron (ms)
Sequential for-loop	9.9	40.5
Sequential stream	9.9	40.8
Parallel stream	2.8	1.7
Best thread-parallel	3.0	4.9
Best task-parallel	2.6	1.9

- Functional streams give the simplest solution
- Nearly as fast as tasks and threads, or faster:
  - Intel i7 (4 cores) speed-up: 3.6 x
  - AMD Opteron (32 cores) speed-up: 24.2 x
- The future is parallel – and functional ☺

Purity: side-effect freedom

- From the java.util.stream package docs:



Side-effects

Side-effects in behavioral parameters to stream operations are, in general, discouraged, as they can often lead to unwitting violations of the statelessness requirement, as well as other thread-safety hazards.

This means ”catastrophic”

- Java compiler (types) cannot enforce purity
- Java runtime cannot detect violation of purity

Creating streams 1

- Explicitly or from array, collection or map:

```
IntStream is = IntStream.of(2, 3, 5, 7, 11, 13);

String[] a = { "Hoover", "Roosevelt", ...};
Stream<String> presidents = Arrays.stream(a);

Collection<String> coll = ...;
Stream<String> countries = coll.stream();

Map<String,Integer> phoneNumbers = ...;
Stream<Map.Entry<String,Integer>> phones
  = phoneNumbers.entrySet().stream();
```

Example164.java

- Finite, ordered, sequential, lazily generated

Creating streams 2

- Useful special-case streams:
- `IntStream.range(0, 10_000)`
- `random.ints(5_000)`
- `bufferedReader.lines()`
- `bitset.stream()`
- Functional iterators for infinite streams
- Imperative generators for infinite streams
- StreamBuilder<T>: eager, only finite streams

Example164.java

Creating streams 3: generators

- Generating 0, 1, 2, 3, …

Functional

Example165.java

```
IntStream nats1 = IntStream.iterate(0, x -> x+1);
```

Most efficient (!!), and parallelizable

Imperative

```
IntStream nats2 = IntStream.generate(new IntSupplier() {
  private int next = 0;
  public int getAsInt() { return next++; }
});
```

Imperative, using final array for mutable state

```
final int[] next = { 0 };
IntStream nats3 = IntStream.generate(() -> next[0]++);
```

Creating streams 4: StreamBuilder

- Convert own linked IntList to an IntStream

```
class IntList {
  public final int item;
  public final IntList next;
  ...
  public static IntStream stream(IntList xs) {
    IntStream.Builder sb = IntStream.builder();
    while (xs != null) {
      sb.accept(xs.item);
      xs = xs.next;
    }
    return sb.build();
  }
}
```

Example182.java

- Eager: no stream element output until end
- Finite: does not work on cyclic lists

Streams for backtracking

- Generate all n-permutations of 0, 1, ..., n-1
  - Eg [2,1,0], [1,2,0], [2,0,1], [0,2,1], [0,1,2], [1,0,2]

Set of numbers not yet used

An incomplete permutation

```
public static Stream<IntList> perms(BitSet todo, IntList tail) {
  if (todo.isEmpty())
    return Stream.of(tail);
  else
    return todo.stream().boxed()
     .flatMap(r -> perms(minus(todo, r), new IntList(r, tail)));
}
```

Example175.java

```
public static Stream<IntList> perms(int n) {
  BitSet todo = new BitSet(n); todo.set(0, n);
  return perms(todo, null);
}
```

{ 0, ..., n-1 }

Empty permutation [ ]

A closer look at generation for n=3

- ({0,1,2}, [])
- ({1,2}, [0])
  - ({2}, [1,0])
    - ({}, [2,1,0])

      Output to stream
  - ({1}, [2,0])
    - ({}, [1,2,0])

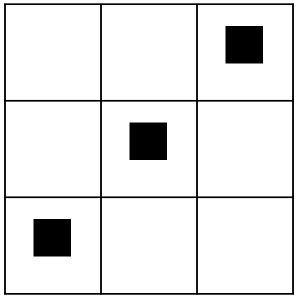
      Output to stream
- ({0,2}, [1])
  - ({2}, [0,1])
    - ({}, [2,0,1])

