Java 8

Stream Performance

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objective

- how do streams perform?
  - explore whether / when parallel streams outperfom seq. streams
  - compare performance of streams to performance of regular loops
- what determines stream performance?
  - take a glance at some stream internal mechanisms

speaker's relationship to topic

- independent trainer / consultant / author
  - teaching C++ and Java for ~20 years
  - curriculum of half a dozen challenging Java seminars
  - JCP observer and Java champion since 2005
  - co-author of "Effective Java" column
  - author of Java Generics FAQ
  - author of Lambda Tutorial & Reference

agenda

- **introduction**
- loop vs. sequential stream
- sequential vs. parallel stream

what is a stream?

- equivalent of
  sequence from functional programming languages
  - object-oriented view: *internal iterator pattern*
    - see GOF book for more details

- idea

```
myStream. forEach (  s -> System.out.print(s)  );
```

↑ *stream operation*

↑ *user-defined functionality applied to each element*

fluent programming

```
myStream. filter   ( s -> s.length() > 3 )
        . mapToInt ( s -> s.length() )

        . forEach  ( System.out::print );
```

intermediate operations

terminal operation

stream operation (points to `forEach`)

user-defined functionality applied to each element (points to `System.out::print`)

obtain a stream

- collection:

```
myCollection.stream(). ...
```

- array:

```
Arrays.stream(myArray). ...
```

- resulting stream
  - does not store any elements
  - just a view of the underlying stream source

- more stream factories, but not in this talk

parallel streams

- collection:

```
myCollection.parallelStream(). ...
```

- array:

```
Arrays.stream(myArray).parallel(). ...
```

- performs stream operations in parallel
  - i.e. with multiple worker threads from fork-join common pool

```
myParallelStream.forEach(s -> System.out.print(s));
```

stream functionality rivals loops

- Java 8 streams:

```
myStream.filter(s -> s.length() > 3)
        .mapToInt(s -> s.length())
        .forEach(System.out::print);
```

```
myStream.filter(s -> s.length() > 3)
        .forEach(s->System.out.print(s.length()));
```

- since Java 5:

```
for (String s : myCol)
  if (s.length() > 3)
    System.out.print(s.length());
```

- pre-Java 5:

```
Iterator iter = myCol.iterator();
while (iter.hasNext()) {
  String s = iter.next();
  if (s.length() > 3)
     System.out.print(s.length());
}
```

obvious question …

… how does the performance compare ?

- loop vs. sequential stream vs. parallel stream

benchmarks …

… done on an older desktop system with:

- Intel E8500,
  - 2 x 3,17GHz
  - 4GB RAM
- Win 7
- JDK 1.8.0_05

- disclaimer: *your mileage may vary*
  - i.e. parallel performance heavily depends on number of CPU-Cores

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- **loop vs. sequential stream**
- sequential vs. parallel stream

how do sequential stream work?

