Lambda expressions in Java: a compiler writer's perspective

Maurizio Cimadamore
Type-system engineer, Oracle Corporation
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BACKGROUND
Where are we?

• Multicore hardware is now the default
  – Moore’s law delivering more cores, not faster cores
• We must learn to write software that parallelizes gracefully
  – Right now, the serial code and the parallel code for a given operation don’t look anything like each other
  – Fork-join (added in Java SE 7) is a good start, but not enough
Problem: external iteration

List<Student> students = ...
double highestScore = 0.0;
for (Student s : students) {
    if (s.gradYear == 2011) {
        if (s.score > highestScore) {
            highestScore = s.score;
        }
    }
}

Client controls iteration

Inherently serial: iterate from beginning to end

Not thread-safe (shared mutable variable)
Internal iteration w/ lambdas

SomeCoolList\(<\text{Student}>) \text{ students } = \ldots$

double \text{ highestScore } =$
    \text{ students.} \text{ filter(} \text{ Student s } \rightarrow \text{ s.getGradYear()} == 2011\)\text{. map(} \text{ Student s } \rightarrow \text{ s.getScore()}\)\text{. max();}
Why closures for Java?

• Provide libraries a path to multicore
  – Today, developer’s primary tool for computing over aggregates is the for loop – which is fundamentally serial
  – Parallel-friendly APIs need internal iteration
  – Internal iteration needs a concise code-as-data mechanism

• Empower library developers
  – Closures are useful for all kinds of libraries, serial or parallel
  – Enable a higher degree of cooperation between libraries and client code

• It’s about time!
  – Java is the lone holdout among mainstream OO languages at this point to not have closures
  – Adding closures to Java is no longer a radical idea
LAMBDA EXPRESSIONS
Lambda Expressions

- One construct, several syntactic forms:

LambdaExpression:
  TypeParametersopt LambdaParameters '->' LambdaBody

LambdaExpressionAfterCast:
  LambdaParameters '->' LambdaBody

LambdaParameters:
  Identifier
  '('(' InferedFormalParameterList ')'')'
  '('(' FormalParameterListopt ')'')'

InferredFormalParameterList:
  Identifier
  InferedFormalParameterList ',' Identifier

LambdaBody:
  Expression
  Block
Explicit vs. Implicit parameters

- Lambda parameter types can be omitted
  - Compiler to the rescue: implicit parameters will be inferred from the context
  - Keywords only allowed on explicit parameters

<table>
<thead>
<tr>
<th>explicit</th>
<th>implicit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(int x) -&gt; x+1</td>
<td>x -&gt; x+1</td>
</tr>
<tr>
<td>(int x, int y) -&gt; x+y</td>
<td>(x,y) -&gt; x+y</td>
</tr>
<tr>
<td>(final String msg) -&gt; { log(msg); }</td>
<td>msg -&gt; { log(msg); }</td>
</tr>
</tbody>
</table>
Expression vs. Statement

true ? 1 : 2
Foo.class
1 + 2

a.foo()
a++
a = foo

if ( ... )
String s = ...

for ( ... )
Expression lambdas

- Expression lambda
  - Body is an expression which is also the return value of the lambda

<table>
<thead>
<tr>
<th>expr</th>
<th><code>int x -&gt; x*x</code></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><code>(int x, int y) -&gt; x + y</code></td>
</tr>
<tr>
<td></td>
<td><code>Object o -&gt; o.toString()</code></td>
</tr>
</tbody>
</table>
Statement lambdas

• Statement lambda
  – Body is an ordinary block
  – A statement lambda can return (where return means ‘local’ return)

```java
boolean c-> { assert c; }
(int x, int y)-> { if (cond) return x; return y; }
Object o-> { System.out.println(o); }
```
Expression or statement?

- An expression statement can be used in both statement and expression lambdas
  - Semantics could depend on the context
  - Syntax helps to disambiguate (no semi-colon tricks!)