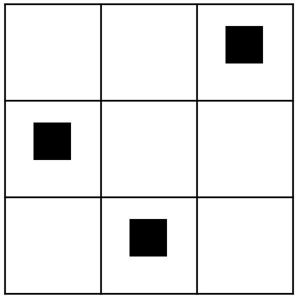
      Output to stream
  - ({0}, [2,1])
    - ({}, [0,2,1])

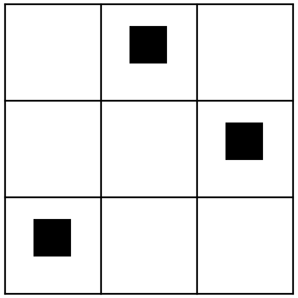
      Output to stream
- ({0,1}, [2])
  - …

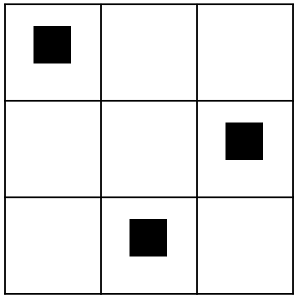
A permutation is a rook (tårn) placement on a chessboard

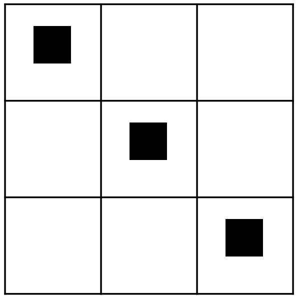
- Uses each column (position) exactly once
- Uses each row (number) exactly once

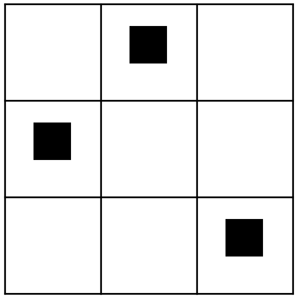

[2, 1, 0]


[1, 2, 0]


[2, 0, 1]


[0, 2, 1]


[0, 1, 2]


[1, 0, 2]

Solutions to the n-queens problem

- For queens, just take diagonals into account:
  - consider only r that are safe for the partial solution

```
public static Stream<IntList> queens(BitSet todo, IntList tail) {
  if (todo.isEmpty())
    return Stream.of(tail);
  else
    return todo.stream()
     .filter(r -> safe(r, tail)).boxed()
     .flatMap(r -> queens(minus(todo, r), new IntList(r, tail)));
}
```

Diagonal check

.parallel()

Example176.java

```
public static boolean safe(int mid, IntList tail) {
  return safe(mid+1, mid-1, tail);
}
public static boolean safe(int d1, int d2, IntList tail) {
  return tail==null || d1!=tail.item && d2!=tail.item && safe(d1+1, d2-1, tail.next);
}
```

- Simple, and parallelizable for free, 3.5 x faster
- Solve and generate sudokus: much the same

Versatility of streams

- Many uses of a stream of solutions
  - Print the number of solutions

```
System.out.println(queens(8).count());
```

  - Print all solutions

```
queens(8).forEach(System.out::println);
```

  - Print an arbitrary solution (if there is one)

```
System.out.println(queens(8).findAny());
```

  - Print the 20 first solutions

```
queens(8).limit(20).forEach(System.out::println);
```

Example174.java

- Much harder in an imperative version
- Separation of concerns (Dijkstra): *production* of solutions versus *consumption* of solutions

Streams for quasi-infinite sequences

- van der Corput numbers
  - 1/2, 1/4, 3/4, 1/8, 5/8, 3/8, 7/8, ...
  - Dense and uniform in interval [0, 1]
  - For simulation and finance, Black-Scholes options
- Trick: v d Corput numbers as base-2 fractions

  0.1, 0.01, 0.11, 0.001, 0.101, 0.011, 0.111 ...

