Classless Closures for a Small Embedded VM

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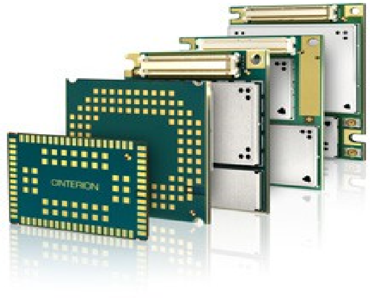
Agenda

- Introduction to Monty JVM
- Closures in Java
- Classless implementation of closures
- Q & A

Introduction to Monty JVM

CLDC HI VM Overview

- Connected Limited Device Configuration JVM
  - Build-time choice of CLDC 1.0, 1.1, 1.1.1 and 8 profiles
  - First release: October, 2003



- HotSpot Implementation (optional)
  - Profiler-driven dynamic compilation
  - Optimistic speculative optimizations
  - Dynamic deoptimization (when necessary)

- Targeted to small mobile & embedded devices
  - Slow processor and memory
  - Constrained memory (16K-16M RAM)
  - May not have a fully capable OS
    - Single process
    - Single native thread
    - May or may not support page protection and memory-mapped files
    - May have no OS (bare metal)

Target processors

- ARM 9, 11 with optional coprocessors and instruction set extensions
  - Thumb, Thumb 2
  - JazelleDBX (HW bytecode interpreter)
  - ARM VFP (Vector Floating Point coprocessor)
- ARM Cortex A, M3, M4
- Intel x386+
  - For debugging and cross-compilation
- SuperHitachi SH3, SH4
- SPARC
  - For cross-compilation only

Evolution of CLDC profile

- CLDC 1.0, 1.1, 1.1.1
  - Subsets of J2SE (JDK 1.3)
  - No user-defined class loaders
  - No reflection (except for *Class.forName*)
  - No serialization
  - No JNI and native code in applications
  - No user-defined finalizers
  - Requires 32K RAM, 160K ROM for VM and class library
- CLDC 8
  - Subset of Java SE 8, released April 2014
  - Supports new language features (Generics, Annotations...)
  - Retains all limitations of the older CLDC profiles
  - No invokedynamic
  - No annotations with RUNTIME retention policy
  - Requires 128K RAM, 512K ROM for VM and class library

VM technologies under hood

- Manually optimized assembly interpreter
  - Most of the code is interpeted due to the lack of memory
  - Can use h/w acceleration
  - Execution stacks are elastic and allocated in the object heap
    - Grow and shrink when necessary
  - Can be easily extended with new internal bytecodes
    - But not many spare bytecodes left
- (Almost) Everything is a runtime object
  - But not necessarily Java object
    - Method, Compiled method, Execution stack...
    - Any runtime object could be made Java object
  - New kind of runtime objects can be easily defined
    - *object_size*(obj) – compute the object size
    - *oops_do*(obj, func) – apply a function to every reference field
    - *print_on*(stream) – pretty-printing for convenience of debugging (optional)
    - Statically register the kind and get the kind_id

VM technologies under hood (1)

- Single-pass dynamic adaptive compiler (optional)
  - Pauseless incremental schedulable compilation
  - Driven by a dynamic profiler
    - Combined sampling and instrumentaion
  - Compiled code and temporary data allocated in a distinguished area of the heap
    - Relocatable and resizable
    - Execution of compiled code is profiled
    - “Cold” code is evicted, no GC is necessary
  - No IR constructed: direct abstract interpretation of bytecodes
  - Optimizations:
    - Constant folding
    - Type, constant and copy propagation
    - CSE (with a dictionary of bytecode strings)
    - Null check and checkcast elimination
    - Limited-depth inlining of method calls
    - Speculative devirtualization (unguarded)
    - Loop and branch optimizations

VM technologies under hood (2)

- System class pre-linking (*ROMization*)
  - System libraries and pre-installed applications loaded at build time
  - The classes are selectively initialized
  - Aggressively optimized for size and speed
    - Open- and closed-world models supported
    - Reduction of interface and virtual method calls
    - Elimination of unreachable methods, fields and classes
    - Selective AOT compilation
    - Symbolic information stripped
    - Constant pools are merged
    - Immutable data separated, stored in ROM, shared between isolates
  - The generated image is compiled & linked into VM executable
  - Reduces static and dynamic footprint
  - Greatly reduces VM start-up time

