Lambda: A peek under the hood
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About this talk

- This talk outlines the technical details of how lambda expressions are implemented in Java SE 8 at the bytecode level
  - This will be a highly technical talk!
  - We assume some familiarity with JVM and bytecode
    - Including JSR-292 facilities
Lambda expressions for Java

- A lambda expression is like an “anonymous method”
  - Has an argument list, a return type, and a body
    ```java
    people.forEach((Person e) -> { names.add(e.getName()); });
    ```
  - Many of these can be inferred by the compiler
    ```java
    people.forEach(e -> { names.add(e.getName()); });
    ```
- Lambda expressions can capture values from the enclosing context
  ```java
  people.removeIf(e -> e.getAge() < minAge);
  ```
Why lambdas for Java?

- Provide libraries a path to multicore
  - Parallel-friendly APIs need internal iteration
  - Internal iteration needs a concise code-as-data mechanism
- Empower library developers
  - 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
- Inner classes give us some of these benefits, but are too clunky
  - Clunkiness is not entirely syntactic!
- How to represent lambda expressions at runtime is not a trivial question
  - That’s what this talk is about
Big question #1: typing

- What is the type of a lambda expression?
  - Most languages with lambdas have some notion of a function type
    - “function from int to int”
  - Early proposals included adding function types to the type system
  - Seems an obvious idea, but…
    - How would we represent functions in VM type signatures?
    - How would we represent invocation in bytecode?
    - How would we create instances of function-typed variables?
    - How would we deal with variance?
Why not “just” add function types?

- JVM has no native (unboxed) representation of function type in VM type signatures
  - Closest tool we have is generics
  - Boxed and erased function types would be no fun
  - Gaps between language and VM representation are always pain points
- Teaching the VM about “real” function types would be a huge effort
  - New type signatures for functions
  - New bytecodes for invocation
  - New verification rules
Functional interfaces

- Historically modeled functions using single-method interfaces
  - Runnable, Comparator
- Rather than complicate the type system, let’s just formalize that
  - Give them a name: “functional interfaces”
  - Always convert lambda expressions to instance of a functional interface

```java
interface Predicate<T>  { boolean test(T x); }  
people.removeIf(p -> p.getAge() >= 18); 
- Compiler identifies Predicate as a functional interface (structurally)
- Compiler infers the lambda is a Predicate<Person>
“Just add function types” was obvious … and wrong
  – Would have introduced complexity and corner cases
  – Would have bifurcated libraries into “old” and “new” styles
  – Would have created interoperability challenges

**Bonus:** existing libraries are now *forward-compatible* to lambdas
  – Libraries that never imagined lambdas still work with them!
  – Maintains significant investment in existing libraries
  – Fewer new concepts

**Lesson learned:** a stodgy old approach is sometimes better than a shiny new one!
Big question #2: representation

- How does the lambda instance get created?
  - Need to convert a function into an instance of a functional interface
  - Need to handle captured variables

```
Predicate<Person> pred = (Person p) -> p.age < minAge;
```

- The obvious choice is … inner classes
Why not “just” use inner classes?

- We could say that a lambda is “just” an inner class instance

```java
class Foo$1 implements Predicate<Person> {
    private final int $minAge;
    Foo$1(int v0) { this.$minAge = v0; }
    public boolean test(Person p) {
        return p.age < $minAge;
    }
}
```

- Then, lambda capture becomes constructor invocation

```java
list.removeIf(p -> p.age < minAge);
list.removeIf(new Foo$1(minAge));
```
Why not “just” use inner classes?

- Inner class constructor invocation translates as

