

301AA - Advanced Programming

Lecturer: **Andrea Corradini**

andrea@di.unipi.it

<http://pages.di.unipi.it/corradini/>

AP-22: Streams in Java 8


Java 8: language extensions


Java 8 is the biggest change to Java since the inception of the language. Main new features:

- **Lambda expressions**
 - Method references
 - Default methods in interfaces
 - Improved type inference
- **Stream API**



A big challenge was to introduce lambdas without requiring recompilation of existing binaries

Streams in Java 8

The **java.util.stream** package provides utilities to support functional-style operations on streams of values. **Streams** differ from **collections** in several ways: 



- **No storage.** A stream is not a data structure that stores elements; instead, it conveys elements from a *source* (a data structure, an array, a generator function, an I/O channel,...) through a *pipeline* of computational operations.
- **Functional in nature.** An operation on a stream produces a result, but does not modify its source. 





Streams in Java 8 (cont'd)

- **Laziness-seeking**. Many stream operations, can be implemented lazily, exposing opportunities for optimization. Stream operations are divided into **intermediate** (stream-producing) operations and **terminal** (value- or side-effect-producing) operations. *Intermediate operations are always lazy.* 
- **Possibly unbounded**. Collections have a finite size, streams need not. Short-circuiting operations such as *limit(n)* or *findFirst()* can allow computations on infinite streams to complete in finite time. 
- **Consumable**. The elements of a stream are only visited once during the life of a stream. Like an *Iterator*, a new stream must be generated to revisit the same elements of the source.

Pipelines



- A typical pipeline contains
 - A **source**, producing (by need) the elements of the stream
 - Zero or more **intermediate operations**, producing streams
 - A **terminal operation**, producing side-effects or non-stream values 
- Example of typical pattern: filter / map / reduce 



```
double average = listing // collection of Person
 .stream() // stream wrapper over a collection
    .filter(p -> p.getGender() == Person.Sex.MALE) // filter 
    .mapToInt(Person::getAge) // extracts stream of ages
    .average() // computes average (reduce/fold) 
 .getAsDouble(); // extracts result from OptionalDouble
```

Anatomy of the Stream Pipeline


- A Stream is processed through a **pipeline** of operations
- A Stream starts with a **source**
- **Intermediate methods** are performed on the Stream elements. These methods produce Streams and are not processed until the **terminal method** is called.
- The Stream is considered **consumed** when a terminal operation is invoked. No other operation can be performed on the Stream elements afterwards
- A Stream pipeline may contain some **short-circuit methods** (which could be intermediate or terminal methods) that cause the earlier intermediate methods to be processed only until the short-circuit method can be evaluated.

Stream sources

Streams can be obtained in a number of ways:


- From a **Collection** via the **stream()** and **parallelStream()** methods;
- From an array via **Arrays.stream(Object[])**; 
- From static factory methods on the stream classes, such as **Stream.of(Object[])**, **IntStream.range(int, int)** or **Stream.iterate(Object, UnaryOperator)**; 
- The lines of a file can be obtained from **BufferedReader.lines()**;
- Streams of file paths can be obtained from methods in **Files**;
- Streams of random numbers can be obtained from **Random.ints()**;
- Generators, like **generate** or **iterate**;
- Numerous other methods in the JDK...

Intermediate Operations

- An intermediate operation keeps a stream open for further operations. Intermediate operations are lazy.
- Several intermediate operations have arguments of *functional interfaces*, thus *lambdas* can be used 

```
Stream<T> filter(Predicate<? super T> predicate) // filter
```


```
IntStream mapToInt(ToIntFunction<? super T> mapper) // map f:T -> int
```

```
<R> Stream<R> map(Function<? super T,? extends R> mapper)  map f:T->R
```

```
Stream<T> peek(Consumer<? super T> action)  /performs action on elements
```

```
Stream<T> distinct() // remove duplicates - stateful 
```


```
Stream<T> sorted() // sort elements of the stream - stateful 
```

```
Stream<T> limit(long maxSize) // truncate 
```

```
Stream<T> skip(long n) // skips first n elements
```



Using peek...