VM technologies under hood (3)

- Generational mark & compact garbage collector
  - Heap occupancy > 80%
  - Linear allocation, sliding window compaction
  - Preserves allocation order
    - Improves locality
    - Helps to eliminate cross-references in persistent groups of objects
- Multiple virtual threads over single native thread
- Multitasking within single native process (*Isolates*)
  - With task priorities, resource quotas and shared libraries
  - Synchronous native finalization on isolate termination
- Lightweight native interface
  - Direct access to Java objects via the generated C++ structures
  - KNI

Bytecode Quickening

- Interpreter rewrites some bytecodes during execution
  - When necessary, a method can be quickened by request
- Resolve symbolic references
- Validate the semantics
- If successful, patch the bytecode with a quicker version
  - To avoid repeated quickening of the same bytecode
  - Bytecode size has to remain the same
    - Can be padded with *nop*'s

  quick_getstatic, quick_<T>getfield,

  quick_invokevirtual, quick_invokeinvirtual_final, quick_invokespecial, quick_invokeinterface,

  quick_instanceof, quick_checkcast
- Frequently used sequences of bytecodes can be replaced with faster *super-instructions*
  - i.e. *aload_0_fast_agetfield_1*

Closures in Java

Closures

- *Closure* is a function (or reference to a function) together with the environment referenced by the function
  - Introduced in *Scheme* programming language (1975-80)
- In stateful programming language a function can modify its environment
  - Block in *Smalltalk* and *Self*
  - Activation record in *Beta*
  - Locals of outer scopes can be modified

```
|count incrementCount|
count := 0.
incrementCount := [count := count + 1].
1 to: 10 do: [:i | i even ifTrue: incrementCount].
^count
```

- Closures in Java can be modeled with inner classes and lambda expressions (in Java 8+)
  - Non-local variables are captured and cannot be modified

Lambda expressions in Java 8+

- Lambda expression produces an instance of functional interface
  - Essentially an interface with a single abstract method
  - Notional interface can be induced by an intersection type

    FunctionalInterface & MarkerInterface(s)
  - The JLS 8 carefully avoids unnecessary restrictions on the implementation of the interface
  - Usually local class implementing the functional interface is created
- Lambda expression is compiled to:
  - the method representing the lambda body
  - invokedynamic for a method of java.lang.invoke.LambdaMetafactory
- Can we use lambda expressions in CLDC?
  - They are convenient and expressive
  - But there is no *invokedynamic* and *java.lang.invoke* package
  - Invokedynamic for LambdaMetafactory can be treated as an idiom