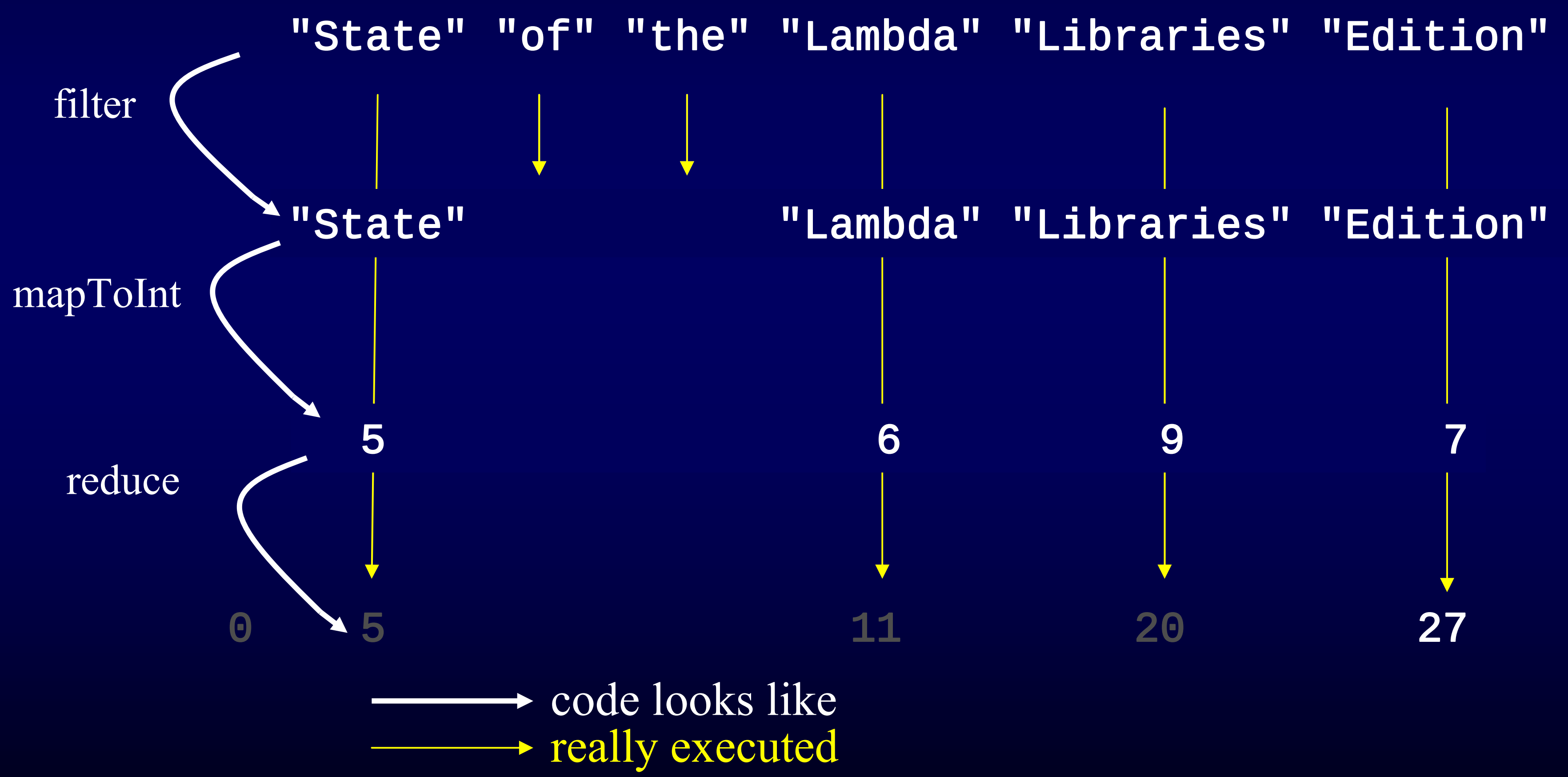
- example

```
String[] txt = { "State", "of", "the", "Lambda",
                                "Libraries", "Edition"};

IntStream is = Arrays.stream(txt).filter(s -> s.length() > 3)
                                 .mapToInt(s -> s.length())
                                 .reduce(0, (l1, l2) -> l1 + l2);
```

- `filter()` and `mapToInt()` return streams
  - intermediate operations
- `reduce()` returns `int`
  - terminal operation,
  - that produces a single result from all elements of the stream

pipelined processing

```
Arrays.stream(txt).filter(s -> s.length() > 3)
                  .mapToInt(s -> s.length())
                  .reduce(0, (l1, l2) -> l1 + l2);
```



benchmark with `int`-array

- `int[500_000]`, find largest element

  - `for`-loop:

```
int[] a = ints;
int e = ints.length;
int m = Integer.MIN_VALUE;

for (int i = 0; i < e; i++)
   if (a[i] > m) m = a[i];
```

  - sequential stream:

```
int m = Arrays.stream(ints)
              .reduce(Integer.MIN_VALUE, Math::max);
```

results

```
for-loop:     0.36 ms
seq. stream:  5.35 ms
```

- `for`-loop is ~15x faster

- are seq. streams always much slower than loops?
  - no, this is the most extreme example
  - lets see the same benchmark with an `ArrayList<Integer>`
    - underlying data structure is also an array
    - this time filled with `Integer` values, i.e. the boxed equivalent of `int`

benchmark with ArrayList<Integer>

- find largest element in an ArrayList with 500_000 elements
  - for-loop:

```
int m = Integer.MIN_VALUE;
for (int i : myList)
   if (i > m) m = i;
```

  - sequential stream:

```
int m = myList.stream()
              .reduce(Integer.MIN_VALUE, Math::max);
```

results

```
ArrayList, for-loop:     6.55 ms
ArrayList, seq. stream:  8.33 ms
```

