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Lambda: A peek under the hood

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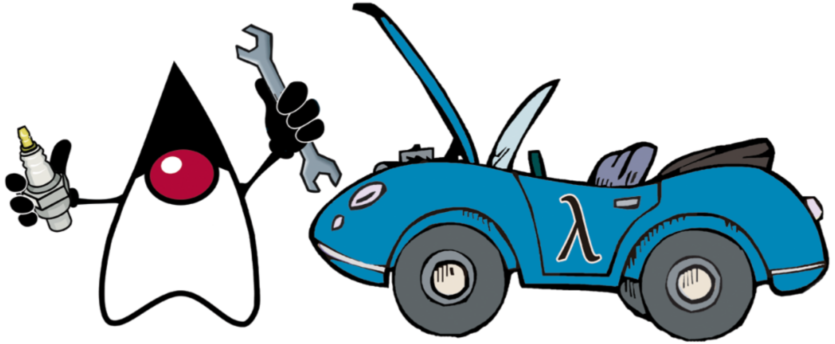
About this talk

- 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



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Lambda expressions for Java

- A lambda expression is like an “anonymous method”
  - Has an argument list, a return type, and a body

    ```
    people.forEach((Person e) -> { names.add(e.getName()); });
    ```

  - Many of these can be inferred by the compiler

    ```
    people.forEach(e -> { names.add(e.getName()); });
    ```

- Lambda expressions can capture values from the enclosing context

    ```
    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 (unerased) 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

```
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>

Functional interfaces

- "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

```
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

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

→

```
list.removeIf(new Foo$1(minAge));
```

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Why not “just” use inner classes?

- Inner class constructor invocation translates as

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

```
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:

```
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:
  `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!

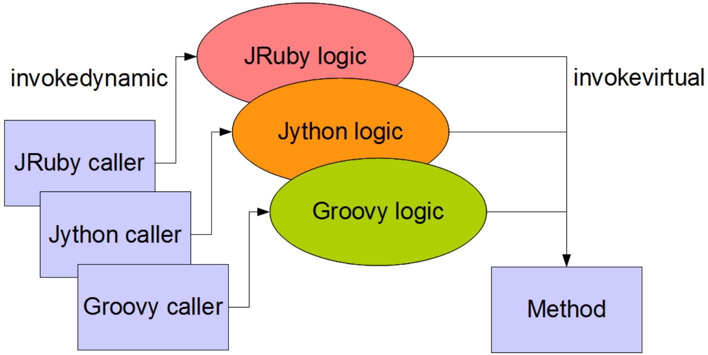
Bytecode invocation modes

- 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

```
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
    ```
    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

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

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

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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

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

```
Predicate $p = indy[bootstrap=LambdaMetafactory,
                    staticargs=[Predicate, lambda$1],
                    dynargs=[minAge])
list.removeIf($p);
```

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

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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)

	Anonymous	Lambda	Difference
-Capturing -Tiered	7473ms	6891ms	8.4%
-Capturing +Tiered	7038	5743	14.4%
+Capturing -Tiered	7885	6550	20.3%
+Capturing +Tiered	7638	5727	24%

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…

	Single-threaded	Saturated	Scalability
Inner class	150	750	5x
Non-capturing lambda	230	15500	67x
Capturing lambda	150	740	5x

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

```
interface Foo extends Serializable {
    public boolean eval();
}
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

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