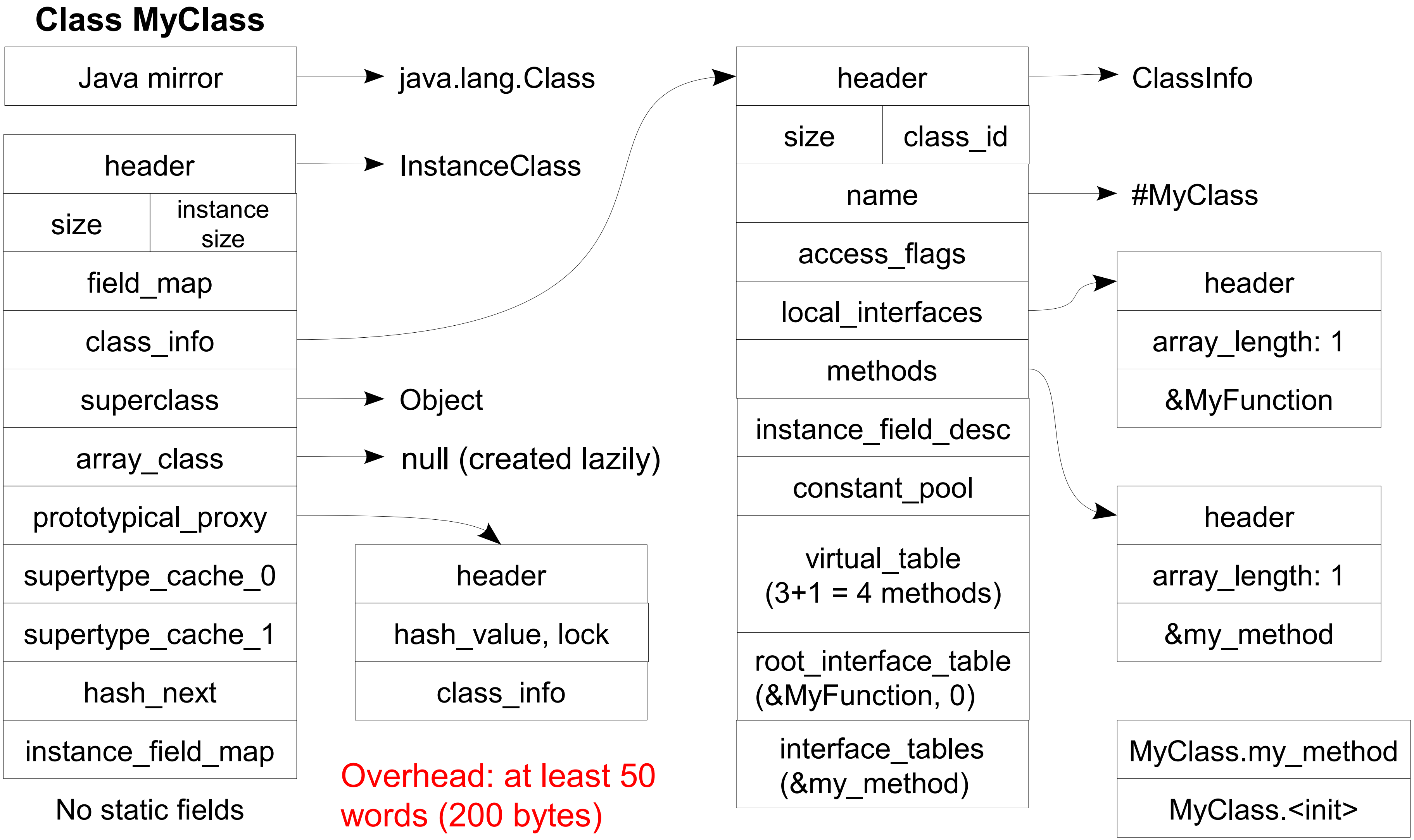
Example: Inner class implementing a functional interface and capturing one value

```
interface MyFunction {
  int my_function();
}

class OuterClass {
  int x;

  class MyClass implements MyFunction {
    int my_function() {
      return x;
    }
  }
}
```

Internals of MyClass implementing MyFunction and capturing one value



Class MyClass

Java mirror

→ java.lang.Class

header	
size	instance size
field_map	
class_info	
superclass	
array_class	
prototypical_proxy	
supertype_cache_0	
supertype_cache_1	
hash_next	
instance_field_map	

header → InstanceClass

superclass → Object

array_class → null (created lazily)

No static fields

prototypical_proxy →

header
hash_value, lock
class_info

class_info →

header	
size	class_id
name	
access_flags	
local_interfaces	
methods	
instance_field_desc	
constant_pool	
virtual_table (3+1 = 4 methods)	
root_interface_table (&MyFunction, 0)	
interface_tables (&my_method)	

