The Road To Lambda

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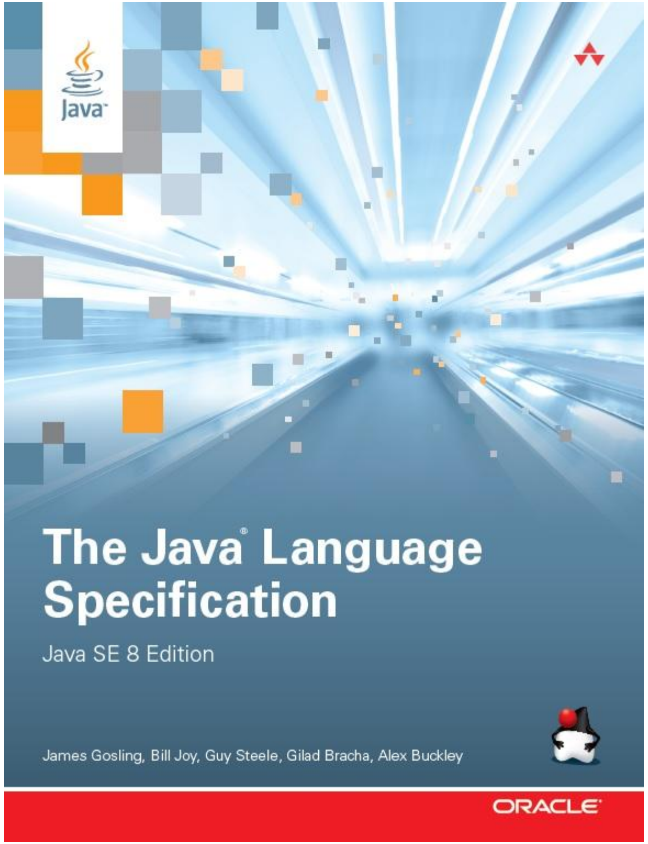
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The Java® Language Specification
Java SE 8 Edition
James Gosling, Bill Joy, Guy Steele, Gilad Bracha, Alex Buckley
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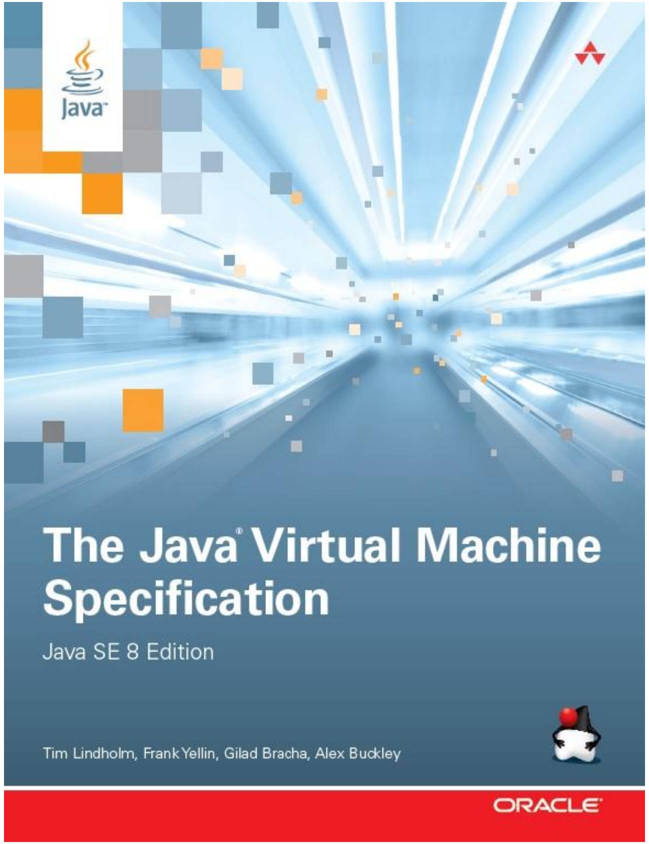
Java
The Java® Virtual Machine Specification
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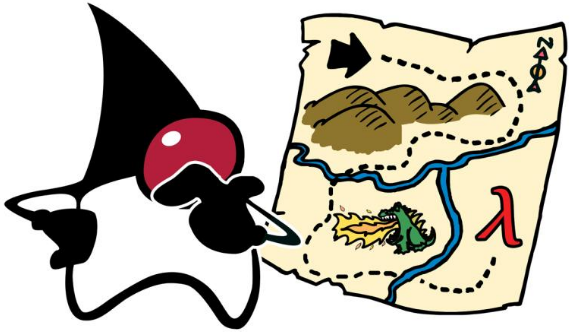
Modernizing Java