- for-loop still faster, but only 1.27x
- iteration for `ArrayList` is more expensive
  - boxed elements require an additional memory access (indirection)
  - which does not work well with the CPU's memory cache
- bottom-line:
  - iteration cost dominates the benchmark result
  - performance advantage of the `for`-loop is insignificant

some thoughts

- previous situation:
  - costs of iteration are relative high, but
  - costs of functionality applied to each element are relative low
    - after JIT-compilation:
      more or less the cost of a compare-assembler-instruction

- what if we apply a more expensive functionality
  to each element ?
  - how will this affect the benchmark results ?

expensive functionality

- `slowSin()`
  from Apache Commons Mathematics Library
  - calculates a Taylor approximation of the sine function value for the parameter passed to this method
  - (normally) not in the public interface of the library
    - used to calculate values for an internal table,
    - which is used for interpolation by `FastCalcMath.sin()`

benchmark with `slowSin()`

- `int` array / `ArrayList` with 10_000 elements
  - for-loop:

```
int[] a = ints;
int e = a.length;
double m = Double.MIN_VALUE;

for (int i = 0; i < e; i++) {
   double d = Sine.slowSin(a[i]);
   if (d > m) m = d;
}
```

  - sequential stream:

```
Arrays.stream(ints)
      .mapToDouble(Sine::slowSin)
      .reduce(Double.MIN_VALUE, Math::max);
```

  - code for `ArrayList` changed respectively

results

```
int[], for-loop:          11.72 ms
int[], seq. stream:       11.85 ms
ArrayList, for-loop:      11.84 ms
ArrayList, seq. stream:   11.85 ms
```

- for-loop is not really faster
- reason:
  - applied functionality costs dominate the benchmark result
  - performance advantage of the `for`-loop has evaporated

other aspect (without benchmark)

- today, compilers (javac + JIT) can optimize loops better than stream code

- reasons:
  - linear code (loop) vs. injected functionality (stream)
  - lambdas + method references are new to Java
  - loop optimization is a very mature technology
  - …

for-loop vs. seq. stream / re-cap

- sequential stream can be slower or as fast as for-loop
- depends on
  - costs of the iteration
  - costs of the functionality applied to each element
- the higher the cost (iteration + functionality)
  the closer is stream performance
  to for-loop performance

agenda

- introduction
- loop vs. sequential stream
- **sequential vs. parallel stream**
  - **introduction**
  - stateless functionality
  - stateful functionality

parallel streams

- library side parallelism
  - important feature
    - you need not know anything about threads, etc.
    - very little implementation effort, just: `parallel`
- performance aspect
  - outperform loops, which are inherently sequential

how do parallel stream work?