<table>
<thead>
<tr>
<th>expr</th>
<th>(Collection&lt;?&gt; c, Object o) -&gt; c.add(o);</th>
</tr>
</thead>
<tbody>
<tr>
<td>stmt</td>
<td>(Collection&lt;?&gt; c, Object o) -&gt; { c.add(o); }</td>
</tr>
</tbody>
</table>
To return or not to return?

- A lambda might/might not have a return value
  - A statement lambda that does not return is void-compatible
  - A statement lambda that has one or more return values is value-compatible
  - An expression lambda is always value-compatible

<table>
<thead>
<tr>
<th>void</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(String s) -&gt; {}</td>
<td>(String s) -&gt; s</td>
</tr>
<tr>
<td>System.out.println(s);</td>
<td>return s;</td>
</tr>
<tr>
<td>(boolean cond) -&gt; {}</td>
<td>if (cond) return;</td>
</tr>
</tbody>
</table>
Don't call me, I'll call you!

• A lambda expression can be executed when the scope in which it has been created is no longer available in the execution stack
  – This can happen if the lambda is saved and then executed at a later stage (laziness)

• Implications:
  – Restrictions on local variable capture
  – Restrictions on jumps
Local variable capture

- Lambda expressions can refer to *effectively final* local variables from the enclosing scope
  - An effectively final variable meets the requirements for final variables (i.e. assigned once), even if not declared as such
  - Close over *values*, not over *variables*!

```
x long before = 1;
... (File p) -> p.lastModified() <= before;
  before = 3;
```

```
✓ long before = 1;
... (File p) -> p.lastModified() <= before;
```
Jumps

- `break/continue` are allowed if the target is within the lambda expression
  - Non-local jumps are disallowed

```java
for (Object o : elems) {
    ... ()-> { break; };
}

()-> switch(s) {
    case "Hello!": break;
}
```
Correspondence Principle

[…] the underlying semantic notions for both parameter and definition mechanisms are simply expression evaluation (of an actual parameter or the right-hand side of a definition) and identifier binding (of a formal parameter or the left-hand side of a definition.) […] For any parameter mechanism, an analogous definition mechanism is possible, and vice versa. This is known as the principle of correspondence.

from R. D. Tennent’s Principle’s of Programming Languages (1981)

• For a given expression `expr`, `lambda expr` should be semantically equivalent.

• Implications:
  – Shadowing
  – Meaning of names (i.e. `this`)
Scope of lambda parameters

• Lambda parameters share same scope with locals variables defined in the enclosing scope
  – Error when lambda declares parameter with same name as a local in the enclosing scope

```java
void shadowTest(Object i) {
  ... (int i) -> i*i;
}

void shadowTest(Object i) {
  ... (int i2) -> i2*i2;
}
```
Meaning of names

- The meaning of names are the same inside the lambda as outside
  - `this` refers to the enclosing object, not the lambda itself
  - Easier than inner classes: no ambiguity between enclosing vs. inherited symbols

```java
class Foo {
    ... () -> { Foo f = this; };
}
```
METHOD REFERENCES
Internal iteration w/ lambdas (reloaded)

SomeCoolList<Student> students = ...
double highestScore =
    students.filter(Student s -> s.getGradYear() == 2011)
    .map(Student s -> s.getScore())
    .max();

Library-based iteration
Traversal might be done in parallel
Thread-safe (stateless)
More readable and less error prone!
Accidental horizontal verbosity
Internal iteration w/ method references

SomeCoolList<Student> students = ...  
double highestScore =  
    students.filter(Student s -> s.getGradYear() == 2011)  
        .map(Student::getScore)  
        .max();

- Library-based iteration
- Traversal might be done *in parallel*
- Thread-safe (stateless)
- More readable and less error prone!
- Reuse of existing code!
Method References

- Syntactic shortcut for creating a lambda expression out of an existing method/constructor
  - Many flavors of method references:

MethodReference:
- ExpressionName '::' NonWildTypeArgumentsopt Identifier
- Primary '::' NonWildTypeArgumentsopt Identifier
- ReferenceType '::' NonWildTypeArgumentsopt Identifier

ConstructorReference:
- ClassType '::' NonWildTypeArgumentsopt 'new'
# Overview of Method References

## Qualifier Expression

<table>
<thead>
<tr>
<th>Name</th>
<th>toplevel type</th>
<th>inner type</th>
<th>expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static identifier</td>
<td>static method reference</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instance identifier</td>
<td>unbound method reference</td>
<td></td>
<td>bound method reference</td>
</tr>
<tr>
<td>new</td>
<td>toplevel constructor reference</td>
<td>inner constructor reference</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Desugaring method references

- Three kinds of method references
  - Static - access static methods
  - Bound - access instance method *explicitly*
  - Unbound - access instance method *implicitly*

<table>
<thead>
<tr>
<th></th>
<th>: :</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>static</strong></td>
<td>Logger::log</td>
<td>(String msg) (\rightarrow) Logger.log(msg)</td>
</tr>
<tr>
<td><strong>bound</strong></td>
<td>getP()::name</td>
<td>final Person p = getP(); () (\rightarrow) p.name()</td>
</tr>
<tr>
<td><strong>unbound</strong></td>
<td>Person::name</td>
<td>(Person p) (\rightarrow) p.name()</td>
</tr>
</tbody>
</table>
Desugaring constructor references

- Two kinds of method references
  - *Toplevel* - access toplevel constructor
  - *Inner* - access inner constructor *implicitly*
- Desugaring of inner constructor reference depends on whether an enclosing instance is in scope!

<table>
<thead>
<tr>
<th></th>
<th>::</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>toplevel</strong></td>
<td>Person::new</td>
<td>(String name) ( \rightarrow ) new Person(name)</td>
</tr>
<tr>
<td><strong>inner(_1)</strong></td>
<td>Inner::new</td>
<td>() ( \rightarrow ) Outer.this.new Inner()</td>
</tr>
<tr>
<td><strong>inner(_2)</strong></td>
<td>Inner::new</td>
<td>(Outer o) ( \rightarrow ) o.new Inner()</td>
</tr>
</tbody>
</table>
FUNCTIONAL INTERFACES
Not all expressions are created equal!

100

new ArrayList<>()

e.toString()

{ 1, 2 }
Standalone expressions

100 \rightarrow \text{int}

new ArrayList<>()

e.toString()

\{ 1, 2 \} \rightarrow \text{String}
Poly expressions

100

new ArrayList<>()

e.toString()

{ 1, 2 }

double[]
Lambda and method references as poly expressions

- Lambda expression/method references are *just* new kinds of poly expressions
  - The type of lambda/method reference cannot be computed in isolation (i.e. w/o a target type)
  - A lambda/method reference can be used whenever a *compatible* functional interface is expected!

```
Runnable r = () -> { System.out.println("hi"); }
```

```
Runnable r = System::gc;
```
Functional interfaces

A functional interface is an interface that has just one abstract method, and thus represents a single function contract. In some cases, this "single" method may take the form of multiple abstract methods with override-equivalent signatures inherited from superinterfaces; in this case, the inherited methods logically represent a single method.

from the Project Lambda EDR
Where are my arrow types?