- Java SE 8 is a big step forward for the Java Language
  - Lambda Expressions for better abstraction
  - Default Methods for interface evolution
- Java SE 8 is a big step forward for the Java Libraries
  - Bulk data operations on Collections
  - More library support for parallelism
- Together, perhaps the *biggest upgrade ever* to the Java programming model
- Why did we choose the features we did?
- How do we evolve a mature language?



The Language

What is a Lambda Expression?

- A lambda expression is an anonymous method
  - Has a parameter list, a return type, and a body

    `(Object o) -> o.toString()`

  - Body can refer to *effectively final* variables in the enclosing lexical scope

    `(Person p) -> p.getName().equals(name)`

- A method reference is a reference to an existing method

    `Object::toString`

- Allow you to *treat code as data*
  - Behavior can be expressed succinctly, stored in variables, and passed to methods
  - A huge deal because of the impact on library design

What is the Type of a Lambda Expression?

- Many languages have some notion of a *function type*
  - “Function from long to int”
  - Seemed reasonable (at first) to consider adding them to Java
- But…
  - JVM has no native representation of function type in VM type signatures
  - Obvious tool for representing function types is generics
    - But then function types would be erased (and boxed)
  - Is there a simpler alternative?

Functional Interfaces

- Historically we used single-method interfaces to represent functions
  - Runnable, Comparator, ActionListener, FileFilter, …
  - Let’s call them *functional interfaces*
  - And add some new ones like Predicate<T>, Consumer<T>, Supplier<T>
- A lambda expression evaluates to an instance of a functional interface

```
Predicate<String> isEmpty = s -> s.isEmpty();
Predicate<String> isEmpty = String::isEmpty;
Runnable r = () -> { System.out.println("Boo!"); };
```

- We define functional interfaces *structurally*
  - No syntax or opt-in needed
  - Existing libraries are forward-compatible with lambda expressions

Times Change

- In 1995, most popular languages did *not* support lambda expressions
- By 2013, Java was just about the last holdout
  - C# added them in 2007, Objective-C in 2010, C++ in 2011
  - New languages being designed today all do

"In another thirty years people will laugh at anyone who tries to invent a language without closures, just as they'll laugh now at anyone who tries to invent a language without recursion."
- Mark Jason Dominus

Lambdas for Java – a long and winding road

- 1997 – Odersky / Wadler experimental “Pizza” work
  - “IMHO Pizza makes finally a usefull language out of java” comp.lang.java 3/6/97
- 1997 – Java 1.1 added inner classes
  - Too bulky, complex name resolution rules, many limitations
- 2006-2008 – vigorous community debate
  - Multiple proposals, including BGGA and CICE
  - Each had a different orientation
    - BGGA – facilitating control abstraction in libraries
    - CICE – reducing syntactic overhead of inner classes
  - Things ran aground at this point…

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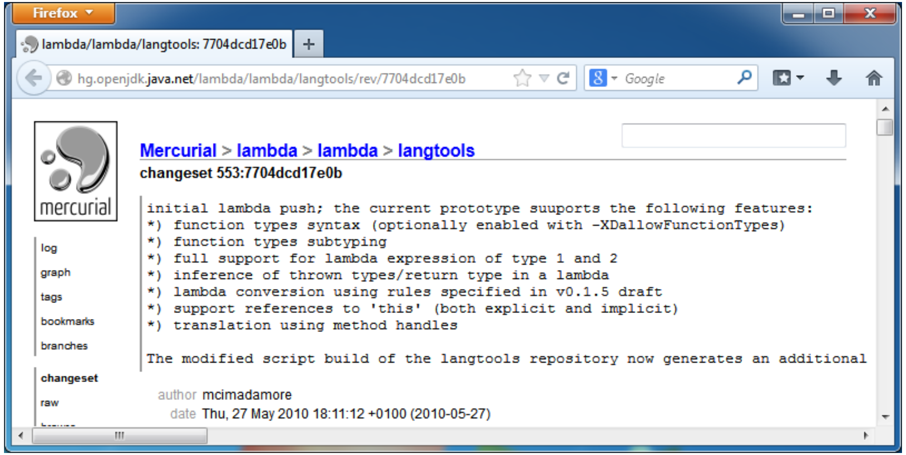
Lambdas for Java – a long and winding road

