John R. Rose, Da Vinci Machine Project, JSR 292 Lead
Method Handles and Beyond...
Some basis vectors

John R. Rose, Da Vinci Machine Project, JSR 292 Lead
Victory in JDK 7!

Tuesday, July 19, 2011
Victory in JDK 7!

JSR 292 is finished.
Victory in JDK 7!
JSR 292 is finished.

(Or is it?)
Victory in JDK 7!

JSR 292 is finished.

(Or is it?)
Back to the future!
...a perspective from the original JVM Specification
The Java Virtual Machine knows nothing about the Java programming language, only of a particular binary format, the class file format. A class file contains Java Virtual Machine instructions (or bytecodes) and a symbol table, as well as other ancillary information. Any language with functionality that can be expressed in terms of a valid class file can be hosted by the Java virtual machine. Attracted by a generally available, machine-independent platform, implementors of other languages are turning to the Java Virtual Machine as a delivery vehicle for their languages. In the future, we will consider bounded extensions to the Java Virtual Machine to provide better support for other languages.
Overview...

• What we did in JDK 7
• How it works in Hotspot
• Advice to users
• Next steps in JSR 292
• Building the future
Overview...

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• How it works in Hotspot
• Advice to users
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• is a natural general purpose primitive
  • Not tied to semantics of a specific programming language
  • Flexible building block for a variety of method invocation semantics

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Gilad Bracha
Sun Microsystems, JAOO 2005
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JSR 292 Timeline
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- 2010: API refinement (e.g., BootstrapMethods)
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- 2011: Final balloting.
Key Features
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• New unit of behavior: \textit{method handle}
  – The content of a dynamic call site is a method handle.
  – Method handles are function pointers for the JVM.
  – (Or if you like, each MH implements a single-method interface.)
Dynamic program composition
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- Bytecodes are created by Java compilers or dynamic runtimes.
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• Dynamic call sites

  Bytecodes

  Method handles
Dynamic program composition

- Bytecodes are created by Java compilers or dynamic runtimes.
- The JVM seamlessly integrates execution, optimizing to native code as necessary.
- Each call site is bound to one or more method handles, which point back to bytecoded methods.

- A dynamic call site is created for each invokedynamic bytecode.
### What’s in a method call? *(before invokedynamic)*

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## What’s in a method call? *(using invokedynamic)*

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Coding directly with method handles
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import static java.lang.invoke.MethodHandles.*;
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MethodHandles.Lookup LOOKUP = lookup();
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MethodHandles.Lookup LOOKUP = lookup();
MethodHandle HASHCODE = LOOKUP
    .findStatic(System.class,
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import static java.lang.invoke.MethodHandles.*;
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MethodHandle HASHCODE = LOOKUP
    .findStatic(System.class, "identityHashCode", methodType(int.class, Object.class));
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MethodHandle CONCAT = LOOKUP
    .findVirtual(String.class,
        "concatenate", methodType(Object[].class, Object.class));
{assertEquals(String.valueOf("abc"),
    CONCAT.invoke(new Object[] {"a", "bc"}, "d"));}
```

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MethodHandle CONCAT_FU = CONCAT.bindTo("fu");
{assertEquals("futbol", CONCAT_FU.invoke("tbol"));}
```
Pseudo-coding with invokedynamic

http://hg.openjdk.java.net/jdk7/jdk7/jdk/file/tip/test/java/lang/invoke/InvokeDynamicPrintArgs.java
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static CallSite bsm2(
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static private class INDY_baz {
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        MethodType mt = methodType(void.class,
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        CallSite cs = (CallSite) MH_bsm2().invoke(
            lookup(), "baz", mt  // standard BSM arguments
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            , 1234.5); // optional static argument
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    CallSite cs = (CallSite) MH_bsm2().invoke(
      lookup(), "baz", mt // standard BSM arguments
      , 1234.5);          // optional static argument
    CALL_SITE = cs.dynamicInvoker();
  }
}
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John McWhorter
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Interesting account of *human* language change.
Bonus book plug!

Interesting account of human language change.

The POWER of BABEL
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Bonus book plug!

Interesting account of *human* language change.

Makes computer language change look easy.
Overview...