• For years, we’ve used single-method interfaces to represent functions and callbacks
  – A functional interface is an interface with one method
• Functional interfaces provide an hook to switch between nominal/structural type information:
  – A functional interface is just a (nominal) interface type…
  – Each functional interface is associated with a functional descriptors that carries *structural* type information:
    • Argument types
    • Return type
    • Thrown types
# Functional interfaces in the JDK

<table>
<thead>
<tr>
<th>Interface</th>
<th>Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparator&lt;T&gt;</td>
<td>boolean compare(T x, T y);</td>
</tr>
<tr>
<td>FileFilter</td>
<td>boolean accept(File x);</td>
</tr>
<tr>
<td>Callable&lt;T&gt;</td>
<td>T call();</td>
</tr>
<tr>
<td>Runnable</td>
<td>void run();</td>
</tr>
<tr>
<td>ActionListener</td>
<td>void actionPerformed(ActionEvent e);</td>
</tr>
</tbody>
</table>
Lambda as functional descriptors

- A lambda $\lambda$ is said to be compatible with a functional descriptor $F$ iff:
  - Parameter types in $\lambda$ matches the parameter types in $F$
  - Return value(s) in $\lambda$ is compatible with the return type of $F$
  - The checked exceptions thrown by $\lambda$ are a subset of the exceptions declared by $F$

- Implicit lambda parameters are inferred from argument types in $F$
Lambda as functional descriptors

FileFilter ff = (File f) -> f.isDirectory();
Comparator<String> cs = (s1,s2) -> s1.length() - s2.length();
Runnable r = () -> { throw new Exception(); }
Comparator<String> cs = (s1,s2) -> true;
FileFilter ff = (String s) -> s.endsWith("Hello!");
The long arm of void-compatibility

- If return type of the functional descriptor is `void`, the lambda must be void-compatible!

<table>
<thead>
<tr>
<th>Example</th>
<th>Correct</th>
<th>Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runnable r = () -&gt; { System.out.println(&quot;Hello!&quot;); }</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Runnable r = () -&gt; System.out.println(&quot;Hello&quot;)!</td>
<td></td>
<td>✗</td>
</tr>
</tbody>
</table>
TARGET-TYPING IN METHOD CONTEXT
Internal iteration w/ lambdas and method references (reloaded)

SomeCoolList<Student> students = ...  
double highestScore =  
    students.filter(Student s -> s.getGradYear() == 2011)  
    .map(Student::getScore)  
    .max();

- Library-based iteration
- Traversal might be done in parallel
- Thread-safe (stateless)
- More readable and less error prone!
- Reuse of existing code!
- Redundant type-information
Internal iteration w/ lambdas, method references and target-typing

```java
SomeCoolList<Student> students = ...
double highestScore =
    students.filter(s -> s.getGradYear() == 2011)
    .map(Student::getScore)
    .max();
```

- Library-based iteration
- Traversal might be done \textit{in parallel}
- Thread-safe (stateless)
- More readable and less error prone!
- Reuse of existing code!
- Don't repeat yourself!
Target-typing in Java

• Lambda expressions/method references are a new form of poly expressions
  – They cannot be type-checked w/o a target type

• This is a problem as the target-type information is not always propagated (as in JDK 7)

<table>
<thead>
<tr>
<th>Correct Example</th>
<th>Incorrect Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>List&lt;String&gt; ls = new ArrayList&lt;&gt;();</code></td>
<td><code>List&lt;String&gt; ls = true ? new ArrayList&lt;&gt;(): new ArrayList&lt;&gt;();</code></td>
</tr>
<tr>
<td>Void m(List&lt;String&gt; ls) { ... } m(new ArrayList&lt;&gt;());</td>
<td></td>
</tr>
</tbody>
</table>
Consistent use of target-typing

- Goal: it should be possible to use a lambda/method reference in all contexts where a target-type exists.

| = | squareMapper = x -> x*x; |
| [] | Mapper<Integer>[] mappers = { x -> x*x, x -> x+x; } |
| return | return x -> x*x; |
| () | numbers.map(x -> x*x) |
| ? | square ? x -> x*x : x -> x+x; |
Overload resolution in JDK 7

1. Inference
   - Generic declaration
   - Argument expressions
   - Types of arguments
   - Applicable?
   - Inferred types
   - Type of expression
   - Target-type
Target-typing and overload resolution