- 2009-Dec – OpenJDK Project Lambda formed
- 2010-May – First prototype
- 2010-Nov – JSR-335 filed
- 2011-Nov – Early Draft Review #1
- 2011-Nov – Developer Preview binaries on java.net
- 2012-Jun – Early Draft Review #2
- 2013-Feb – Early Draft Review #3
- 2014-Jan – Proposed Final Draft



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Evolving a Mature Language – Key Forces

- Encouraging change
  - Adapting to change
    - Everything changes: hardware, attitudes, fashions, problems, demographics
  - Righting what's wrong
    - Inconsistencies, holes, poor user experience
- Discouraging change
  - Maintaining compatibility
    - Low tolerance for change that will break anything
  - Preserving the "feel of Java"
    - Can't alienate user base in quest for "something better"
    - Easy to focus on cool new stuff, but there's lots of cool old stuff too

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Lambdas: Adapting to Change

- In 1995, pervasive sequentiality infected programming language design
  - for-loops are sequential and impose a specific order
    - Why wouldn't they be? Why invite nondeterminism?
    - Determinism is convenient – when free
    - This sequentiality assumption propagated into libraries (e.g., Iterator)
  - Pervasive mutability
    - Mutability is convenient – when free
    - Object creation was expensive and mutation was cheap
- In today's multicore world, these are the wrong defaults!
  - Can't just outlaw for-loops and mutability
  - Instead, gently *encourage* something better
- Lambda expressions are that gentle push

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Problem: External Iteration

- Snippet takes the red blocks and colors them blue
- Uses for-each loop
  - Loop is *inherently sequential*
  - Client has to manage iteration
  - This is called *external iteration*

```
for (Shape s : shapes) {
    if (s.getColor() == RED)
        s.setColor(BLUE);
}
```

- for-each loop hides complex interaction between library and client
  - Iterable, iterator(), Iterator.next(), Iterator.hasNext()
- What's the problem? Conflates the *what* with the *how*.
- A language construct that is inherently sequential is a significant problem.

Solution: Internal Iteration

- Re-written to use lambda and Collection.forEach
  - Not just a syntactic change!
  - Now the library is in control
  - This is *internal iteration*
  - More *what*, less *how*

```
shapes.forEach(s -> {
    if (s.getColor() == RED)
        s.setColor(BLUE);
})
```

- Library is free to use parallelism / out-of-order execution / laziness
- Client passes behavior (lambda) into the API as data
- Enables API designers to build more powerful, expressive APIs
  - Greater power to abstract over behavior

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Lambdas & Libraries

Lambdas Enable Better APIs

- Lambda expressions *enable delivery of more powerful APIs*
- The client-library boundary is more permeable
  - Client can provide bits of functionality to be mixed into execution
  - Client determines the *what*
  - Library remains in control of the *how*
- Safer: less state management in the client
- Faster: exposes more opportunities for optimization

Example: Sorting

- If we want to sort a List today, we'd write a Comparator

```
Collections.sort(people, new Comparator<Person>() {
    public int compare(Person x, Person y) {
        return x.getLastName().compareTo(y.getLastName());
    }
});
```

- Could replace Comparator with a lambda, but only gets us so far
- Comparator conflates *extraction of sort key* with *ordering* of that key
  - Better to separate the two aspects

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Example: Sorting

- Added static method Comparator.comparing(f)
  - Takes a “key extractor” function from T to some Comparable key
  - Returns a Comparator<T>
  - This is a *higher-order function* – functions in, functions out

```
interface Comparator<T> {
    public static <T, U extends Comparable<? super U>>
    Comparator<T> comparing(Function<T, U> f) {
        return (x, y) -> f.apply(x).compareTo(f.apply(y));
    }
}
Comparator<Person> byLastName
      = Comparator.comparing(Person::getLastName);
```


