Project Lambda: To Multicore and Beyond

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Introduction to Project Lambda

- OpenJDK Project Lambda started Dec 2009
- Targeted for Java SE 8 as JSR 335
- Aims to support programming in a multicore environment by adding closures and related features to the Java SE platform
MOTIVATION
Hardware trends – the future is parallel

- Chip designers have nowhere to go but parallel
  - Moore’s Law gives more cores, not faster cores
  - Have hit the wall in power dissipation, instruction-level parallelism, clock rate, and chip scale
- We must learn to write software that parallelizes gracefully

(Graphic courtesy Herb Sutter)
Developers need simple parallel libraries

• One of Java’s strengths has always been its libraries
  – Better libraries are key to making parallelization easier
  – Ideally, let the libraries worry about algorithmic decomposition, scheduling, computation topology

• Obvious place to start: parallel operations in collections
  – filter, sort, map/reduce
  – select, collect, detect, reject

• High-level operations tend to improve the readability of code, as well as its performance

• Why don’t we see more parallel libraries today?
Without more language support for parallel idioms, people will instinctively reach for serial idioms.
The biggest serial idiom of all: the for loop

double highestScore = 0.0;
for (Student s : students) {
    if (s.gradYear == 2010) {
        if (s.score > highestScore) {
            highestScore = s.score;
        }
    }
}

• This code is *inherently serial*
  – Traversal logic is fixed (iterate serially from beginning to end)
  – Business logic is stateful (use of > and accumulator variable)
The biggest serial idiom of all: the for loop

double highestScore = 0.0;
for (Student s : students) {
    if (s.gradYear == 2010) {
        if (s.score > highestScore) {
            highestScore = s.score;
        }
    }
}

- Existing collections impose *external iteration*
  - Client of collection determines mechanism of iteration
  - Implementation of accumulation is over-specified
  - Computation is achieved via side-effects
Let’s try a more parallel idiom: internal iteration

double highestScore =
    students.filter(new Predicate<Student>() {
        public boolean op(Student s) {
            return s.gradYear == 2010;
        }
    }).map(new Extractor<Student,Double>() {
        public Double extract(Student s) {
            return s.score;
        }
    }).max();

• Not inherently serial!
  – Traversal logic is not fixed by the language
  – Business logic is stateless (no stateful accumulator)
Let’s try a more parallel idiom: internal iteration

define highestScore =
    students.filter(new Predicate<Student>() {
        public boolean op(Student s) {
            return s.gradYear == 2010;
        }
    }).map(new Extractor<Student,Double>() {
        public Double extract(Student s) {
            return s.score;
        }
    }).max();

- Iteration and accumulation are embodied in the library
  - e.g. filtering may be done in parallel
  - Client is more flexible, more abstract, less error-prone
But … Yuck!

double highestScore =
    students.filter(new Predicate<Student>() {
        public boolean op(Student s) {
            return s.gradYear == 2010;
        }
    }).map(new Extractor<Student,Double>() {
        public Double extract(Student s) {
            return s.score;
        }
    }).max();

- Can’t see the beef for the bun!
A wise customer once said:

“The pain of anonymous inner classes makes us roll our eyes in the back of our heads every day.”
LAMBDA EXPRESSIONS
double highestScore =
    students.filter(#( Student s -> s.gradYear == 2010 )
                       .map( #( Student s -> s.score )
                      .max());

• Lambda expression is introduced with #
• Zero or more formal parameters
  – Like a method
• Body may be an expression or statements
  – Unlike a method
  – If body is an expression, no need for ‘return’ or ‘;’
A better way to represent “code as data”

double highestScore =
students.filter(#{ Student s -> s.gradYear == 2010 })
.map( #{ Student s -> s.score })
.max();

• Code reads like the problem statement:
  “Find the highest score of the students who graduated in 2010”
Lambda expressions support internal iteration

double highestScore =
    students.filter(#{ Student s -> s.gradYear == 2010 })
    .map(#{ Student s -> s.score })
    .max();

• Shorter than nested for loops, and potentially faster because implementation determines how to iterate
  – Virtual method lookup chooses the best filter() method
  – filter() method body can exploit representation knowledge
  – Opportunities for lazy evaluation in filter() and map()
  – Opportunities for parallelism
The science of lambda expressions

• The name comes from the lambda calculus created by Church (1936) and explored by Steele and Sussman (1975-1980)

• A lambda expression is like a lexically scoped anonymous method
  – Lexical scoping: can read variables from the lexical environment, including ‘this’, unlike with inner classes
  – No shadowing of lexical scope, unlike with inner classes
  – Not a member of any class, unlike with inner classes
Syntax wars

#() (7)

{ => 7 }

() -> 7;

{ -> 7 }

lambda() (7);

[ ] { return 7; }

#(->int) { return 7; }

#: int i { i = 7; }

new #<int() > (7)
What is the type of a lambda expression?