header → ClassInfo

name → #MyClass

local_interfaces →

header
array_length: 1
&MyFunction

methods →

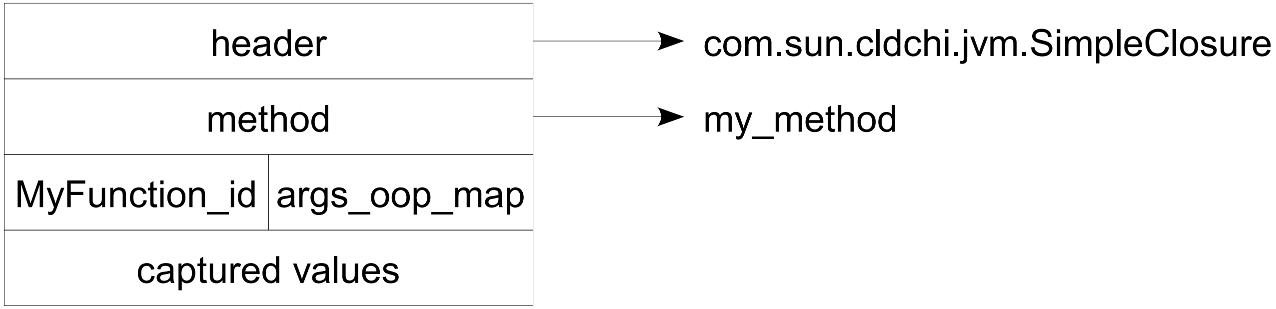
header
array_length: 1
&my_method

MyClass.my_method
MyClass.<init>

Overhead: at least 50 words (200 bytes)

Classless Implementation of Closures

Classless closure for MyFunction



- SimpleClosure
  - Hidden abstract instance class, extends Object
  - May (but not required to) override inherited methods (equals, hashCode, toString)
- Method
  - A reference to a method of any class, must have compatible type
- MyFunction_id
  - Every class and interface has unique id
  - Max 16K classes per Isolate: fits in 14 bits
- args_oop_map
  - Number of captured words and a bitmap of pointers among them
    - 4 bits for size + 14 for bitmap, or 17 for bitmap + 1 for the terminator bit

Relaxed type compatibility for fully quickened methods

- Quick bytecodes are fully resolved
  - Symbolic references are replaced by adresses, offsets and indices
  - Access rights are already validated during the quickening
- Method is fully quickened if:
  - Contains only quick versions of bytecodes
  - Is invoked only by quick bytecodes
- Type compatibility of static and virtual methods
  - SomeClass.static_method(SomeClass receiver, args) and SomeClass.virtual_method(args) are type-compatible
  - Only total number of arguments, their order and types are important
- Mobility of static methods
  - Fully quickened static method of one class can be moved to any other class while all references to the method preserved

Invocation of Simple Closures

- Polymorphism of functional interfaces
  - Java type system cannot distinguish regular Java class and SimpleClosure implementations of the same interface
    - Type system of dynamic/AOT compiler can be richer – it can be able to make it for some call site at compile time
  - The same code must work with both representations
  - Bytecodes may need to handle the difference in run time
- Four bytecodes require modification
  - *quick_invokespecial*
  - *quick_invokeinterface*
  - *quick_isinstanceof*
  - *quick_checkcast*
- No need to modify *quick_invokevirtual*
  - For final classes *invokevirtual* is always quickened to *quick_invokevirtual_final*
  - Calls a resolved reference to the method in the constant pool

Modification of quick_invokespecial

- quick_invokespecial <method_index> (receiver ...)

```
Method method;
if (receiver.class == SimpleClosure) {
  method = ((SimpleClosure)receiver).method;
} else {
  // Regular Java class
  method = receiver.classinfo.get_virtual_method(method_index);
}
invoke(method);
```

Modification of quick_invokeinterface

- quick_invokeinterface <interface_id, method_index, n_args> (receiver ...)

```
Method method;
if (receiver.class == SimpleClosure) {
  method = ((SimpleClosure)receiver).method;
} else {
  // Regular Java class
  const ClassInfo classinfo = receiver.classinfo;
  method = classinfo.lookup_interface_table(interface_id)
                [method_index];
}
invoke(method);
```

Modification of quick_isinstanceof

- quick_isinstanceof <class_id> (obj)

```
Class klass = obj.class;
if (klass == SimpleClosure) {
  // Lookup the superclasses of SimpleClosure
  // Object is the only accessible superclass of SimpleClosure
  if (class_id == Object_id) {
    return true;
  }
  klass = get_class_by_id(((SimpleClosure)obj).interface_id);
}
return klass.is_subtype_of(class_id);
```

- quick_checkcast <class_id> (obj)
  - Is similar but throws an exception instead of returning a boolean