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Lambdas Enable Better APIs

- The comparing() method is one built for lambdas
  - Consumes an “extractor” function and produces a “comparator” function
  - Factors key extraction (client concern) from comparison (library concern)
  - Eliminates redundancy, boilerplate
- Key effect on APIs is: *more composability*
  - Centralize generation of Comparators in one place
  - Leads to better factoring, more regular client code, more reuse
- Lambdas in the language

  → can write better libraries

  → more readable, less error-prone user code

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Lambdas Enable Better APIs

- Generally, we prefer to evolve the programming model through libraries
  - Time to market – can evolve libraries faster than language
  - Decentralized – more library designers than language designers
  - Risk – easier to change libraries, more practical to experiment
  - Impact – language changes require coordinated changes to multiple compilers, IDEs, and other tools
- But sometimes we reach the limits of what is practical to express in libraries, and need a little help from the language
  - But a little help, in the right places, can go a long way!

Problem: Interface Evolution

- The example used a new Collection method – forEach()
  - If Java had lambdas in 1997, our Collections would surely look different
- Interfaces are a double-edged sword
  - Cannot compatibly evolve them unless you control all implementations
  - Reality: APIs age
    - As we add cool new language features, existing APIs look even older!
  - Lots of bad options for dealing with aging APIs
    - Let the API stagnate
    - Replace it in entirety (every few years!)
    - Nail bags on the side (e.g., Collections.sort())

Default Methods

- Need a proper mechanism for compatibly evolving APIs
- New feature: *default methods*
  - Virtual interface method with default implementation
  - “default” is the dual of “abstract”

```
interface Collection<T> {
  default void forEach(Consumer<T> action) {
    for (T t : this) { action.apply(t); }
  }
}
```

- Lets us compatibly evolve libraries over time
  - Default implementation provided in the interface
  - Subclasses can override with better implementations
  - Adding a default method is binary-compatible *and source-compatible*

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Default Methods

- Is this multiple inheritance in Java?
  - Java always had multiple inheritance of *abstract methods*
  - This adds multiple inheritance of *behavior*
  - But not of *state*, where most of the trouble comes from
- Compared to C# extension methods:

  Java's default methods are *virtual* and *declaration-site,* not *static* and *use-site*
- Compared to Scala's Traits:

  Java interfaces are stateless (more like Fortress' Traits)
- How do we resolve conflicts between declarations in multiple supertypes?
  - Three simple rules

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Rule #1: Class Wins

- If a class can inherit a method from a superclass and a superinterface, prefer the superclass method
  - Defaults *only* considered if no method declared in superclass chain
  - True for both concrete and abstract superclass methods
- Ensures compatibility with pre-SE 8 inheritance
  - Any call site that linked under previous rules links to the same target
- Otherwise…

Rule #2: Subtypes Win

- If a class can inherit a method from two interfaces, and one is more specific than (a subtype of) the other, prefer the more specific
  - An implementation in List would take precedence over one in Collection
- The shape of the inheritance tree doesn't matter
  - Only consider the set of supertypes, not order in which they are inherited
- Otherwise…

Rule #3: There is No Rule 3

- If rule #1 does not apply, and rule #2 does not yield a *unique, most specific default-providing interface…*
  - Explicitly reabstract it
  - Implement the method yourself
  - Implementation can delegate to non-inherited implementation with new construct ***X*.super.m()**

```
interface A {
    default void m() { ... }
}
interface B {
    default void m() { ... }
}
class C implements A, B {
    // Must implement/reabstract m()
    void m() { A.super.m(); }
}
```


Diamonds – No Problem

- Diamonds do not pose a problem for behavior inheritance
  - More problematic for state inheritance
- For D, there is a unique most-specific default-providing interface – A
  - D inherits m() from A, via two paths
  - “Redundant” inheritance does not affect the resolution

```
interface A {
    default void m() { ... }
}
interface B extends A { }
interface C extends A { }
class D implements B, C { }
```


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Example – Evolving Interfaces