`#{ Student s -> s.gradYear == 2010 }`

- Morally, a function type from Student to boolean
- But Java does not have function types, so:
  - How would we write a function type?
  - How would it interact with autoboxing?
  - How would it interact with generics?
  - How would it describe checked exceptions?
“Use what you know”

- Java already has an idiom for describing “functional things”: single-method interfaces (or abstract classes)

```java
interface Runnable {
    void run();
}
interface Callable<T> {
    T call();
}
interface Comparator<T> {
    boolean compare(T x, T y);
}
interface ActionListener {
    void actionPerformed(...);
}
abstract class TimerTask {
    ... abstract void run(); ...
}
```

- Let’s reuse these, rather than introduce function types

  ```java
  Comparator<T> ~ a function type from (T,T) to boolean
  Predicate<T> ~ a function type from T to boolean
  ```
Introducing: SAM types

- A SAM type is an interface or abstract class with a Single Abstract Method

```java
interface Runnable       { void run(); }
interface Callable<T>    { T call();   }
interface Comparator<T>  { boolean compare(T x, T y); }
interface ActionListener { void actionPerformed(…);   }
abstract class TimerTask { ... abstract void run(); ... }
```

- No special syntax to declare a SAM type
  - Recognition is automatic for suitable interfaces and abstract classes
  - Not just for java.* types!
**Interface DirectoryStream.Filter<T>**

Type Parameters:

- T - the type of the directory entry

Enclosing interface:

- DirectoryStream<T>

```java
public static interface DirectoryStream.Filter<T>
```

An interface that is implemented by objects that decide if a directory entry should be accepted or filtered. A Filter is passed as the parameter to the `newDirectoryStream` method when opening a directory to iterate over the entries in the directory.

Since:

- 1.7

### Method Summary

<table>
<thead>
<tr>
<th>Modifier and Type</th>
<th>Method and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>boolean</td>
<td><code>accept(T entry)</code></td>
</tr>
</tbody>
</table>

Decides if the given directory entry should be accepted or filtered.
The type of a lambda expression is a SAM type

• “SAM conversion” infers a SAM type for a lambda expression

\[
\text{Predicate}\langle \text{Student}\rangle \ p = \#\{ \ \text{Student} \ s \rightarrow \ s.\text{gradYear} == 2010 \ \};
\]

• Invoking the SAM type’s method invokes the lambda’s body

\[
\text{boolean} \ \text{ok} = p.\text{isTrue}(\text{aStudent});
\]

• Instant compatibility with existing libraries!

\[
\text{executor.submit}(\#\{ \ \rightarrow \ \text{println(“Boo”)}; \ });
\]

\[
\text{btn.addActionListener}(\#\{ \ \text{ActionEvent} \ e \rightarrow \ \text{println(“Boo”) } \});
\]
The science of SAM conversion

• Lambda expression must have:
  – Same parameter types and arity as SAM type’s method
  – Return type compatible with SAM type’s method
  – Checked exceptions compatible with SAM type’s method

• SAM type’s method name is not relevant:
  
  ```java
  interface Predicate<T> { boolean op(T t); }
  Predicate<Student> p = #{ Student s -> s.gradYear == 2010 };
  interface StudentQualifier { Boolean check(Student s); }
  StudentQualifier c = #{ Student s -> s.gradYear == 2010 };
  ```

• Lambda expressions may only appear in contexts where they can undergo SAM conversion (assignment, method call/return, cast)
But wait, there’s more

- Lambdas solve the “vertical problem” of inner classes
- Parameter types can still be a “horizontal problem”

```java
double highestScore =
    students.filter(#{ Student s -> s.gradYear == 2010 })
    .map(#{ Student s -> s.score })
    .max();
```
But wait, there’s more

- Lambdas solve the “vertical problem” of inner classes
- Parameter types can still be a “horizontal problem”

```java
double highestScore =
    students.filter(#{ Student s -> s.gradYear == 2010 })
    .map(#{ Student s -> s.score })
    .max();
```

- SAM conversion can usually infer them!

```java
double highestScore =
    students.filter(#{ s -> s.gradYear == 2010 })
    .map(#{ s -> s.score })
    .max();
```

- Lambda expressions are always statically typed
SAM conversion includes target typing.

