JVM INTERNALS

Mastering the mechanics of Java method invocation

Special bytecodes make calling methods particularly efficient. Knowing how they operate reveals how the JVM executes your code.

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[*Java Magazine* is pleased to republish this article from Ben Evans, published in 2017, about Java Virtual Machine internals. —*Ed*.]

This article explains how the JVM executes methods in Java 8 and Java 9. [And later. —*Ed*.] This is a fundamental topic about the internals of the JVM that is essential background for anyone who wants to understand the JVM's just-in-time (JIT) compiler or tune the execution of applications.

To get started, look at the following simple bit of Java code:

```
long time = System.currentTimeMillis();
HashMap<String, String> hm = new HashMap<>();
hm.put("now", "bar");
Map<String, String> m = hm;
m.put("foo", "baz");
```

To see the bytecode that the Java compiler produces for this code, use the `javap` tool with the `-c` switch to display the decompiled code, as follows (indented lines are merely continued from the previous line):

```
0: invokestatic #2 // Method
                                java/lang/Sys
3: lstore_1
4: new #3 // class java/util/HashMap
7: dup
8: invokespecial #4 // Method java/util/HashM
```

```
11: astore_3
12: aload_3
13: ldc #5 // String now
15: ldc #6 // String bar
17: invokevirtual #7 // Method java/util/Hash
                        (Ljava/lang/Object
                        Ljava/lang/Object;
20: pop
21: aload_3
22: astore 4
24: aload 4
26: ldc #8 // String foo
28: ldc #9 // String baz
30: invokeinterface #10, 3 // InterfaceMethod
                           (Ljava/lang/Objec
                           Ljava/lang/Object
35: pop
```

Java programmers who are new to looking at code at the JVM level might be surprised to learn that Java method calls are actually turned into one of several possible bytecodes of the form `invoke*`: `invokestatic`, `invokevirtual`, or `invokeinterface`.

Let's take a closer look at the first part of the decompiled code.

```
0: invokestatic #2 // Method java/lang/System
3: lstore_1
```

The static call to `System.currentTimeMillis()` is turned into an `invokestatic` opcode that appears at position 0 in the bytecode. This method takes no parameters, so nothing needs to be loaded onto the evaluation stack before the call is dispatched.

Next, the two bytes 00 02 appear in the byte stream. These are combined into a 16-bit number (`#2`, in this case) that is used as an offset into a table—called the *constant pool*—within the class file. All constant pool indices are 16 bits, so whenever an opcode needs to refer to an entry in the pool, there will always be two subsequent bytes that encode the offset of the entry.

The decompiler helpfully includes a comment that lets you know which method offset #2 corresponds to. In this case, as expected, it's the method `System.currentTimeMillis()`. In the decompiled output, `javap` shows the name of the called method, the types of parameters the method takes (in parentheses), followed by the return type of the method.

Upon return, the result of the call is placed on the stack, and at offset 3 you see the single, argument-less opcode, `lstore_1`, which saves the return value in a local variable of type `long`.

Human readers are, of course, able to see that this value is never used again. However, one of the design goals of the Java compiler is to represent the contents of the Java source code as faithfully as possible—whether it makes logical sense or not. Therefore, the return value of `System.currentTimeMillis()` is stored, even though it is not used after this point in the program.

Now look at the next chunk of the decompiled code.

```
4: new #3 // class java/util/HashMap
7: dup
8: invokespecial #4 // Method java/util/HashM
11: astore_3
12: aload_3
13: ldc #5 // String now
15: ldc #6 // String bar
17: invokevirtual #7 // Method java/util/Hash
                                        (Ljava/l
                                        Ljava/la
20: pop
```

Bytecodes 4 to 10 create a new `HashMap` instance before instruction 11 saves a copy of it in a local variable. Next, instructions 12 to 16 set up the stack with the `HashMap` object and the arguments for the call to `put()`. The actual invocation of the `put()` method is performed by instructions 17 to 19.

The invoke opcode used this time is `invokevirtual`. This differs from a static call, because a static call does not have an instance on which the method is called; such an instance is sometimes called the *receiver* object. (In bytecode, an instance call must be set up by placing the receiver and any call arguments on the evaluation stack and then issuing the invoke instruction.) In this case, the return value from `put()` is not used, so instruction 20 discards it.

The sequence of bytes from 21 to 25 seems rather odd at first glance.

```
21: aload_3
22: astore 4
24: aload 4
26: ldc #8 // String foo
28: ldc #9 // String baz
30: invokeinterface #10, 3 // InterfaceMethod
                                          (Ljava
                                          Ljava/
35: pop
```

The `HashMap` instance that was created at bytecode 4 and saved to a local variable `3` at instruction 11 is now loaded back onto the stack, and then a copy of the reference is saved to local variable `4`. This process removes it from the stack, so it must be reloaded (from variable `4`) before use.