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- Next steps in JSR 292
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Invokedynamic “plumbing”, take 1

```java
aload_1; aload_2
invdyn lessThan:Z
if_icmpeq
...
```

direct MH

class Runtime

lessThan(,)Z:
...

this pointer links to the target method, a "Method Handle"
Invokedynamic pseudo-code
Invokedynamic pseudo-code

Object a1 = ..., a2 = ...;
Invokedynamic pseudo-code

Object a1 = ..., a2 = ...

CallSite cs = INDY_lessThan.CALL_SITE;  // linked as a constant
Invokedynamic pseudo-code

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MethodHandle mh = cs.getTarget();       // can be variable
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boolean z = (boolean) mh.invokeExact(a1, a2);
Invokedynamic pseudo-code

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CallSite cs = INDY_lessThan.CALL_SITE;  // linked as a constant
MethodHandle mh = cs.getTarget();       // can be variable

boolean z = (boolean) mh.invokeExact(a1, a2);

if (z) { ... }
Method handle invocation pseudo-code
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MethodHandle mh = ...;
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Method handle invocation pseudo-code

MethodHandle mh = ...;
// (boolean) mh.invokeExact(a1, a2);

MethodType mt = methodType(boolean.class,
  Object.class, Object.class);   // internal constant
if (mh.type() != mt) throw new WrongMethodTypeException();
Method handle invocation pseudo-code

MethodHandle mh = ...;
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MethodType mt = methodType(boolean.class,
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goto (*mh.vmentry)   // jump indirect to invokestatic_mh
Method handle invocation pseudo-code

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invokestatic_mh:  // vmentry for direct MH to a static method
Method handle invocation pseudo-code

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if (mh.type() != mt) throw new WrongMethodTypeException();

goto (*mh.vmentry)  // jump indirect to invokestatic_mh

invokestatic_mh:  // vmentry for direct MH to a static method
addr = mh.vmtarget  // Runtime#lessThan
Method handle invocation pseudo-code

MethodHandle mh = ...;
// (boolean) mh.invokeExact(a1, a2);

MethodType mt = methodType(boolean.class,
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invokestatic_mh:   // vmentry for direct MH to a static method
addr = mh.vmtarget // Runtime#lessThan

goto (*addr.from_interpreted_entry)  // entry point of #lessThan
Method handle invocation pseudo-code

MethodHandle mh = ...;
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addr = mh.vmtarget // Runtime#lessThan

goto (*addr.from_interpreted_entry) // entry point of #lessThan

static boolean lessThan(Object x, Object y) { ... }
More details about method handles
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- A *direct method handle* points to a Java method.
  - A DMH can emulate any of the pre-existing invoke instructions.
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• A *direct method handle* points to a Java method.
  – A DMH can emulate any of the pre-existing invoke instructions.

• A *bound method handle* includes an saved argument.
  – The bound argument is specified on creation, and is used on call.
  – The bound argument is inserted into the argument list.
  – Any MH can be be bound, and the binding is invisible to callers.
More details about method handles

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  – The bound argument is specified on creation, and is used on call.
  – The bound argument is inserted into the argument list.
  – Any MH can be be bound, and the binding is invisible to callers.

• An adapter method handle adjusts values on the fly.
  – Both argument and return values can be adjusted.
  – Adaptations include cast, box/unbox, collect/spread, filter, etc.
  – Any MH can be adapted. Adaptation is invisible to callers.
Invokedynamic “plumbing”, take 2

```java
class Runtime {
    invoke_2(String message, Object, Object):
    ...
}
```

**Diagram Notes:**
- `aload_1; aload_2
  invdyn lessThan:Z
  if_icmpeq
  ...`
- `toBoolean Adapter`
- `Bound MH`
- `String "lessThan"`

**Textual Note:**
- This chain of targets converts a return value to boolean, and inserts an extra message argument.
Method handle invocation pseudo-code (take 2)
Method handle invocation pseudo-code (take 2)

MethodHandle mh1 = cs.getTarget(); // an adapter method handle
Method handle invocation pseudo-code (take 2)

MethodHandle mh1 = cs.getTarget(); // an adapter method handle
goto (*mh1.vmentry) // jump indirect to adapter_collect_args
adapter_collect_args:
Method handle invocation pseudo-code (take 2)

MethodHandle mh1 = cs.getTarget(); // an adapter method handle
goto (*mh1.vmentry)    // jump indirect to adapter_collect_args
adapter_collect_args:
push_frame             // for eventual call to #booleanValue
Method handle invocation pseudo-code (take 2)