- example

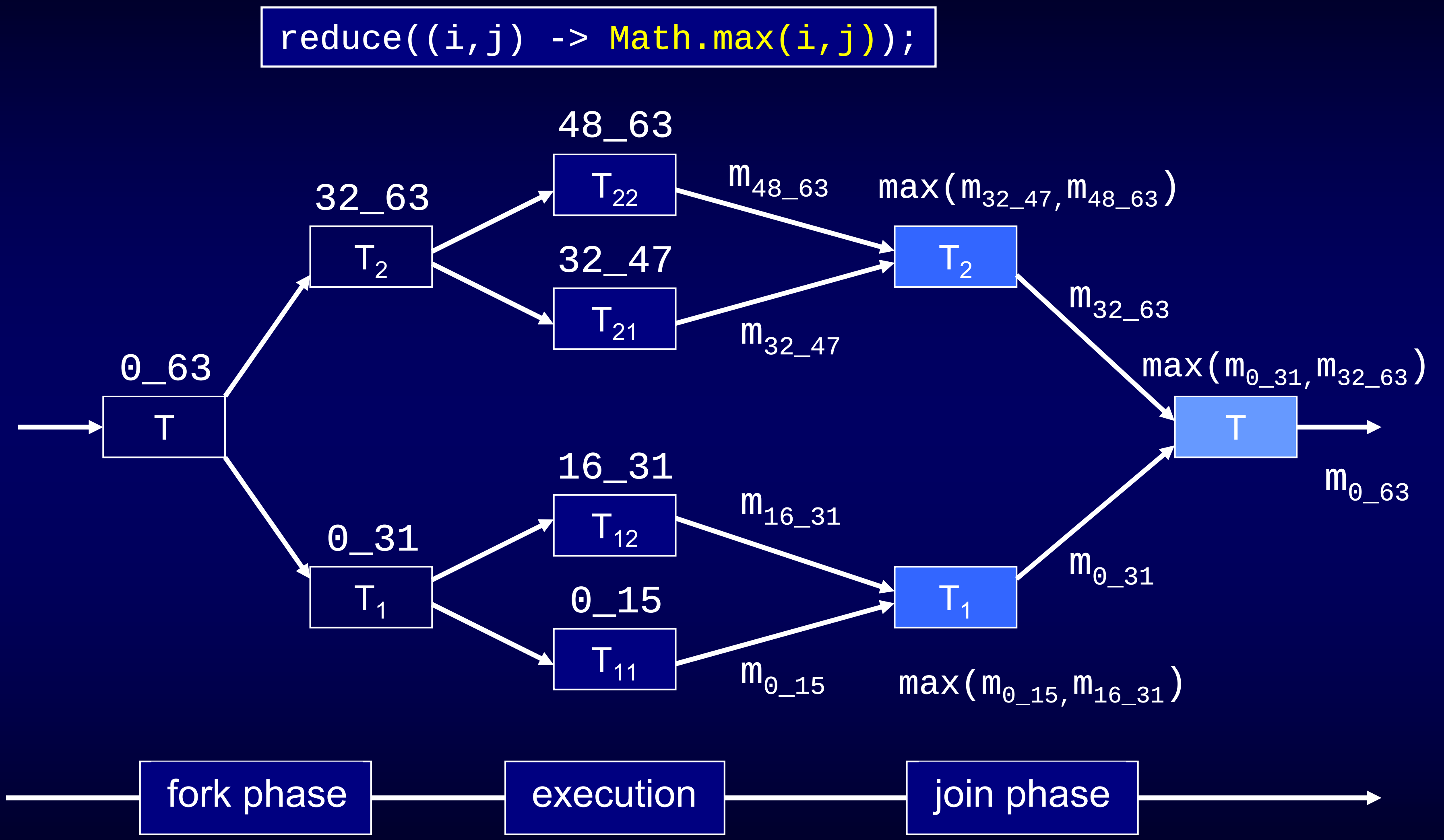
```
final int SIZE = 64;
int[] ints = new int[SIZE];
ThreadLocalRandom rand = ThreadLocalRandom.current();
for (int i=0; i<SIZE; i++) ints[i] = rand.nextInt();

Arrays.stream(ints)
      .parallel()
      .reduce(Math::max)
      .ifPresent(System.out.println(m -> “max is: ” + m));
```

- `parallel()`’s functionality is based on the fork-join framework

fork join tasks

- original task is divided into two sub-tasks
  by splitting the stream source into two parts
  - original task's result are based on sub-tasks' results
  - sub-tasks are divided again … *fork phase*
- at a certain depth partitioning stops
  - tasks at this level (leaf tasks) are executed
  - *execution phase*
- completed sub-task results
  are 'combined' to super-task results
  - *join phase*

find largest element with parallel stream



split level

- deeper split level than shown !!!
  - execution/leaf tasks: ~ 4*numberOfCores
    - 8 tasks for a dual core CPU (only 4 in the previous diagram)
  - i.e. one additional split (only 2 in the previous graphic)

- key abstractions
  - `java.util.Spliterator`
  - `java.util.concurrent.ForkJoinPool.commonPool()`

what is a Spliterator ?

- spliterator = splitter + iterator
- each type of stream source has its own spliterator type
  - knows how to split the stream source
    - e.g. `ArrayList.ArrayListSpliterator`
  - knows how to iterate the stream source
    - in execution phase

what is the CommonPool ?

