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
- 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
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.
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

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();

• 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
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
A better way to represent “code as data”

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”

do 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 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
"But why not..."

- `#()(7)`
- `{ => 7 }
- `() -> 7;
- `{ -> 7 }
- `lambda() (7);`
- `[ ] { return 7; }
- `#(->int) { return 7; }
- `#(: int i) { i = 7; }
- `new #<int() > (7)`
“But why not...”

Syntax wars:
Just say no
TYPING
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

  - `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>accept(T entry)</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

```java
Predicate<Student> p = #{ Student s -> s.gradYear == 2010 };
```

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

```java
boolean ok = p.isTrue(aStudent);
```

- Instant compatibility with existing libraries!

```java
executor.submit(#{ -> println("Boo"); });
btn.addActionListener(#{ ActionEvent e -> 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

```java
interface Collection<T> {
    Collection<T> filter(Predicate<T> t);
}
Collection<Student> students = …
… students.filter(#{ s -> s.gradYear == 2010 }) …
```

- `students.filter()` takes a Predicate<Student>
- Predicate<Student> is a SAM type whose method takes Student
- Therefore, `s` must be a Student
- Programmer can give parameter types in case of ambiguity
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

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  - 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 sort method keyed off an extractor:

   ```java
   public <T, U extends Comparable<? super U>>
   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?

```java
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
  - “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
- Field references
- Underscore placeholders
- Partial application
- Control abstraction
- ‘var’
- ‘letrec’
- Tennent’s Correspondence Principle
- Dynamic typing
- Continuations
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)
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. down with this sort of thing.

the learning... it hurts.

we demand an xml-based spring closure template helper class!

http://twitch.com/61/
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
Interface evolution

- There is a spectrum of inheritance expressiveness

- Object Pascal
  Single inheritance

- Java
  The happy middle

- C++
  Multiple everything

- Traits

- Mixins
There is a spectrum of inheritance expressiveness.

- Object Pascal: Single inheritance
- Java: The happy middle
- C++: Multiple everything
- Traits
- Mixins
- New target: Extension methods
Extension methods: a measured step towards more flexible inheritance

```java
public interface Set<T> extends Collection<T> {
    public int size();
    ...
    public 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

```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()) });
```

More essence, less ceremony
Project Lambda: A Journey

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

Lambda expressions

```
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

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

Better libraries
Lambda expressions
SAM conversion

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

More abstraction

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

Lambda expressions  

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

SAM conversion  

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

Better libraries  

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

Type inference  

Static typing can be fun too!
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```java
Collections.sort(people, new Comparator<Person>() {
    public int compare(Person x, Person y) {
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    }
});
```

- **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**
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
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

Better libraries

Type inference

Method references

Extension methods

```java
people.sortBy(#Person.getLastName);
```
Project Lambda: A Journey

```java
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: To Multicore and Beyond

• 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
SOFTWARE. HARDWARE. COMPLETE.