Creation of SimpleClosures

- New internal bytecode new_simple_closure<interface_id, method, args_map>
  - Args_map combines n_args and oop_map in a short value
  - Creates new SimpleClosure for n_args of captured values
  - Initializes interface_id and method fields
  - Pops a block of n_args words from stack to the captured fields
    - Plain data copy (could use memcpy) followed by the adjustment of *SP*
    - No need in write barrier – it is an initialization of a young object
    - Type correctness must be guaranteed by bytecode construction
- Do we have enough space at the capture site to generate this bytecode without the method expansion?
  - For the old Java the answer is positive
  - For the new Java it is negative
    - Have to move interface_id from the bytecode to the cpool or the method: new_simple_closure<method_cp_index, args_map>

Creating a Simple Closure in Old Java

```
new <MyClass>                    ; 3 bytes
dup                              ; 1 byte
aload_0                          ; N captured values (N >= 0)
…
invokespecial <MyClass.<init>> ; 3 bytes
```

↓

```
aload_0                          ; N captured values
…
new_simple_closure <MyFunction_id, method, N> ; 7 bytes:
       ; interface_id – immediate 2 bytes
       ; method – constant pool index to resolved method, 2 bytes
       ; args_map – immediate 2 bytes
```

- Exception table may need to be updated
  - Bytecode indices have changed

Creating a Simple Closure in New Java

```
aload_0                             ; N captured values
…
invokedynamic <call site specifier> ; 5 bytes
```

↓

```
aload_0                             ; N captured values
…
new_simple_closure <method, N> ; 5 bytes:
       ; method – constant pool index to the pair of indices
       ;   (resolved_static_method, class_id)
       ; n_args_and_oopmap – immediate 2 bytes
```

- Constant pool entries can be shared between the bytecodes
  - It may be easier to store interface_id somewhere in the method and to share just a ResolvedStaticMethod entry between equivalent call sites

Simple Closure conversion for old Java

- Class implementing the interface is created statically
  - It contains a virtual method implementing the interface method
- Check if the class can be converted to Simple Closure
- Adjust the reads of captured values in the method
  - Offset of captured fields is different in Simple Closure (3 words) and the original Java class (1 word)
  - Java stack may grow downwards
    - It is easier to reorder fields once than to modify code generators for all supported ISAs
  - Adjust field offset in the instance field descriptors before quickening the method
- Convert the signature to the static method
- Move the method to the closest outer Java class
- Dispose the implementing class

When an instance class can be converted to Simple Closure

- Final, extends Object, implements single functional interface
- Contains no fields or methods except for the implemented functional method and the constructor
- The constructor initializes every field by the respective argument
- Contains only resolvable symbolic references
  - And so can be fully quickened
- Referenced only at capture site to create a closure
  - Anonymous class is just a class with mangled name
  - The enclosing scope of inner class definition is lost during compilation to the class file
    - Closed syntactic scope within a method or a class is expanded to the package
    - A loaded later class can refer to the any other class in its package
  - We can guess but cannot really prove the class is properly used

Simple Closure conversion for new Java

- Lambda body is represented by a method of the enclosing class
  - All captured values are passed as arguments
- Can the interpreter push a block of previously captured values and call this method?

  `closure lambda_args --> closure lambda_args captured_values`
  - Unfortunately, no: the number and the order of arguments differ
  - … and their types can be different too
- Adapter method has to be generated
  - Let's make it a static method in the same class as the lambda body
  - LambdaMetafactory has to be partially re-implemented in the runtime
  - The generation of the adapter may require boxing/unboxing and widening conversions of the arguments and the result

Transparency of Simple Closures

- Is there an observable difference between Simple Closure and anonymous internal Java class implementing the same interface?
  - closure.getClass() returns a different class
    - It is the same for all simple closures, and this is observable
  - SimpleClosure cannot have the same properties as the respective internal class
    - closure.getClass().newInstance() never creates a closure, throws an exception
    - MyFunction.isAssignableFrom(SimpleClosure) returns false regardless of the interface implemented by its instances
      - Not a part of older CLDC profiles
      - Specified in CLDC 8 but never used anywhere in the libraries
  - If required, closure.getClass() could create a fake Java class lazily
    - Must be shared between all Simple Closures created by the same capture site
      - class_id has to be allocated eagerly
    - Must be in correct relation with its instances and the implemented interface
    - Disposable when not referenced