- **peek** does not affect the stream
- A typical use is for debugging

```
IntStream.of(1, 2, 3, 4)   
    .filter(e -> e > 2)  
    .peek(e -> System.out.println("Filtered value: " + e))  
    .map(e -> e * e)  
    .peek(e -> System.out.println("Mapped value: " + e))  
    .sum();
```


Terminal Operations


- A **terminal operation** must be the final operation on a stream. Once a terminal operation is invoked, the stream is consumed and is no longer usable.
- Typical: collect values in a data structure, reduce to a value, print or other side effects.

```
void forEach(Consumer<? super T> action) 
```

```
Object[] toArray()
```

```
T reduce(T identity, BinaryOperator<T> accumulator) // fold
```

```
Optional<T> reduce(BinaryOperator<T> accumulator) // fold 
```


```
Optional<T> min(Comparator<? super T> comparator) 
```

```
boolean allMatch(Predicate<? super T> predicate) // short-circuiting
```

```
boolean anyMatch(Predicate<? super T> predicate) // short-circuiting
```

```
Optional<T> findAny() // short-circuiting
```

Types of Streams


- Streams only for reference types, int, long and double 
 - Minor primitive types are missing


```
"Hello world!".chars()  
    .forEach(System.out::print) ;  
  
// prints  
721011081081113211911111410810033
```

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




From Reduce to Collect: Mutable Reduction



- Suppose we want to concatenate a stream of strings.
- The following works but is highly inefficient (it builds one new string for each element):

```
String concatenated = listOfStrings  
    .stream()  
    .reduce("", String::concat) 
```

- Better to “accumulate” the elements in a mutable object (a StringBuilder, a collection, ...) 

- The **mutable reduction operation** is called **collect()**. It requires three functions: 


- a **supplier** function to construct new instances of the result container, 
- an **accumulator** function to incorporate an input element into a result container, 
- a **combining function** to merge the contents of one result container into another. 


```
 <R> R collect( Supplier<R> supplier,  
               BiConsumer<R, ? super T> accumulator,  
               BiConsumer<R, R> combiner); 
```

Mutable reductions: examples


- Collecting the String representations of the elements of a stream into an ArrayList: 

```
// no streams
ArrayList<String> strings = new ArrayList<>();
for (T element : stream) {
    strings.add(element.toString());
}
```

```
// with streams and lambdas
ArrayList<String> strings =
    stream.collect(() -> new ArrayList<>(), //Supplier 
        (c, e) -> c.add(e.toString()),    // Accumulator
        (c1, c2) -> c1.addAll(c2));       //Combining
```

```
// with streams and method references 
ArrayList<String> strings = stream.map(Object::toString)
    .collect(ArrayList::new, ArrayList::add, ArrayList::addAll);
```

Mutable reductions: Collectors

- Method `collect` can also be invoked with a `Collector` argument: 

```
<R,A> R collect(Collector<? super T,A,R> collector)
```


- A `Collector` encapsulates the functions used as arguments to `collect(Supplier, BiConsumer, BiConsumer)`, allowing for reuse of collection strategies and composition of collect operations.

```
// The following will accumulate strings into an ArrayList:
```


```
List<String> asList = stringStream.collect(Collectors.toList());
```


```
// The following will classify Person objects by city:
```

```
Map<String, List<Person>> peopleByCity =
```

```
personStream.collect(Collectors.groupingBy(Person::getCity)); 
```

Infinite Streams

- Streams wrapping collections are finite 
- Infinite streams can be generated with:
 - iterate
 - generate

```
static <T> Stream<T> iterate(T seed, UnaryOperator<T> f) 
```

```
// Example: summing first 10 elements of an infinite stream
```

```
int sum = Stream.iterate(0, x -> x+1).limit(10).reduce(0, (x, s) -> x+s);
```

```
static <T> Stream<T> generate(Supplier<T> s)
```

```
// Example: printing 10 random numbers 
```

```
Stream.generate(Math::random).limit(10).forEach(System.out::println);
```


Parallelism

- Streams facilitate parallel execution 🗨️
- Stream operations can execute either in serial (default) or in parallel

```
double average = persons //average age of all male
    .parallelStream()      // members in parallel
    .filter(p -> p.getGender() == Person.Sex.MALE)
    .mapToInt(Person::getAge)
    .average()
    .getAsDouble();
```

- The runtime support takes care of using multithreading for parallel execution, in a transparent way 🗨️
- If operations don't have side-effects, **thread-safety is guaranteed** even if non-thread-safe collections are used (e.g.: ArrayList)

Parallelism (2)