- *common pool* is a singleton fork-join pool instance
  - introduced with Java 8
  - all parallel stream operations use the common pool
    - so does other parallel JDK functionality (e.g. CompletableFuture), too
- default: parallel execution of stream tasks uses
  - (current) thread that invoked terminal operation, and
  - (number of cores – 1) many threads from common pool
    - if (number of cores) > 1
- this default configuration used for all benchmarks

parallel streams + intermediate operations

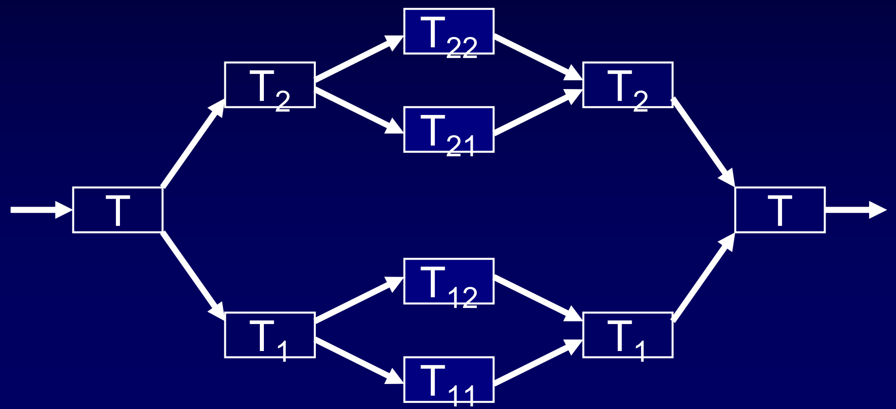
- what if the stream contains
  upstream intermediate operations

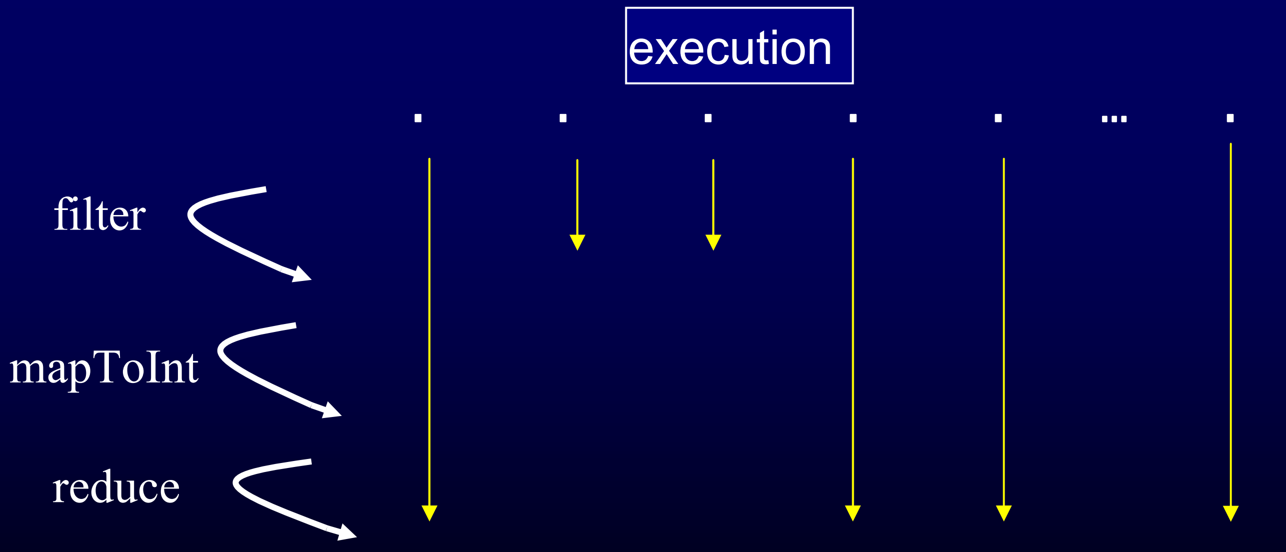
```
... .parallelStream().filter(...)
                     .mapToInt(...)
                     .reduce((i,j) -> Math.max(i,j));
```

when/where are these applied to the stream ?

find largest element in parallel

```
filter(...).mapToInt(...).reduce((i,j) -> Math.max(i,j));
```





parallel overhead …

… compared to sequential stream algorithm

- algorithm is more complicated / resource intensive
  - create fork-join-task objects
    - splitting
    - fork-join-task objects creation
  - thread pool scheduling
  - …
- plus additional GC costs
  - fork-join-task objects have to be reclaimed

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  - **stateless functionality**
  - stateful functionality

back to the first example / benchmark parallel

- find largest element, array / collection, 500_000 elements
  - sequential stream:

```
int m = Arrays.stream(ints)
              .reduce(Integer.MIN_VALUE, Math::max);
```

```
int m = myCollection.stream()
              .reduce(Integer.MIN_VALUE, Math::max);
```