- Adding a new method with default is source- and binary-compatible
- Default methods are instance methods
  – Type of ‘this’ is the declaring interface
  – Default implementation can invoke methods from enclosing interface, e.g. iterator()

```
interface Collection<E> {
    default boolean removeIf(Predicate<? super E> filter) {
        boolean removed = false;
        Iterator<E> it = iterator();
        while (it.hasNext()) {
          …
        }
        return removed;
    }
}
```


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Example – "Optional" Methods

- Adding a default *to an existing method* is source- and binary-compatible
- Default methods can reduce implementation burden
  - Most implementations of Iterator don't provide a useful remove()
  - So why make implementers write one that just throws?

```
interface Iterator<T> {
    boolean hasNext();

    T next();

    default void remove() {
        throw new UnsupportedOperationException();
    }
}
```

Example – Combinators

- Comparator.reversed() – reverses sort order of a Comparator
  - Default method on Comparator, just invokes compare()

```
interface Comparator<T> {
    default Comparator<T> reversed() {
        return (o1, o2) -> compare(o2, o1);
    }
}
Comparator<Person> byLastNameDescending
      = Comparator.comparing(Person::getLastName).reversed();
```

The Java Libraries

Bulk operations on Collections

- “Color the red blocks blue” can be decomposed into filter+forEach

```
shapes.forEach(s -> {
    if (s.getColor() == RED)
        s.setColor(BLUE);
})
```

⬇

```
shapes.stream()
      .filter(s -> s.getColor() == RED)
      .forEach(s -> { s.setColor(BLUE); });
```

- Why is this code better? Each part does one thing, and is clearly labeled.

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Bulk operations on Collections

- Collect the blue Shapes into a List

```
List<Shape> blueBlocks
    = shapes.stream()
            .filter(s -> s.getColor() == BLUE)
            .collect(Collectors.toList());
```

- If each Shape lives in a Box, find Boxes containing a blue shape

```
Set<Box> hasBlueBlock
    = shapes.stream()
            .filter(s -> s.getColor() == BLUE)
            .map(Shape::getContainingBox)
            .collect(Collectors.toSet());
```

Bulk operations on Collections

- The new bulk operations are expressive and composable
  - Compose compound operations from basic building blocks (lambdas)
  - Each stage does one thing
  - Client code reads more like the problem statement
  - Structure of client code is less brittle (anti-fragile)
    - Small changes to the problem -> small changes to the code
  - Less extraneous “noise” from intermediate results
    - No ‘accumulator’ or state variables

Which do you prefer?

```
Set<Seller> sellers = new HashSet<>();
for (Txn t : txns) {
    if (t.getBuyer().getAge() >= 65)
        sellers.add(t.getSeller());
}
List<Seller> sorted = new ArrayList<>(sellers);
Collections.sort(sorted, new Comparator<Group>() {
    public int compare(Seller a, Seller b) {
        return a.getName().compareTo(b.getName());
    }
});
for (Seller s : sorted)
    System.out.println(s.getName());
```

- Or…

```
txns.stream()
    .filter(t -> t.getBuyer().getAge() >= 65)
    .map(Txn::getSeller)
    .distinct()
    .sort(comparing(Seller::getName))
    .forEach(s -> System.out.println(s.getName());
```


From Collections to Streams

- To add bulk operations, we create a new abstraction: Stream
  - Represents a stream of values
  - Not a data structure – doesn't store the values
  - Source can be a Collection, array, generating function, I/O…
- Operations that produce new streams are lazy
  - Encourages a "fluent" usage style
  - Efficient – does a single pass on the data

```
collection.stream()
          .filter(f::isBlue)
          .map(f::getBar)
          .forEach(System.out::println);
```


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Comparing Approaches

Collections	Streams
Code deals with individual data items	Code deals with data set
Focused on *how*	Focused on *what*
Code doesn’t read like the problem statement	Code reads like the problem statement
Steps mashed together	Well-factored
Leaks extraneous details	No “garbage variables”
Inherently sequential	Same code can be sequential or parallel

Parallelism

Parallelism

- Goal: Handle parallelism in the libraries, not the language
  - Libraries can hide a host of complex concerns (task scheduling, thread management, load balancing)
- Goal: Reduce conceptual and syntactic gap between sequential and parallel forms of the same computation
  - Historically, sequential and parallel code for a given computation don't look anything like each other