- Concurrent mutable reduction supported for parallel streams
 - Suitable methods of `Collector` 
- Order of processing stream elements depends on serial/parallel execution and intermediate operations

```
Integer[] intArray = {1, 2, 3, 4, 5, 6, 7, 8 };
List<Integer> listOfIntegers = new ArrayList<>(Arrays.asList(intArray));
listOfIntegers .stream()
                .forEach(e -> System.out.print(e + " "));
// prints: 1 2 3 4 5 6 7 8
listOfIntegers .parallelStream()
                .forEach(e -> System.out.print(e + " "));
// may print: 3 4 1 6 2 5 7 8
```

A simple parallel stream example

Slide by Josh Bloch

- Consider this for-loop (.96 s runtime; dual-core laptop)

```
long sum = 0;
for (long j = 0; j < Integer.MAX_VALUE; j++) sum += j;
```

- Equivalent stream computation (1.5 s)

```
long sum = LongStream.range(0, Integer.MAX_VALUE).sum();
```


- Equivalent parallel computation (.77 s)

```
long sum = LongStream.range(0, Integer.MAX_VALUE)
    .parallel().sum();
```



- Fastest handcrafted parallel code I could write (.48 s)
 - You don't want to see the code. It took hours.

When to use a parallel stream – loosely speaking

Slide by Josh Bloch

- When operations are independent, and
- Either or both:
 - Operations are computationally expensive 
 - Operations are applied to many elements of efficiently splittable data structures
- **Always measure before and after parallelizing!**
 - Jackson's third law of optimization

SplitIterator: Streams from collections


- A stream wrapping a collection uses a **SplitIterator** over the collection
- This is the parallel analogue of an **Iterator**: it describes a (possibly infinite) collection of elements with support for 
 - sequentially advancing,
 - *applying an action* to the next or to all remaining elements
 - splitting off some portion of the input into another spliterator which can be processed in parallel. 
- At the lowest level, all streams are driven by a spliterator.

When to use a parallel stream – in detail

Slide by Josh Bloch

- Consider `s.parallelStream().operation(f)` if
 - `f`, the per-element function, is independent
 - i.e., computation for each element doesn't rely on or impact any other
 - `s`, the source collection, is efficiently splittable
 - Most collections, and `java.util.SplittableRandom`
 - NOT most I/O-based sources
 - Total time to execute sequential version roughly $> 100\mu\text{s}$
 - “Multiply N (number of elements) by Q (cost per element of `f`), guestimating Q as the number of operations or lines of code, and then checking that $N*Q$ is at least 10,000.

Critical issues

- Non-interference
 - Behavioural parameters (like lambdas) of stream operations should not affect the source (*non-interfering behaviour*)
 - Risk of **ConcurrentModificationExceptions**, even if in single thread 
- Stateless behaviours
 - Stateless behaviour for intermediate operations is encouraged, as it facilitates parallelism, and functional style, thus maintenance
- Parallelism and thread safety
 - For parallel streams with side-effects, ensuring thread safety is the programmers' responsibility

Interference: an example


```
try {
    List<String> listOfStrings =
        new ArrayList<>(Arrays.asList("one", "two"));



    String concatenatedString = listOfStrings
        .stream()
        // Don't do this! Interference occurs here.
        .peek(s -> listOfStrings.add("three"))
        .reduce((a, b) -> a + " " + b)
        .get();

    System.out.println("Concatenated string: " + concatenatedString);
} catch (Exception e) {
    System.out.println("Exception caught: " + e.toString());
}
```

MONADS IN JAVA....

Monads in Java: Optional and Stream

```
public static <T> Optional<T> of(T value)   
// Returns an Optional with the specified present non-null value.  
  
<U> Optional<U> flatMap(Function<? super T,Optional<U>> mapper)  
/* If a value is present, apply the provided Optional-bearing mapping  
function to it, return that result, otherwise return an empty  
Optional. */
```

```
static <T> Stream<T> of(T t)   
// Returns a sequential Stream containing a single element.  
  
<R> Stream<R> flatMap(  
    Function<? super T,? extends Stream<? extends R>> mapper)  
/* Returns a stream consisting of the results of replacing each element  
of this stream with the contents of a mapped stream produced by applying  
the provided mapping function to each element. */
```

Functional programming and monads in Java

- About the way monads entered the Java landscape I suggest reading the slides on **Monadic Java** by Mario Fusco.
- More on functional programming in Java in the book **Java 8 in action**