- Lambda/method reference in method context can be checked more than once
  - Speculative type-checking - the lambda/method reference is type-checked against each possible target-type
- Presence of multiple overload candidates
  - checking of lambda/method reference is used to discard some candidates
- Structural most specific check
  - When multiple compatible functional interfaces found
- Let go of the assumption that we must know argument types *ahead* of overload resolution!
Overload resolution revisited

- Generic declaration
- Argument expressions
- Inferred types
- Types of arguments
- Inference
- Applicable?
- Target-type
- Inferred types
- Type of expression
Speculative type-checking

- Lambda/method reference in method context can be checked more than once
  - Speculative type-checking - the lambda/method reference is type-checked against each possible target-type

```
void m(SAM1 s1)  String apply1(Integer i);
void m(SAM2 s2)  Integer apply2(Integer i);
void m(SAM3 s3)  Object apply3(Integer i);
```

```m(x -> x.toString());```
The art of pruning

- Overload candidates are *filtered* using the information derived when checking lambda/method reference
  - If an overloaded method does not satisfy those constraints, it is dropped from the applicable set

<table>
<thead>
<tr>
<th>m(x -&gt; x.toString());</th>
</tr>
</thead>
<tbody>
<tr>
<td>?</td>
</tr>
<tr>
<td>void m(SAM1 s1)</td>
</tr>
<tr>
<td>x</td>
</tr>
<tr>
<td>void m(SAM2 s2)</td>
</tr>
<tr>
<td>?</td>
</tr>
<tr>
<td>void m(SAM3 s3)</td>
</tr>
</tbody>
</table>
Structural most specific

- When multiple overload candidates are available, a most specific signature is selected
  - If formals are functional interfaces, a full structural check is performed on the underlying descriptors

<table>
<thead>
<tr>
<th>$m(x \rightarrow x \text{.}toString())$;</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓  void $m$(SAM1 $s1$)</td>
</tr>
<tr>
<td>❌ void $m$(SAM2 $s2$)</td>
</tr>
<tr>
<td>❌ void $m$(SAM3 $s3$)</td>
</tr>
</tbody>
</table>
Target-typing and generic methods

• An overload candidate could be a generic method
  – The target-type might depend on yet-to-infer inference variables!

• Lambda expressions in method context cannot be type-checked because of the presence of inference variables in the target-type
  – Such lambdas are said to be stuck

• Possible solutions (still under consideration):
  – Inference errors
  – Wait for lambda to become unstuck
A cycle too far?

- It looks like there is cycle in the inference machinery:
  - The compiler needs type-information on actual arguments in order to proceed with method type-inference
  - The compiler needs a fully instantiated target-type in order to type-check certain actual arguments

```java
m(x->1, "Hello!");
interface SAM<X> {
    int apply(X i);
}
```
Out-of-order method checking

• Alternatively, let go of the assumption that arguments are checked from left to right
  – i.e. instantiate all inference variables in the target-types first using constraints derived from unstuck arguments
  – As arguments become unstuck, type-check them until no further progress can be made

```java
m(x->1, "Hello!");
```

```java
interface SAM<X> {
    int apply(X i);
}
```
WRAP UP
**Project Lambda / JSR-335 Status**

- Project Lambda started December 2009
  - Explorations done through OpenJDK
- JSR-335 filed November 2010
  - Prototype compiler developed in OpenJDK
- Current status
  - Compiler prototype binaries available at [http://jdk8.java.net/lambda/](http://jdk8.java.net/lambda/)
    - Includes VM support for extension method dispatch!
- Feedback is welcome!
Conclusion

- Adding closures to Java is key to promote fluent, functional-oriented code that is multicore-ready
- One goal, two constructs
  - Lambda expressions
  - Method references
- Functional interface allows smooth interoperability with existing code
- The devil is in the details
  - Evolving an existing language is always hard – lots of interactions with existing features
  - Novel target-typing support requires overload resolution/inference overhaul