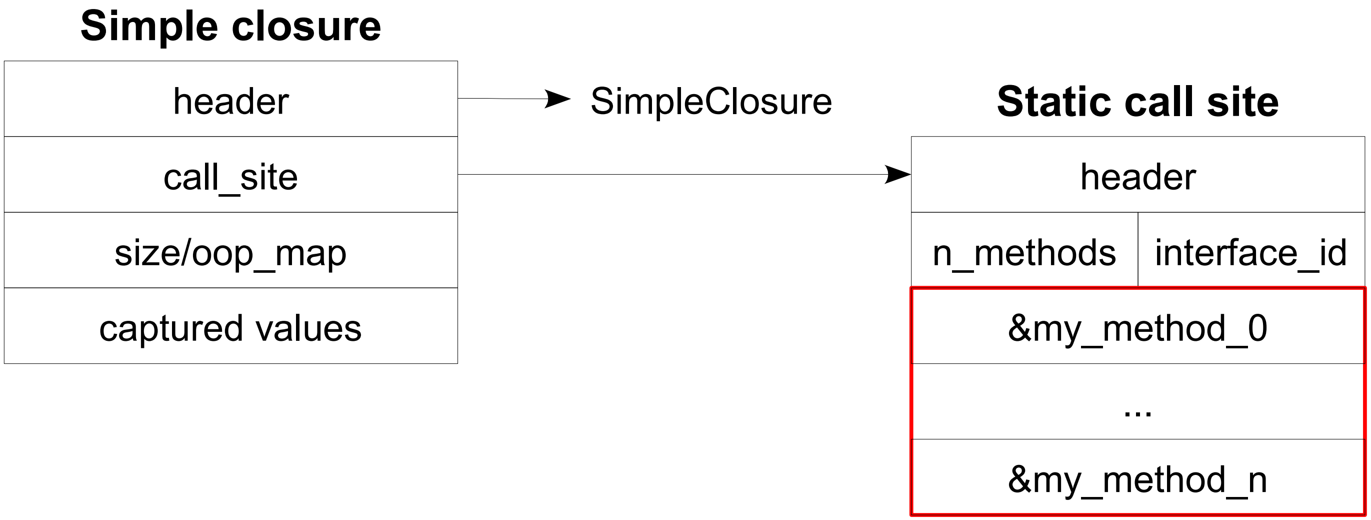
Which Java is better for Simple Closures

- Ideally, there should be one statically generated method
  - Captured values can be represented as fields or the tail arguments
  - The head arguments must be compatible with the interface
- Both the old and the new Java deviate from the ideal
- The old Java:
  - Generates a method with the matching arguments
  - … but it is located in a wrong package-private class
  - All references to the class have to be analyzed
    - The analysis would be easier if the class could be local within a method
  - Bytecodes of the capture site must be analyzed and rewritten
- The new Java:
  - Generates a method in the proper class but with wrong arguments
  - An additional adapter method must be generated by VM
    - Memory and performance overhead
    - Bytecode generator does not naturally belong to this VM

Bridge methods and marker interfaces

- Bridge methods are artifacts of generics in Java type system
  - Do not naturally belong to closures or lambda expressions
- Marker interfaces is a value add-on for lambdas
  - Do not naturally belong to closures or lambda expressions
  - Memory overhead
  - Performance overhead in current implementation of *invokeinterface*, *instanceof* and *checkcast* bytecodes
    - The interface table lookup is linear on the number of implemented interfaces regardless of the number of the methods
- Hopefully, they can be omitted in CLDC subset
- … But what if we had to implement them anyway?