```java
list.removeIf(p -> p.age < minAge);
```

```java
aload_1          // list
new #2           // class Foo$1
dup
iload_2          // minAge
invokespecial #3 // Method Foo$1."<init>":(I)V
invokeinterface #4 // java/util/List.removeIf:(Ljava/util/functions/Predicate;)Z
```
Why not “just” use inner classes?

- Translating to inner classes means we inherit most of their problems
  - Performance issues
    - One class per lambda expression
    - Type profile pollution
    - Always allocates a new instance
      - Complicated and error-prone “comb” lookup for names
- Whatever we do becomes a *binary representation* for lambdas in Java
  - Would be stuck with it forever
  - Would rather not conflate implementation with binary representation
- Another “obvious but wrong” choice
New bytecode tool: MethodHandle

- Java SE 7 adds VM-level *method handles*
  - Can store references to methods in the constant pool, load with LDC
  - Can obtain a method handle for any method (or field access)
  - VM will happily inline through MH calls
  - API-based combinators for manipulating method handles
    - Add, remove, reorder arguments
    - Adapt (box, unbox, cast) arguments and return types
    - Compose methods
  - Compiler writers swiss-army knife!
Why not “just” use MethodHandle?

- At first, translating lambdas to MethodHandle seems obvious
  - Lambda is language-level method object
  - MethodHandle is VM-level method object
- We could
  - Desugar lambdas expressions to methods
  - Represent lambdas using MethodHandle in bytecode signatures
Why not “just” use MethodHandle?

- If we represented lambdas as MethodHandle, we’d translate:

```java
list.removeIf(p -> p.age < minAge);

private static boolean lambda$1(int minAge, Person p) {
    return p.age < minAge;
}

MethodHandle mh = LDC[lambda$1];
mh = MethodHandles.insertArguments(mh, 0, minAge);
list.removeIf(mh);
```
Why not “just” use MethodHandle?

- If we did this, the signature of List.removeIf would be:
  ```java
  void removeIf(MethodHandle predicate)
  ```
- This is erasure on steroids!
  - Can’t overload two methods that take differently “shaped” lambdas
  - Still would need to encode the erased type information somewhere
- Also: is MH invocation performance yet competitive with bytecode invocation?
- Again: conflates binary representation with implementation
  - Obvious but wrong … again
Stepping back…

- We would like a binary interface not tied to a specific implementation
  - Inner classes have too much baggage
  - MethodHandle is too low-level, is erased
  - Can’t force users to recompile, ever, so have to pick now

- What we need is … another level of indirection
  - Let the static compiler emit a declarative recipe, rather than imperative code, for creating a lambda
  - Let the runtime execute that recipe however it deems best
  - And make it darned fast
  - This sounds like a job for invokedynamic!
Bytecode invocation modes

- Prior to Java SE 7, the JVM had four bytecodes for method invocation
  - `invokestatic`: for static methods
  - `invokevirtual`: for class methods
  - `invokeinterface`: for interface methods
  - `invokespecial`: for constructors, private methods, and super-calls

- Each specifies a class name, method name, and method signature

```java
aload_1             // list
new #2              // class Foo$1
dup
iload_2             // minAge
invokespecial #3    // Method Foo$1."<init>":(I)V
invokeinterface #4   // java/util/List.removeIf:(Ljava/util/functions/Predicate;)Z
```
New bytecode tool: invokedynamic

- Java SE 7 adds a fifth invocation mode: *invokedynamic* (indy)
- Behavior of `invoke{virtual,static,interface}` are fixed and Java-like
  - Other languages need custom method linkage
- Basic idea: let some “language logic” determine call target
  - But then *get out of the way*
  - Language and VM become partners in flexible and efficient method dispatch
New bytecode tool: invokedynamic

- Invokedynamic started out as a tool for dynamic languages
  - A typical application would be invoking a method like
    ```java
def add(a, b) { a+b }
```
- Here, the types of a and b are not known at compile time
  - And can change from call to call … *but probably don’t*
    - Good chance that, if called with two ints, next call will be with two ints
  - We win by not having to re-link the call site for every invocation
New bytecode tool: invokedynamic

- The first time the JVM executes an invokedynamic
  - Consults the *bootstrap method* for the call site (the “language logic”)
  - Bootstrap returns a linked call site
  - Call site can embed conditions under which it needs relinking (if any)
    - Such as the argument types changing
    - Otherwise, JVM does not have to consult bootstrap again
- After linkage, JVM can treat the call site as fully linked
  - Can inline through linked indy callsites like any other
New bytecode tool: invokedynamic