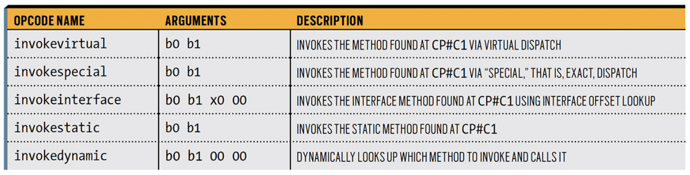
This shuffling occurs because in the original Java code, an additional local variable (of type `Map` rather than `HashMap`) is created, even though it always refers to the same object as the original variable. This is another example of the bytecode staying as close as possible to the original source code. One of the main reasons for this so-called “dumb bytecode” approach that Java takes is to provide a simple input format for the JVM’s JIT compiler.

After the stack and variable shuffling, the values to be placed in the `Map` are loaded at instructions 26 to 29. Now that the stack has been prepared with the receiver and the arguments, the call to `put()` is dispatched at instruction 30. This time, the opcode is `invokeinterface`—even though the same method is being called. Once again, the return value from `put()` is discarded, via the `pop` at instruction 35.

So far, you’ve seen that `invokestatic`, `invokevirtual`, or `invokeinterface` can be produced by the Java compiler, depending on the context of the call.

JVM bytecodes for invoking methods

Look at all the five JVM bytecodes that can be used to invoke methods (see **Table 1**). In each case, the bytes `b0` and `b1` are combined into the constant pool offset represented by `c1`.



OPCODE NAME	ARGUMENTS	DESCRIPTION
invokevirtual	b0 b1	INVOKES THE METHOD FOUND AT CP#C1 VIA VIRTUAL DISPATCH
invokespecial	b0 b1	INVOKES THE METHOD FOUND AT CP#C1 VIA “SPECIAL,” THAT IS, EXACT, DISPATCH
invokeinterface	b0 b1 x0 00	INVOKES THE INTERFACE METHOD FOUND AT CP#C1 USING INTERFACE OFFSET LOOKUP
invokestatic	b0 b1	INVOKES THE STATIC METHOD FOUND AT CP#C1
invokedynamic	b0 b1 00 00	DYNAMICALLY LOOKS UP WHICH METHOD TO INVOKE AND CALLS IT

Table 1. JVM bytecodes for invoke methods

It can be a useful exercise to write some Java code, and then disassemble it with `javap`, to see what circumstances produce each form of the bytecodes.

The most common type of method invocation is `invokevirtual`, which refers to virtual dispatch. The term *virtual dispatch* means that the exact method to be invoked is determined at runtime. To understand this, you need to know that each class present in a running application has an area of memory inside the JVM that holds metadata corresponding to that type. This area is called a *klass* (in Java HotSpot VM, at least) and can be thought of as the JVM’s representation of information about the type.

In Java 7 and earlier, the klass metadata lived in an area of the Java heap called *permgen*. Because objects within the Java heap must have an object header (called an *oop*), the klasses were known as *klassOops*. In Java 8 and Java 9, the klass metadata was moved out of the Java heap into the native heap, so the object headers are no longer required. Some of the information from the klass is available to Java programmers via the `Class<?>` object corresponding to the type—but they are separate concepts.

One of the most important areas of the klass is the *vtable*. This area is essentially a table of function pointers that point to the implementations of methods defined by the type. When an instance method is called via `invokevirtual`, the JVM consults the vtable to see exactly which code needs to be executed. If a klass does not have a definition for the method, the JVM follows a pointer to the klass corresponding to the superclass and tries again.

This process is the basis of method overriding in the JVM. To make the process efficient, the vtables are laid out in a specific way. Each klass lays out its vtable so that the first methods to appear are the methods that the parent type defines. These methods are laid out in the exact order that the parent type used. The methods that are new to this type and are not declared by the parent class come at the end of the vtable.

The result? When a subclass overrides a method, it will be at the same offset in the vtable as the implementation being overridden. This makes the lookup of overridden methods completely trivial because their offset in the vtable will be the same as the offset of their parent.

Figure 1 shows an example defined by the classes `Pet`, `Cat`, and `Bear` and the interface `Furry`.

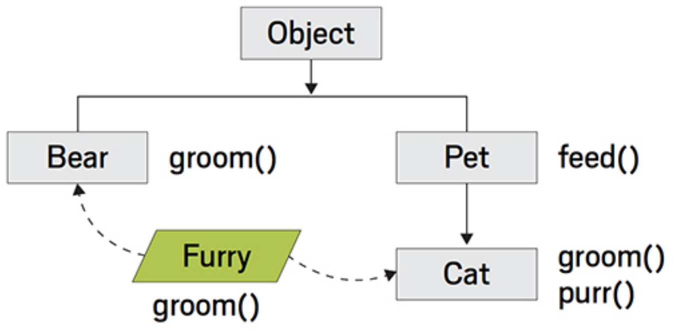


Figure 1. Simple inheritance hierarchy

The vtables for these classes are laid out in Java 7, as shown in **Figure 2**. As you can see, this figure shows the Java 7 layout within permgen, so it refers to klassOops and has the two words of the object header (shown as `m` and `kk` in the figure). As discussed previously, these entries would not be present in Java 8 and Java 9, but all else in the diagram remains the same.