  are bit-reversals of 1, 2, 3, 4, 5, 6, 7, ... in binary

```
public static DoubleStream vanDerCorput() {
  return IntStream.range(1, 31).asDoubleStream()
        .flatMap(b -> bitReversedRange((int)b));
}

private static DoubleStream bitReversedRange(int b) {
  final long bp = Math.round(Math.pow(2, b));
  return LongStream.range(bp/2, bp)
        .mapToDouble(i -> (double)(bitReverse((int)i) >>> (32-b)) / bp);
}
```

Example183.java

Collectors: aggregation of streams

- To format an IntList as string "`[2, 3, 5, 7]`"
  - Convert the list to an IntStream
  - Convert each element to get Stream<String>
  - Use a predefined Collector to build final result

```
public String toString() {
  return stream(this).mapToObj(String::valueOf)
        .collect(Collectors.joining(",", "[", "]"));
}
```

Example182.java

```
public static String toString(IntList xs) {
  StringBuilder sb = new StringBuilder();
  sb.append("[");
  boolean first = true;
  while (xs != null) {
    if (!first)
      sb.append(", ");
    first = false;
    sb.append(xs.item);
    xs = xs.next;
  }
  return sb.append("]").toString();
}
```

The alternative "direct" solution requires care and cleverness

Java 8 stream properties

- Some stream dimensions
  - Finite vs infinite
  - Lazily generated (by **`iterate`**, **`generate`**, ...) vs eagerly generated (stream builders)
  - Ordered (**`map`**, **`filter`**, **`limit`** ... preserve element order) vs unordered
  - Sequential (all elements processed on one thread) vs parallel
- Java streams
  - can be lazily generated, like Haskell lists
  - but are *use-once*, unlike Haskell lists
    - reduces risk of space leaks (and limits expressiveness)

Parallel (functional) array operations

Example25.java

- Simulating random motion on a line
  - Take n random steps of length at most [-1, +1]:

```
double[] a = new Random().doubles(n, -1.0, +1.0)
             .toArray();
```

  - Compute the positions at end of each step: a[0], a[0]+a[1], a[0]+a[1]+a[2], ...

```
Arrays.parallelPrefix(a, (x,y) -> x+y);
```

  - Find the maximal absolute distance from start:

```
double maxDist = Arrays.stream(a).map(Math::abs)
                 .max().getAsDouble();
```

- A lot done, fast, without loops or assignments
  - Just arrays and streams and functions

Array and streams and parallel ...

- Side-effect free associative array aggregation

```
Arrays.parallelPrefix(a, (x,y) -> x+y);
```

- Such operations can be parallelized well
  - So-called *prefix scans* (Blelloch 1990)
  - Lots of applications: sum, product, sorting, comparison, lexing, polynomial evaluation, ...

- Streams and arrays *complement* each other
  - Streams: lazy, possibly infinite, non-materialized, use-once, parallel pipelines
  - Arrays: eager, finite, materialized, use-many-times, parallel prefix scans

Some problems with Java streams

- Streams are use-once & have other restrictions
  - Probably to permit easy parallelization
- Hard to create lazy finite streams
  - Probably to allow high-performance implementation
- Difficult to control resource consumption
- A single side-effect may mess everything up completely
- Sometimes **`.parallel()`** hurts performance a lot
  - See exercise
  - And strange behavior, in parallel + limit in Sudoku generator
- Laziness in Java is subtle, easily goes wrong:

```
static Stream<String> getPageAsStream(String url) throws IOException {
  try (BufferedReader in
       = new BufferedReader(new InputStreamReader(
                                          new URL(url).openStream()))) {
      return in.lines();
    }
  }
```

Closes the reader too early, so any use of the Stream<String> causes IOException: Stream closed

Example216.java

Useless

This week

- Reading
  - Java Precisely 3rd ed. §11.13, 11.14, 23, 24, 25
- Exercises
  - Extend immutable list class with functional programming; use parallel array operations; use streams of words and streams of numbers
- Read before next week's lecture
  - Goetz chapters 6 and 8
  - Bloch items 68, 69