  - parallel stream:

```
int m = Arrays.stream(ints).parallel()
              .reduce(Integer.MIN_VALUE, Math::max);
```

```
int m = myCollection.parallelStream()
              .reduce(Integer.MIN_VALUE, Math::max);
```

results

	seq.	par.	seq./par.
int-Array	5.35 ms	3.35 ms	1.60
ArrayList	8.33 ms	6.33 ms	1.32
LinkedList	12.74 ms	19.57 ms	0.65
HashSet	20.76 ms	16.01 ms	1.30
TreeSet	19.79 ms	15.49 ms	1.28

result discussion

- why is parallel `LinkedList` performance so bad ?
  - hard to split
  - needs 250_000 `iterator`'s `next()` invocations for the first split
    - with `ArrayList`: just some index computation

- performance of the other collections is also not so great
  - functionality applied to each element is not very CPU-expensive
    - after JIT-compilation: cost of a compare-assembler-instruction
  - iteration (element access) is relative expensive (indirection !)
    - but not CPU expensive
      - but more CPU-power is what we have with parallel streams

result discussion (cont.)

- why is parallel `int`-array performance relatively good ?
  - iteration (element access) is no so expensive (no indirection !)

CPU-expensive functionality

- back to `slowSin()`
  - calculates a Taylor approximation of the sine function value for the parameter passed to this method
  - CPU-bound functionality
    - needs only the initial parameter from memory
    - calculation based on it's own (intermediate) results
  - ideal to be speed up by parallel streams with multiple cores

benchmark parallel with `slowSin()`

- array / collection with 10_000 elements
  - array:

```
Arrays.stream(ints) // .parallel()
      .mapToDouble(Sine::slowSin)
      .reduce(Double.MIN_VALUE, (i, j) -> Math.max(i, j);
```

  - collection:

```
myCollection.stream()  // .parallelStream()
            .mapToDouble(Sine::slowSin)
            .reduce(Double.MIN_VALUE, (i, j) -> Math.max(i, j);
```

results

	seq.	par.	seq./par.
int-Array	10.81 ms	6.03 ms	1.79
ArrayList	10.97 ms	6.10 ms	1.80
LinkedList	11.15 ms	6.25 ms	1.78
HashSet	11.15 ms	6.15 ms	1.81
TreeSet	11.14 ms	6.30 ms	1.77

result discussion

- performance improvements for all stream sources
  - by a factor of ~ 1.8
    - even for `LinkedList`
- the ~1.8 is the maximum improvement on our platform
  - the remaining 0.2 are
    - overhead of the parallel algorithm
    - sequential bottlenecks (Amdahl's law)

sufficient size (without benchmark)

- stream source must have a sufficient size, so that it benefits from parallel processing
- overhead increases with growing number of cores
  - number of tasks ~ 4*number of cores
  - (in most cases) not with the size of the stream source
- Doug Lea mentioned 10_000 for CPU-inexpensive funct.
  - http://gee.cs.oswego.edu/dl/html/StreamParallelGuidance.html
- 500_000 respectively 10_000 in our examples
  - size can be smaller for CPU-expensive functionality

dynamic overclocking (without benchmark)

- modern multi-core CPU typically increases the CPU-frequency when not all of its cores are active
  - Intel call this feature: turbo boost
- benchmark sequential versus parallel stream
  - seq. test might run with a dynamically overclocked CPU
  - will this also happen in the real environment or only in the test?
- no issue with our test system
  - too old
  - no dynamic overclocking supported

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stateful functionality …

… with parallel streams / multiple threads boils down to
shared mutable state

- costs performance to handle this
  - e.g. lock-free CAS, requires retries in case of collision

- traditionally not supported with *sequences*
  - functional programming languages don't have mutable types, and
  - often no parallel sequences either

- new solutions/approaches in Java 8 streams

stateful functionality with Java 8 streams

- intermediate stateful operations, e.g. `distinct()`
  - see javadoc: *This is a stateful intermediate operation.*
  - shared mutable state handled by stream implementation (JDK)

- (terminal) operations that allow stateful functional parameters, e.g.

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

  - see javadoc: *If the `action` accesses shared state, it is responsible for providing the required synchronization.*
  - shared mutable state handled by user/client code

stateful functionality with Java 8 streams (cont.)