- An indy callsite has three groups of operands
  - A *bootstrap method* (the “language logic”)
    - Called by the VM for linking the callsite on first invocation
    - Not called again after that
  - A static argument list, embedded in the constant pool
    - Available to the bootstrap method
  - A dynamic argument list, like any other method invocation
    - Not available to the bootstrap, but their *static types and arity* are
    - Passed to whatever target the callsite is linked to
Its not just for dynamic languages anymore

- So, if indy is for dynamic languages, why is the Java compiler using it?
  - All the types involved are static
  - What is dynamic here is the code generation strategy
    - Generate inner classes?
    - Use method handles?
    - Use dynamic proxies?
    - Use VM-private APIs for constructing objects?
- Indy lets us turn this choice into a pure implementation detail
  - Separate from the binary representation
Its not just for dynamic languages anymore

- We use indy to embed a *recipe* for constructing a lambda, including
  - The desugared implementation method (static)
  - The functional interface we are converting to (static)
  - Additional metadata, such as serialization information (static)
  - Values captured from the lexical scope (dynamic)

- The capture site is called the *lambda factory*
  - Invoked with indy, returns an instance of the desired functional interface
  - Subsequent captures bypass the (slow) linkage path
Desugaring lambdas to methods

- First, we desugar the lambda to a method, as before
  - Signature matches functional interface method
  - Plus captured arguments prepended
  - Simplest lambdas desugar to static methods
    - But some need access to receiver, and so are instance methods

```java
Predicate<Person> pred = p -> p.age < minAge;

private static boolean lambda$1(int minAge, Person p) {
    return p.age < minAge;
}
```
Factories and metafactories

- We generate an indy call site which, when called, returns the lambda
  - This is the *lambda factory*
  - Bootstrap for the lambda factory selects the translation strategy
    - Bootstrap is called the *lambda metafactory*
    - Part of Java runtime
  - Captured args passed to lambda factory

```java
private static boolean lambda$1(int minAge, Person p) {
    return p.getAge() >= minAge;
}

Predicate $p = indy[bootstrap=LambdaMetafactory,
    staticargs=[Predicate, lambda$1],
    dynargs=[minAge])

list.removeIf($p);
list.removeIf(p -> p.age < minAge);
```
Translation strategies

- The metafactory could spin inner classes dynamically
  - Generate the same class the compiler would, just at runtime
  - Link factory call site to constructor of generated class
    - Conveniently, dynamic args and ctor args will line up
  - Our initial strategy until we can prove that there’s a better one
- Alternately could spin one wrapper class per interface
  - Constructor would take a method handle
  - Methods would invoke that method handle
- Could also use dynamic proxies or MethodHandleProxy
- Or VM-private APIs to build object from scratch, or…
Indy: the ultimate procrastination aid

- By deferring the code generation choice to runtime, it becomes a pure implementation detail
  - Can be changed dynamically
  - We can settle on a binary protocol now (metafactory API) while delaying the choice of code generation strategy
    - Moving more work from static compiler to runtime
  - Can change code generation strategy across VM versions, or even days of the week
Indy: the ultimate lazy initialization

- For stateless (non-capturing) lambdas, we can create one single instance of the lambda object and always return that
  - Very common case – many lambdas capture nothing
  - Sometimes we do this by hand in source code – e.g., pulling a Comparator into a static final variable

- Indy functions as a lazily initialized cache
  - Defers initialization cost to first use
  - No heap overhead if lambda is never used
  - No extra field or static initializer
  - All stateless lambdas get lazy initialization and caching for free
Indy: the ultimate indirection aid

- Just because we defer code generation strategy to runtime, we don’t have to pay the price on every call
  - Metafactory only invoked once per call site
  - For non-capturing case, subsequent captures are FREE
    - VM optimizes to constant load
  - For capturing case, subsequent capture cost on order of a constructor call / method handle manipulation
    - MF links to constructor for generated class
Performance costs

- Any translation scheme imposes costs at several levels:
  - Linkage cost – one-time cost of setting up lambda capture
  - Capture cost – cost of creating a lambda instance
  - Invocation cost – cost of invoking the lambda method

- For inner class instances, these correspond to:
  - Linkage: loading the class
  - Capture: invoking the constructor
  - Invocation: invokeinterface
Performance example – linkage cost