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Obtrusive Parallelism

- Java SE 7 has a general-purpose Fork/Join framework
  - Powerful and efficient, but not so easy to program to
  - Based on recursive decomposition
    - Divide problem into subproblems, solve in parallel, combine results
    - Keep dividing until small enough to solve sequentially
  - Tends to be efficient across a wide range of processor counts
  - Generates reasonable load balancing with no central coordination

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Parallel Sum with Fork/Join (SE 7)

```
ForkJoinPool pool = new ForkJoinPool(nThreads);
SumFinder finder = new SumFinder(new SumProblem());
pool.invoke(finder);

class SumFinder extends RecursiveAction {
  private final SumProblem problem;
  int sum;

  protected void compute() {
    if (problem.size < THRESHOLD)
      sum = problem.solveSequentially();
    else {
      int m = problem.size / 2;
      SumFinder left, right;
      left = new SumFinder(problem.subproblem(0, m))
      right = new SumFinder(problem.subproblem(m, problem.size));
      forkJoin(left, right);
      sum = left.sum + right.sum;
    }
  }
}
```

```
class SumProblem {
  final List<Shape> shapes;
  final int size;

  SumProblem(List<Shape> ls) {
    this.shapes = ls;
    size = ls.size();
  }

  public int solveSequentially() {
    int sum = 0;
    for (Shape s : shapes) {
      if (s.getColor() == BLUE)
        sum += s.getWeight();
    }
    return sum;
  }
  public SumProblem subproblem(int start, int end) {
    return new SumProblem(shapes.subList(start, end));
  }
}
```


Parallel Sum with Streams (SE 8)

- Sequential sum-of-weights:

```
int sumOfWeight
    = shapes.stream()
            .filter(s -> s.getColor() == BLUE)
            .mapToInt(Shape::getWeight)
            .sum();
```

- Parallel sum-of-weights:

```
int sumOfWeight
    = shapes.parallelStream()
            .filter(s -> s.getColor() == BLUE)
            .mapToInt(Shape::getWeight)
            .sum();
```

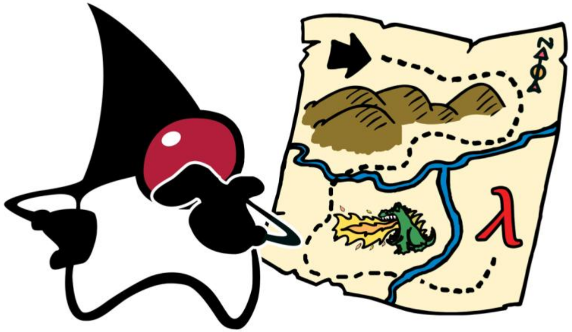
- Explicit but unobtrusive parallelism
- All three operations fused into a single parallel pass

So … Why Lambda?

- It's about time!
  - Java was the lone holdout among mainstream OO languages over lambdas
  - Adding them to Java is no longer a radical idea
- Lambdas provide libraries with a path to multicore
  - Parallel-friendly APIs need internal iteration
  - Internal iteration needs a concise code-as-data mechanism
- Lambdas empower library developers
  - More powerful, flexible libraries
  - Higher degree of cooperation between libraries and client code
  - Better libraries means more expressive, less error-prone code for users!

Modernizing Java

- Java SE 8 is a big step forward for the Java Language
  - Lambda Expressions for better abstraction
  - Default Methods for interface evolution
- Java SE 8 is a big step forward for the Java Libraries
  - java.util.stream.* + java.util.function.*
  - Upgrades throughout java.util.*
- Together, perhaps the *biggest upgrade ever* to the Java programming model
- **Shipping today!**



Books

- “Java SE 8 for the Really Impatient” (Horstmann)
- “Functional Programming in Java: Harnessing the Power of Java 8 Lambda Expressions” (Subramaniam)
- “Mastering Lambdas: Java Programming in a Multicore World” (Naftalin)
- “Java 8 in Action: Lambdas, Streams, and functional-style programming” (Urma, Fusco, Mycroft)
- “Java 8 Lambdas: Pragmatic Functional Programming” (Warburton)
- “Java in a Nutshell” (Evans, Flanagan)

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