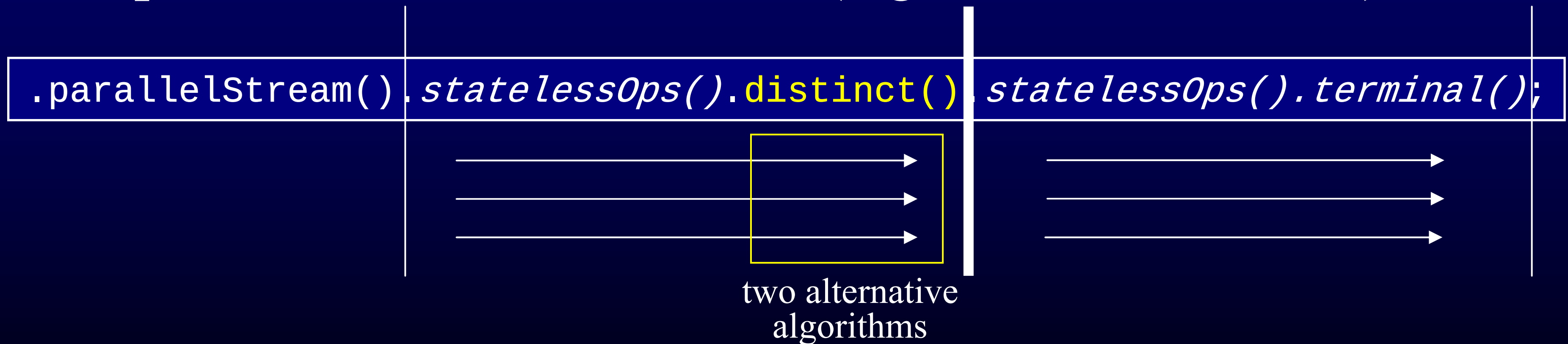
- stream's overloaded method: `collect()`
  - shared mutable state handled by stream implementation, and
  - collector functionality
    - standard collectors from `Collectors` (JDK)
    - user-defined collector functionality (JDK + user/client code)

- don't have time to discuss all situations
  - only discuss `distinct()`
  - shared mutable state handled by stream implementation (JDK)

distinct()

- element goes to the result stream,
  if it hasn't already appeared before
  - appeared before, in terms of `equals()`
  - shared mutable state: elements already in the result stream
    - have to compare the current element to each element of the output stream

- parallel introduces a barrier (algorithmic overhead)



two algorithms for parallel `distinct()`

- ordering + `distinct()`
  - normally elements go to the next stage, in the same order in which they appear for the first time in the current stage

- javadoc from `distinct()`
  - *Removing the ordering constraint with `unordered()` may result in significantly more efficient execution for `distinct()` in parallel pipelines, if the semantics of your situation permit.*

- two different algorithms for parallel `distinct()`
  - one for ordered streams + one for unordered streams

benchmark with distinct()

- `Integer[100_000]`, filled with 50_000 distinct values

```
// sequential
Arrays.stream(integers).distinct().count();
```

```
// parallel ordered
Arrays.stream(integers).parallel().distinct().count();
```

```
// parallel unordered
Arrays.stream(integers).parallel().unordered().distinct().count();
```

- results:

seq.	par. ordered	par. unordered
6.39 ms	34.09 ms	9.1 ms

benchmark with distinct() + slowSin()

- Integer[10_000], filled with numbers 0 … 9999

```
Arrays.stream(newIntegers) //.parallel().unordered()
   .map(i -> new Double(2200* Sine.slowSin(i * 0.001)).intValue())
   .distinct()
   .count();
```

  - after the mapping 5004 distinct values

- results:

seq.	par. ordered	par. unordered
11.59 ms	6.83 ms	6.81 ms

sequential vs. parallel stream / re-cap

to benefit from parallel stream usage …

- … stream source …
  - must have sufficient size
  - should be easy to split
- … operations …
  - should be CPU-expensive
  - should not be stateful

advice

- benchmark on target platform !

- previous benchmark:
  - find largest element, `LinkedList`, 500_000 elements

seq.	par.	seq./par.
12.74 ms	19.57 ms	0.65

- what if we use a quad-core-CPU (Intel i5-4590) ?
  - will the parallel result be worse, better, … better than seq. … ?

seq.	par.	seq./par.
5.24 ms	4.84 ms	1.08

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Q & A