Target typing identifies parameter types for the lambda expression based on the candidate SAM type’s method.

Predicates, such as `Predicate<Student>` is a SAM type whose method takes `Student` as a parameter.

Therefore, `s` must be a `Student`.

Programmer can give parameter types in case of ambiguity.

Example:

```java
interface Collection<T> {
    Collection<Student> filter(Predicate<Student> t);
}

students.filter(s -> s.gradYear == 2010)
```
Recap: SAM types

• Self-documenting

• Build on existing concepts
  – Wildcards have made us wary of aggressive new type systems

• Ensure lambda expressions work easily with existing libraries
  – Java SE will likely define a “starter kit” of SAM types such as Predicate, Filter, Extractor, Mapper, Reducer…

• Type inference gets your eyes to the “beef” quickly
  – Style guide: One-line lambdas may omit parameter types, but multi-line lambdas should include parameter types

• You could think of our lambda expressions as “SAM literals”
METHOD REFERENCES
Motivation

• Consider sorting a list of Person objects by last name:

```java
class Person { String getLastName() {…} }

List<Person> people = …
Collections.sort(people, new Comparator<Person>() {
    public int compare(Person a, Person b) {
        return a.getLastName().compareTo(b.getLastName());
    }
});
```

• Yuck!
  – (Worse if sort key is a primitive)
A lambda expression helps, but only so much

```java
Collections.sort(people,
    #{ a,b -> a.getLastName().compareTo(b.getLastName()) });
```

• More concise, but not more abstract
  – Performs data access (getLastName) and computation (compareTo)
  – Assumes both Person objects are nearby (e.g. same JVM)

• More abstract if *someone else* handles computation
  – If we can extract the data dependency – “Person’s last name” – from
    the code, then sort() can split data access and computation
  – e.g. distribute Person objects across nodes and sort there
A lambda expression helps, but only so much

```java
Collections.sort(people,
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- More concise, but not more abstract
  - Performs data access (getLastName) and computation (compareTo)
  - Assumes both Person objects are nearby (e.g. same JVM)
- More abstract if someone else handles computation
- If we can extract the data dependency – “Person’s last name” – from the code, then sort() can split data access and computation
  - e.g. distribute Person objects across nodes and sort there

**SELECT * FROM PERSON**
**ORDER BY LASTNAME ASC**
How to express “Person’s last name” in Java?

• Assume an interface to extract a value from an object:

```java
interface Extractor<T, U> { U get(T element); }
```

• And a sortBy method keyed off an extractor:

```java
public <T, U extends Comparable<...>>
    void sortBy(Collection<T> coll, Extractor<T,U> ex) {...}
```

• Then, pass a lambda expression that “wraps” a method call:

```java
Collections.sortBy(people, # { p -> p.getLastName() });
```

  - SAM conversion types the lambda as Extractor<Person,String>
  - sortBy() can pre-query last names, cache them, build indices…
Is that the best we can do?

```
Collections.sortBy(people, #{ p -> p.getLastName() });
```

- Writing little wrapper lambdas will be a pain
- If only we could reuse an existing method...
Is that the best we can do?

```java
Collections.sortBy(people, #{ p -> p.getLastName() });
```

- Writing little wrapper lambdas will be a pain
- If only we could reuse an existing method