Simple Closures with bridge methods



Simple closure

header

call_site

size/oop_map

captured values

SimpleClosure

Static call site

header

n_methods

interface_id

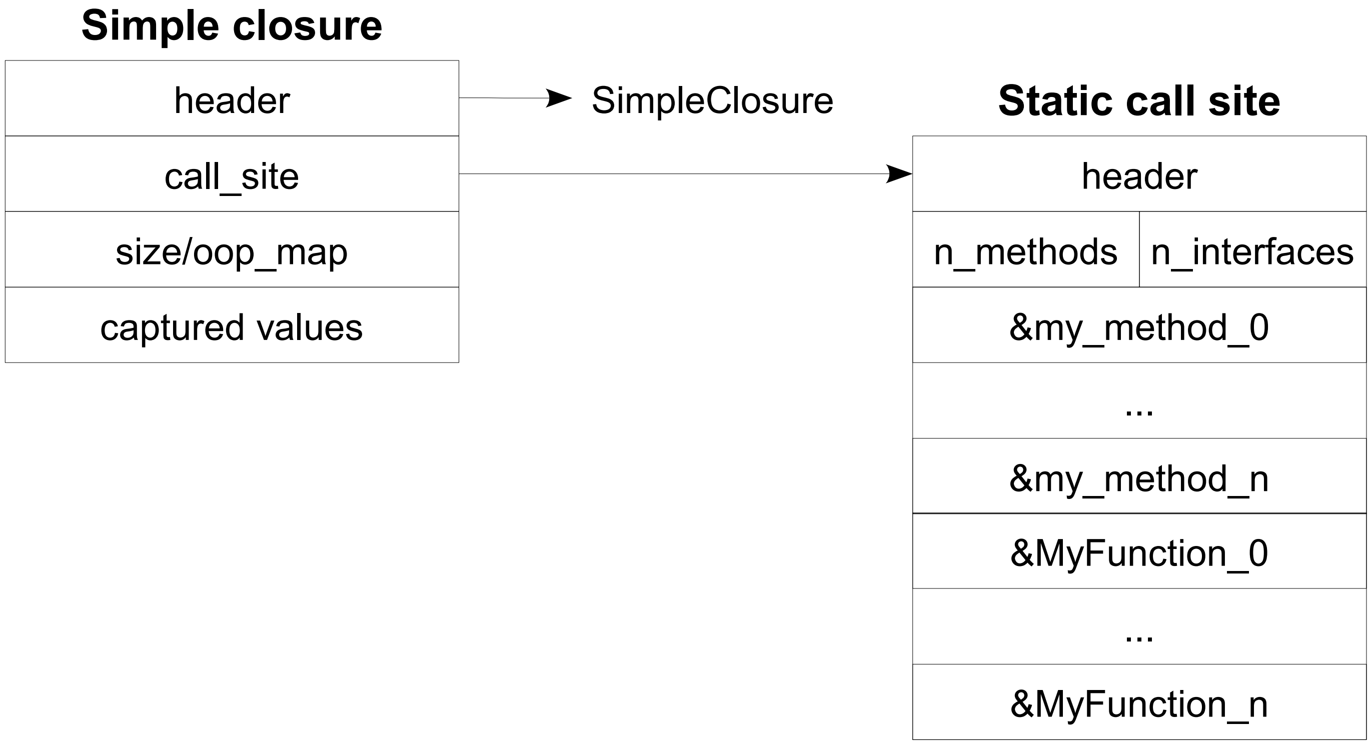
&my_method_0

...

&my_method_n

- Fields *interface_id* and *method* moved from Simple Closure to Static Call Site
- Field *size/oop_map* is the same Simple Closures created by one Static Calls Site. But it cannot be moved to Static Call Site: it defines object size and so must be accessible via no more than one hop from object header.
- A bit more complicated implementation of bytecodes *quick_invokeinterface*, *quick_invokespecial*, *quick_instanceof* and *quick_checkcast*

Simple Closures with bridge methods and marker interfaces



Simple closure

header

call_site

size/oop_map

captured values

SimpleClosure

Static call site

header

n_methods

n_interfaces

&my_method_0

...

&my_method_n

&MyFunction_0

...

&MyFunction_n

- A bit more complicated implementation of bytecodes *quick_instanceof* and *quick_checkcast*
  - Extra 1-2 words for supertype cache could improve the performance
- Getting closer to regular classes... Are they really so terrible?

Alternative Approach

- Adapters can be generated by the runtime-specific external convertor
  - Standard class file format can be used
  - The change can be encoded by a different method of LambdaMetafactory in the call site descriptor
  - The method may not exist – it is just an idiom for the runtime

Q&A