MethodHandle mh1 = cs.getTarget(); // an adapter method handle
goto (*mh1.vmentry)    // jump indirect to adapter_collect_args
adapter_collect_args:
push_frame            // for eventual call to booleanValue
mh2 = mh1.vmtarget    // a bound method handle
Method handle invocation pseudo-code (take 2)

MethodHandle mh1 = cs.getTarget(); // an adapter method handle
goto (*mh1.vmentry) // jump indirect to adapter_collect_args
adapter_collect_args:
push_frame // for eventual call to #booleanValue
mh2 = mh1.vmtarget // a bound method handle
goto (*mh2.vmentry) // jump indirect to bound_ref_mh
bound_ref_mh:
MethodHandle mh1 = cs.getTarget(); // an adapter method handle
goto (*mh1.vmentry) // jump indirect to adapter_collect_args
adapter_collection_args:
push_frame // for eventual call to #booleanValue
mh2 = mh1.vmtarget // a bound method handle
goto (*mh2.vmentry) // jump indirect to bound_ref_mh
bound_ref_mh:
push mh2.vmargument // insert extra argument &"lessThan"
Method handle invocation pseudo-code (take 2)

MethodHandle mh1 = cs.getTarget(); // an adapter method handle
goto (*mh1.vmentry) // jump indirect to adapter_collect_args
adapter_collect_args:
push_frame // for eventual call to #booleanValue
mh2 = mh1.vmtarget // a bound method handle
goto (*mh2.vmentry) // jump indirect to bound_ref_mh
bound_ref_mh:
push mh2.vmargument // insert extra argument &"lessThan"
mh3 = mh2.vmtarget // a direct method handle
Method handle invocation pseudo-code (take 2)

MethodHandle mh1 = cs.getTarget(); // an adapter method handle
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  goto (*mh3.vmentry) // jump indirect to invokestatic_mh
invokestatic_mh: // vmentry for direct MH to static method
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push rax // push object return value as argument
goto (*mh4.vmentry) // jump indirect to conversion method
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...

static boolean convL2Z(Object x) { return (boolean)x; }
Overview...

• What we did in JDK 7
• How it works in Hotspot
• Advice to users
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• Building the future
Method handle life cycle
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• Creation (*direct MHs*)
  – reflective factory API: MethodHandles.Lookup
  – ldc of CONSTANT_MethodHandle
  – special factories: identity, invoker
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  – asType, filterArguments, etc.
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- **Creation** (*direct MHs*)
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  - ldc of CONSTANT_MethodHandle
  - special factories: identity, invoker

- **Transformation** (*bound or adapter MHs*)
  - bindTo, insertArguments, guardWithTest, etc.
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Method handle life cycle: Creation
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- Can be slow; do it just once if possible
Method handle life cycle: Creation

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• Can be slow; do it just once if possible
• If generating bytecode, use CONSTANT_MethodHandle
Method handle life cycle: Transformation
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  – This adds internal pointers seen by GC and MH.invoke
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• In OpenJDK7, creation requires a JNI call
  – This means even a simple transform can be surprisingly slow.
• We hope to fix this soon.
Method handle life cycle: Invocation
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  - Only slightly more expensive than a regular method call.
- Inexact invocation (MH.invoke) can be complex.
  - If the types match exactly, same as MH.invokeExact.
  - If the types do not match, can perform asType transform.
- Invocation via an invokedynamic instruction is fast
  - Always exact (since call sites are strongly typed)
  - No runtime check of the type (VM enforces the invariant)
  - The MH code is typically inlined.
Method handle life cycle: Linking
Method handle life cycle: Linking

- An invokedynamic instruction is a constant CallSite...
Method handle life cycle: Linking

• An invokedynamic instruction is a constant CallSite...
• ...with an optimistically predicted target method handle.
  – Predicted handle is treated as a constant.
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• An invokedynamic instruction is a constant CallSite...
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• “static final” MH variables are also constant.
• Constant method handles (of any source) can be inlined
  – Inlining can boil away adapters and bound arguments.
  – Inlining can continue all the way through a direct method handle.
Bottom lines *(specific to OpenJDK7!)*
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- Don’t make new method handles in inner loops (yet).
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Bottom lines *(specific to OpenJDK7!)*

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- Prefer invokeExact.
- Work with us to prioritize benchmark/optimization work.
Overview...