```java
Collections.sortBy(people, #Person.getLastName);
```

- Method reference introduced with #
- No need for () or parameter types in simple cases
Recap: Method references

• When code outgrows a lambda expression, write a method and take a method reference

• Lambda expressions and method references have SAM types

• Work easily with existing libraries

• Can specify parameter types explicitly if needed

• Three kinds of method references (unbound/bound/static)

• No field references (use method references to getters/setters)
A word about implementation

• Lambda expressions are not sugar for inner classes
  – Implemented with MethodHandle from JSR 292

• Method references are not sugar for wrapper lambdas
  – Implemented with enhanced ldc instruction from JSR 292

• See videos from 2010 JVM Language Summit for more
  – http://wiki.jvmlangsummit.com/
  – “Gathering the threads: JVM Futures”
  – “Efficient compilation of Lambdas using MethodHandle and JRockit”
  – “MethodHandles: an IBM implementation”
“But what about…”

- Function types
- Properties
- Curried functions
- Underscore placeholders
- Partial application
- ‘var’
- ‘letrec’
- Tennent’s Correspondence Principle
- Continuations
- Field references
- Dynamic typing
- Control abstraction
COMIC #61 - POKE THE BEAR

LET'S PLAY “POKE THE BEAR”

OK. TELL PEOPLE WE'RE ADDING CLOSURES TO JAVA.

VECTOR DOES EVERYTHING I NEED.

THE LEARNING... IT HURTS.

DOWN WITH THIS SORT OF THING.

WE DEMAND AN XML-BASED SPRING CLOSURE TEMPLATE HELPER CLASS!

HTTP://TWITITCH.COM/61/
Our view

• Evolving a language with millions of developers is a fundamentally different task from evolving a language with thousands of developers
  – Adding features by the bucket is not good
  – Every feature adds conceptual weight

• We believe Project Lambda’s changes are measured, and in the spirit of Java
  – Focus on readability and developer productivity
  – No new types to learn (compare with wildcards)
  – Respectful of existing idioms (SAM)
LIBRARY EVOLUTION
As the language evolves, the libraries should evolve with it

- Java collections do not support internal iteration largely because the language made it so clunky at the time
- Now the language can easily treat “code as data”, it’s crucial to support parallel/functional idioms in the standard libraries
- Continues a long theme of language/library co-evolution
  - synchronized {} blocks / Thread.wait()/notify()
  - for-each loop / Iterable<T>
  - Generic type inference / <T>Collection.toArray(T[] x)
Without more **library** support for parallel idioms, people will instinctively reach for serial idioms
Library support for internal iteration

- Sometimes, we want to add more types
  - Recall Java SE will likely define a “starter kit” of SAM types
- Sometimes, we want to augment existing interfaces
- No good way to add methods to existing interfaces today
  - Binary compatible: old clients continue to execute 😊
  - Source incompatible: old implementations fail to compile 😞
- Existing techniques for interface evolution are insufficient
  - Adding to j.u.Collections diminishes the value of interface contracts
  - Using abstract classes instead of interfaces
  - Interface inheritance and naming conventions (e.g. IDocument, IDocumentExtension, IDocumentExtension2, IDocumentExtension3)
Interface evolution

- There is a spectrum of inheritance expressiveness

[Diagram showing Object Pascal (Single inheritance) on the left, Java (The happy middle) in the middle, and C++ (Multiple everything) on the right.]
Interface evolution

• There is a spectrum of inheritance expressiveness
Interface evolution

- There is a spectrum of inheritance expressiveness
Extension methods: a measured step towards more flexible inheritance

```java
public interface Set<T> extends Collection<T> {
    public int size();
    ...
    public extension T reduce(Reducer<T> r)
        default Collections.<T>setReducer;
}
```

- Allows library maintainers to effectively add methods after the fact by specifying a default implementation
  - “If you cannot afford an implementation of reduce(), one will be provided for you”
- Less problematic than traits, mixins, full multiple inheritance
Extension methods in a nutshell

- An extension method is just an ordinary interface method
- For a client:
  - Nothing new to learn – calling the extension method works as usual, and the default method is linked dynamically if needed
- For an API implementer:
  - An implementation of an augmented interface may provide the method, or not
- For an API designer:
  - Default method can only use public API of augmented interface
- For a JVM implementer:
  - Lots of work
WRAP-UP
Project Lambda: A Journey

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

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

More essence, less ceremony
Project Lambda: A Journey

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

*Lambda expressions*

```java
Collections.sort(people, #{ Person x, Person y ->
    x.getLastName().compareTo(y.getLastName()) });
```

*SAM conversion*

More essence, less ceremony

Forward compatibility – old API works with new expressions
Project Lambda: A Journey

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

- **Lambda expressions**
- **SAM conversion**

```java
Collections.sort(people, #{ Person x, Person y -> x.getLastName().compareTo(y.getLastName()) });
```

- **Better libraries**

```java
Collections.sortBy(people, #{ Person p -> p.getLastName() });
```

- **More abstraction**
Project Lambda: A Journey

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

*Lambda expressions  SAM conversion*

```java
Collections.sort(people, #{ Person x, Person y ->
    x.getLastName().compareTo(y.getLastName()) });
```

*Better libraries*