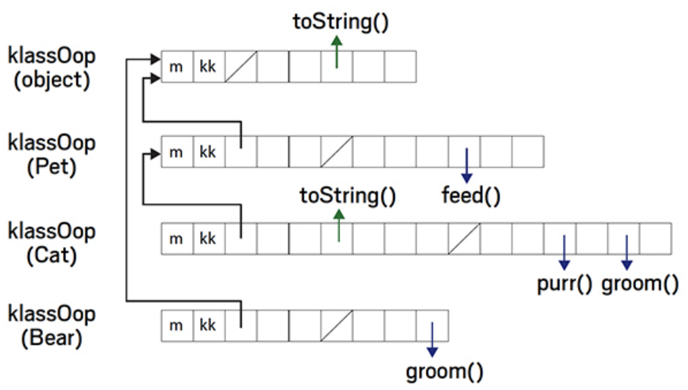


Figure 2. Structure of the vtables for the classes shown in **Figure 1**

If you call `Cat::feed`, the JVM will not find an override in the `Cat` class and instead will follow the pointer to the klass of `Pet`. This klass does have an implementation for `feed()`, so this is the code that will be called. This vtable structure works well because Java implements only single inheritance of classes. This means there is only one direct superclass of any type (except for `Object`, which has no superclass).

In the case of `invokeinterface`, the situation is a little more complicated. For example, the `groom()` method will not necessarily appear in the same place in the vtable for every implementation of `Furry`. The different offsets for `Cat::groom` and `Bear::groom` are caused by the fact that their class inheritance hierarchies differ. The result is that some additional lookup is needed when a method is invoked on an object for which only the interface type is known at compile time.

Note that even though slightly more work is done for the lookup of an interface call, you should *not* try to micro-optimize by avoiding interfaces. Remember that the JVM has a JIT compiler, and it will essentially eliminate any performance difference between the two cases.

Example of invoking methods

Here's another example. Consider this bit of code.

```
Cat tom = new Cat();
Bear pooh = new Bear();
Furry f;
tom.groom();
pooh.groom();
f = tom;
f.groom();
f = pooh;
f.groom();
```

This code produces the following bytecodes:

```
0: new #2 // class scratch/Cat
3: dup
4: invokespecial #3 // Method scratch/Cat."<i
7: astore_1
8: new #4 // class scratch/Bear
11: dup
12: invokespecial #5 // Method scratch/Bear."
15: astore_2
16: aload_1
17: invokevirtual #6 // Method scratch/Cat.gr
20: aload_2
21: invokevirtual #7 // Method scratch/Bear.g
24: aload_1
25: astore_3
26: aload_3
27: invokeinterface #8, 1 // InterfaceMethod
32: aload_2
33: astore_3
34: aload_3
35: invokeinterface #8, 1 // InterfaceMethod
```

The two calls at 27 and 35 look like they are the same, but they actually invoke different methods. The call at 27 will invoke `Cat::groom`, whereas the call at 35 will invoke `Bear::groom`.

With this background on `invokevirtual` and `invokeinterface`, the behavior of `invokespecial` is now easier to understand. If a method is invoked by `invokespecial`, it does not undergo virtual lookup. Instead, the JVM will look only in the exact place in the vtable for the requested method. This means that an `invokespecial` is used for three cases: private methods, calls to a superclass method, and calls to the constructor body (which is turned into a method called `<init>` in bytecode). In all three cases, virtual lookup and the possibility of overriding must be explicitly excluded.

Final methods

There remains one corner case that should be mentioned: the case of final methods. At first glance, it might appear that calls to final methods would also be turned into `invokespecial` instructions. However, *Java Language Specification* section 13.4.17 has something to say about this case: "Changing a method that is declared `final` to no longer be declared `final` does not break compatibility with pre-existing binaries."

Suppose a compiler had compiled a call to a final method into an `invokespecial`. If the method then changed to no longer be final, it could be overridden in a subclass. Now, suppose that an instance of the subclass was passed into the compiled code. The `invokespecial` would be executed, and then the wrong implementation of the method would be called. This would be a violation of the rules of Java's object orientation (strictly speaking, it would violate the Liskov Substitution Principle).

For this reason, calls to final methods must be compiled into `invokevirtual` instructions. In practice, the Java HotSpot VM contains optimizations that allow final methods to be detected and executed extremely efficiently.

Conclusion

I have now examined four of the five invocation instructions that the JVM supports. The remaining case is `invokedynamic`, and it is such a rich and interesting subject that it requires an article all to itself.

Dig deeper

- The javap command
- The Java Virtual Machine instruction set
- Real-world bytecode handling with ASM

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