- What we did in JDK 7
- How it works in Hotspot
- Advice to users
- Next steps in JSR 292
- Building the future
The following is intended to outline our general product direction. It is intended for information purposes only, and may not be incorporated into any contract. It is not a commitment to deliver any material, code, or functionality, and should not be relied upon in making purchasing decisions. The development, release, and timing of any features or functionality described for Oracle’s products remains at the sole discretion of Oracle.
Loose ends in the Java 7 API
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• Method handle introspection (reflection)
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Support for Lambda in OpenJDK8
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Issue tracking
Issue tracking

• http://java.net/jira/browse/MLVM
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• (Is there a JIRA expert in the house?)
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Let’s nurture Project Lambda
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• More than aid to Lisp refugees...
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Let’s continue building our “future VM”

http://hg.openjdk.java.net/mlvm/mlvm/hotspot/
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- mlvm-dev@openjdk.java.net
## Current Da Vinci Machine patches

<table>
<thead>
<tr>
<th>MLVM patches</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>meth</td>
<td>method handles implementation</td>
</tr>
<tr>
<td>indy</td>
<td>invokedynamic</td>
</tr>
<tr>
<td>coro</td>
<td>lightweight coroutines</td>
</tr>
<tr>
<td>inti</td>
<td>interface injection (Tobias Ivarsson)</td>
</tr>
<tr>
<td>tailc</td>
<td>hard tail call optimization (Arnold Schwaighofer)</td>
</tr>
<tr>
<td>tuple</td>
<td>integrating tuple types (new from Michael Barker!)</td>
</tr>
<tr>
<td>hotswap</td>
<td>online general class schema updates (Thomas Wuerthinger)</td>
</tr>
<tr>
<td>anonk</td>
<td>anonymous classes; light weight bytecode loading</td>
</tr>
</tbody>
</table>
Caveat: Change is hard and slow

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- **Specifying** is hard (the last 20%...).
- Running process is time-consuming.
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• No code; for all JVMs (not just OpenJDK).
## JVM design issue tracking by category

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>bytecode loading</td>
<td>Mechanisms for bytecode loading, such as anonymous classes, single-method loads, and whole-module loads.</td>
</tr>
<tr>
<td>coroutines</td>
<td>Coroutines, fibers, continuations, and other extensions to threading.</td>
</tr>
<tr>
<td>immutability</td>
<td>Immutable variables and objects. (I.e., beyond blank finals initialized in constructors.)</td>
</tr>
<tr>
<td>interface injection</td>
<td>JVM features related to online updates to interface APIs.</td>
</tr>
<tr>
<td>invokedynamic</td>
<td>The invokedynamic instruction, with related APIs such as java.lang.invoke.CallSite.</td>
</tr>
<tr>
<td>memory locality</td>
<td>Mechanisms for giving applications control (at the bytecode level) over memory locality, such as native layout, heterogeneous arrays, object fusing, object federation, and object replication.</td>
</tr>
<tr>
<td>method handles</td>
<td>java.lang.invoke.MethodHandle and related APIs. For bootstrap methods and CallSite, use the &quot;invokedynamic&quot; component.</td>
</tr>
<tr>
<td>reification</td>
<td>Mechanisms for reifying erased information, such as generic type instance parameters.</td>
</tr>
<tr>
<td>tailcalls</td>
<td>Bytecode support for hard (user-specified) tail call elimination.</td>
</tr>
<tr>
<td>tuples</td>
<td>Signature-polymorphic structural record types. Proposals may affect arguments, return values, fields, or array elements, and interoperability (via box/unbox) with reference types.</td>
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<tr>
<td>typestate</td>
<td>Mechanisms for updating the runtime type description of an object.</td>
</tr>
</tbody>
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Discussions at previous Summits

http://cr.openjdk.java.net/~jrose/pres/201007-JVMFutureTalk.pdf
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• E.g., see my talk from last year
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• Tail calls

• Better data structures

• Object species (typestate)
  http://blogs.oracle.com/jrose/entry/larval_objects_in_the_vm

Tuesday, July 19, 2011
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• Thread/task/loop decomposition.
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- More fluid code.
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- Immutability & replication.
- Transactional APIs.
- Memory locality.
- More fluid code.
- More fluid data (traits, species).
Q&A
(continuing in today’s workshop)