```java
Collections.sortBy(people, #{ Person p -> p.getLastName() });
```

*Type inference*

```java
Collections.sortBy(people, #{ p -> p.getLastName() });
```

Static typing can be fun too!
Project Lambda: A Journey

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

- **Lambda expressions**
- **SAM conversion**

```java
Collections.sort(people, #{ Person x, Person y -> x.getLastName().compareTo(y.getLastName()) });
```

- **Better libraries**

```java
Collections.sortBy(people, #{ Person p -> p.getLastName() });
```

- **Type inference**

```java
Collections.sortBy(people, #{ p -> p.getLastName() });
```

- **Method references**

```java
Collections.sortBy(people, #{Person.getLastName});
```

Don’t Repeat Yourself
Project Lambda: A Journey

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

Collections.sort(people, #{ Person x, Person y -> x.getLastName().compareTo(y.getLastName()) });

Collections.sortBy(people, #{ Person p -> p.getLastName() });

Collections.sortBy(people, #Person.getLastName);

people.sortBy(#Person.getLastName);

Lambda expressions    SAM conversion
Better libraries
Type inference
Method references
Extension methods
Migration compatibility – Old class implements new interface
Collections.sort(people, new Comparator<Person>() {
    public int compare(Person x, Person y) {
        return x.getLastName().compareTo(y.getLastName());
    }
});

people.sortBy(#Person.getLastName);

Lambda expressions
Better libraries
Type inference
Method references
Extension methods
Project Lambda: A Journey

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

people.sortBy(#Person.getLastName);

Lambda expressions
Better libraries
Type inference
Method references
Extension methods

More concise
More abstract
Less ceremony
More reuse
More object-oriented
• Project Lambda is not just “closures”
• A suite of features to support parallel/functional idioms
• With an eye on compatibility, as always
• Collections story is a work in progress
• JVM evolution in JSR 292 really helps the Java language
• Steady pipeline of measured innovation
Project Lambda @ OpenJDK

- [http://openjdk.java.net/projects/lambda/](http://openjdk.java.net/projects/lambda/)
- 2461 mails (Dec 2009–Sep 2010)
- 292 subscribers (Sep 2010)
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- Special thanks: Maurizio Cimadamore
- Download javac and lambda-ify your code!
- Please report experiences to [lambda-dev@openjdk.java.net](mailto:lambda-dev@openjdk.java.net)
LIBRARY UPGRADES
double highestScore = 0.0;
for (Student s : students) {
    if (s.gradYear == 2010) {
        if (s.score > highestScore) {
            highestScore = s.score;
        }
    }
}

double highestScore = 
    students.filter(#{ Student s -> s.gradYear == 2010 })
    .map(#{ Student s -> s.score })
    .max();
double highestScore =
  students.filter(#{ Student s -> s.gradYear == 2010 })
  .map(#{ Student s -> s.score })
  .max();

• What should students.filter() and map() return?
  – Obvious choice is Collection<Student>

• Intermediate collection objects are unnecessary overhead 😞
  – More abstract, but not more performant: Fail

• filter() and map() should return lazy streams
  – LazyCollection<Student> ?
It’s **still** not parallel

- Laziness and parallelism are independent dimensions
  - Just adding a lazy map is not enough

- Collections must offer parallel “iterators” that encapsulate decomposition, a.k.a. “spliterators”
  - See Guy Steele’s “Iterators Considered Harmful”

- Each sub-part of a decomposed collection evaluates lazily
A modest requirement list

• New bulk-data aggregate operations
  – Collection types must offer aggregate operations
    `Collection.map(Mapper), reduce(Reducer), filter(Predicate)`
  – Generic implementations over decomposable collections
    `Utils.map(Mapper), reduce(Reducer), filter(Predicate)`

• New abstractions for lazy streams
  – Collection types must auto-convert to lazy collections
    `LazyCollection<?>`

• New abstractions for parallel decomposition
  – Collection types must expose parallel decomposition
    `LazyCollection.asParallelStream()`

• What does this all mean for existing non-thread-safe collections?
double highestScore =
    students.filter(#{ Student s -> s.gradYear == 2010 })
      .map(#{ Student s -> s.score })
      .max();

double highestScore =
    students.asParallelStream()
      .filter(#{ Student s -> s.gradYear == 2010 })
      .map(#{ Student s -> s.score })
      .max();
SOFTWARE. HARDWARE. COMPLETE.