- Oracle Performance Team measured linkage costs
  - Time in ms for 32K distinct inner classes / lambdas
  - Fastest possible disk (to negate IO component of anon class loading)

<table>
<thead>
<tr>
<th></th>
<th>Anonymous</th>
<th>Lambda</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>-Capturing -Tiered</td>
<td>7473ms</td>
<td>6891ms</td>
<td>8.4%</td>
</tr>
<tr>
<td>-Capturing +Tiered</td>
<td>7038</td>
<td>5743</td>
<td>14.4%</td>
</tr>
<tr>
<td>+Capturing -Tiered</td>
<td>7885</td>
<td>6550</td>
<td>20.3%</td>
</tr>
<tr>
<td>+Capturing +Tiered</td>
<td>7638</td>
<td>5727</td>
<td>24%</td>
</tr>
</tbody>
</table>
Performance example – capture cost

- Oracle Performance Team measured capture costs (ops / uSec)
  - 4 socket x 10 core x 2 thread Nehalem EX server
- Worst-case lambda numbers equal to inner classes
  - Best-case numbers much better
  - And this is just our V1 strategy…

<table>
<thead>
<tr>
<th></th>
<th>Single-threaded</th>
<th>Saturated</th>
<th>Scalability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner class</td>
<td>150</td>
<td>750</td>
<td>5x</td>
</tr>
<tr>
<td>Non-capturing lambda</td>
<td>230</td>
<td>15500</td>
<td>67x</td>
</tr>
<tr>
<td>Capturing lambda</td>
<td>150</td>
<td>740</td>
<td>5x</td>
</tr>
</tbody>
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Not just for the Java Language!

- The lambda conversion metafactories will be part of java.lang.invoke
  - Semantics tailored to Java language needs
  - But, other languages may find it useful too!
- Java APIs will be full of functional interfaces
  - Collection.forEach(Consumer)
- Other languages probably will want to call these APIs
  - Maybe using their own closures
  - Will want a similar conversion
- Since metafactories are likely to receive future VM optimization attention, using platform runtime is likely to be faster than spinning your own inner classes
Future VM support (?)

- With VM help, we can optimize even further
- VM could intrinsify lambda capture sites
  - Capture semantics are straightforward properties of method handles
  - Capture operation is pure, therefore freely reorderable
  - Can use code motion to delay/eliminate captures
- Lambda capture is essentially a “boxing” operation
  - Boxing a method handle into a lambda object
  - Invocation is the corresponding “unbox”
  - Can use box elimination techniques to eliminate capture overhead
    - Intrinsification of capture + inline + escape analysis
Serialization

- No language feature is complete without some interaction with serialization 😐
  - Users will expect this code to work

```java
interface Foo extendsSerializable {
    public boolean eval();
}
```

```java
Foo f = () -> false;
// now serialize f
```

- We can’t just serialize the lambda object
  - Implementing class won’t exist at deserialization time
  - Deserializing VM may use a different translation strategy
  - Need a dynamic serialization strategy too!
    - Without exposing security holes…
Serialization

- Just as our classfile representation for a lambda is a recipe, our serialized representation needs to be too
  - We can use readResolve / writeReplace
  - Instead of serializing lambda directly, serialize the recipe (to a `java.lang.invoke.SerializedLambda`)
  - This means that for serializable lambdas, MF must provide a way of getting at the recipe
  - We provide an alternate MF bootstrap for that

- On deserialization, reconstitute from recipe
  - Using then-current translation strategy, which might be different from the one that originally created the lambda
  - Without opening new security holes
Summary

- The evolutionary path is often full of obvious-but-wrong ideas
- We use invokedynamic to capture lambda expressions
  - Gives us flexibility and performance
  - Free to change translation strategy at runtime
- Even using the “dumb” translation strategy…
  - No worse than inner classes in the worst case
  - 5-20x better than inner classes in a common case
For more information

- Project Lambda: http://openjdk.java.net/projects/lambda/
  - Lambda spec EDR #3: http://jcp.org/aboutJava/communityprocess/edr/jsr335/index3.html
  - Lambda Overview: http://cr.openjdk.java.net/~briangoetz/lambda/lambda-state-final.html
  - Binary builds: https://jdk8.java.net/download.html