Bytecode Manipulation in the Real World

Geert Bevin
Terracotta Inc. - http://terracotta.org

JavaZone exploring the frontiers 08

09/15/2008

Who am I?

- developer at Terracotta - http://terracotta.org
- founder of Uwyn - http://uwyn.com
- founder of RIFE - http://rifers.org
- contributor to many open-source projects: Terracotta, RIFE, OpenLaszlo, Gentoo, ...
- Sun Java Champion
- creator of native Java language continuations
- biker and gamer

Agenda

- What is bytecode manipulation?
- Some popular projects using it
- Don't be afraid
- Plug in the manipulation
- Best practices
- Q & A

Agenda

- **What is bytecode manipulation?**
- Some popular projects using it
- Don't be afraid
- Plug in the manipulation
- Best practices
- Q & A

What is bytecode manipulation?

- Tools can read bytecode without loading classes (FindBugs)
  - Bytecode inspection
- Languages compile to class files with bytecode (Java, Groovy, Scala, ...)
  - Bytecode generation
- You can modify bytecode just as you can edit other files (AspectJ)
  - Bytecode modification

- All this is bytecode manipulation

Bytecode is not assembler

- I used to think that
  bytecode == assembler
- JVM makes working with bytecode easy
- JDK ships with tools to look at bytecode
- Bytecode is a lot like Java

Let's take a quick look

Hello World

Quick Look

source code HelloWorld.java

```java
public class HelloWorld {
  public HelloWorld() {
  }

  public static void main(String[] args) {
    System.out.println("Hello World!");
  }
}
```

javac -g:none HelloWorld.java

Quick Look

javap -p -v HelloWorld

```
public class HelloWorld extends java.lang.Object
{
public HelloWorld();
  Code:
   Stack=1, Locals=1, Args_size=1
   0: aload_0: this
   1: invokespecial Object.<init>() : void
   4: return
public static void main(java.lang.String[]);
  Code:
   Stack=2, Locals=1, Args_size=1
   0: getstatic System.out : PrintStream
   3: ldc "Hello World!"
   5: invokevirtual PrintStream.println(String) : void
   8: return
}
```

Agenda

- **What is bytecode manipulation?**
- Some popular projects using it
- Don't be afraid
- Plug in the manipulation
- Best practices
- Q & A

Agenda

- What is bytecode manipulation?
- **Some popular projects using it**
- Don't be afraid
- Plug in the manipulation
- Best practices
- Q & A

Persistence

- Hibernate
  - track field changes
  - lazily load many-to-many and many-to-one associations
  - optimize reflection performance
  - ...

Inversion of Control (IoC)

- Spring
  - read class meta data without loading it
  - read annotations without loading classes
  - scan the classpath with inclusion filters
  - discover parameter names for auto wiring
  - ...

Aspect Oriented Programming

- AspectJ / Spring
  - generate proxies if no interfaces are present for dynamic proxies
  - look for pointcuts where AOP advices need to be applied
  - weave advices into the target classes
  - ...

Static code analysis

- FindBugs
  - check for misunderstood API methods
  - check for common typos
  - check for bad practices
  - check for multi-threaded correctness
  - check for performance problems
  - ...

Clustering

- Terracotta
  - cluster several JVMs to create one super JVM out of multiple nodes
  - opcodes like GETFIELD, PUTFIELD, MONITORENTER and MONITOREXIT become coordinated over the cluster
  - inspect and instrument code that works with cluster-wide data structures
  - replace and enhance library classes to be better citizens in a clustered application
  - ...

Conclusion

You're probably already using bytecode manipulation all over the place

Agenda

- What is bytecode manipulation?
- **Some popular projects using it**
- Don't be afraid
- Plug in the manipulation
- Best practices
- Q & A

Agenda

- What is bytecode manipulation?
- Some popular projects using it
- **Don't be afraid**
- Plug in the manipulation
- Best practices
- Q & A

The JVM has a verifier

Why is there a verifier?

- Java compiler produces valid bytecode
- JVM can't assume that the bytecode is valid because it could have been modified
  - it could perform dangerous operations
  - crash your applications
  - even crash the JVM
- As a protection the JVM verifies the bytecode when a class is loaded
- Verification also improves performance since less runtime checks are needed

What is verified?

- The verification process is very extensive
  http://java.sun.com/docs/books/jvms/second_edition/html/ClassFile.doc.html
- Notable steps:
  - Check format of the class file to ensure that the bytes are valid and well structured
  - Check coherence of the class structure
    - presence of superclass
    - ensure 'final' is honored
    - valid constant pool
    - valid field and method references

What is verified?

– Code inspection with data-flow analysis ensures the following:
  - operand stack is always the same size and contains the same types of values
  - local variables only accessed while containing a value of an appropriate type
  - methods invocations have appropriate arguments
  - fields assignment have appropriate types
  - opcodes have appropriate type arguments on the operand stack and in the local variable array
  - much more ...

Libraries hide the hard stuff

Libraries hide the hard stuff

- Libraries are there to make your life easy
  - ASM : http://asm.objectweb.org/
  - BCEL : http://jakarta.apache.org/bcel/
  - CGlib : http://cglib.sourceforge.net/
  - Javassist : http://www.csg.is.titech.ac.jp/~chiba/javassist/

Libraries hide the hard stuff

- My preference goes to ASM
  - Very lightweight
  - Low memory usage : visitor pattern
  - Abstracts enough to make your life easy
  - Close enough to the basics to educate you
  - High-level utilities for common operations
  - Tree-based API for non-linear manipulations
  - Increasingly popular
  - Great documentation
  - Helpful and passionate community

Example of using ASM

Generating Hello World

HelloWorld in Java with ASM

```
ClassWriter cw = new ClassWriter(0); MethodVisitor mv;

cw.visit(V1_5, ACC_PUBLIC + ACC_SUPER, "HelloWorld", null,
    "java/lang/Object", null);

mv = cw.visitMethod(ACC_PUBLIC, "<init>", "()V", null, null);
mv.visitCode();
mv.visitVarInsn(ALOAD, 0);
mv.visitMethodInsn(INVOKESPECIAL, "java/lang/Object", "<init>", "()V");
mv.visitInsn(RETURN);
mv.visitMaxs(1, 1);
mv.visitEnd();

mv = cw.visitMethod(ACC_PUBLIC + ACC_STATIC, "main",
    "([Ljava/lang/String;)V", null, null);
mv.visitCode();
mv.visitFieldInsn(GETSTATIC, "java/lang/System", "out",
    "Ljava/io/PrintStream;");
mv.visitLdcInsn("Hello World!");
mv.visitMethodInsn(INVOKEVIRTUAL, "java/io/PrintStream", "println",
    "(Ljava/lang/String;)V");
mv.visitInsn(RETURN);
mv.visitMaxs(2, 1);
mv.visitEnd();

cw.visitEnd();
```

Modifying a class with ASM

Logging method invocations

Method invocation logging with ASM

- Detect the beginning of each method
- Modify any existing class file
- Insert print statement before any of the method's code

```
System.out.println(class + "." + method + desc)
```

- This statically changes the class so that this functionality is permanently added

Method invocation logging with ASM

```
public class MethodLoggerAdapter extends ClassAdapter implements Opcodes {
  private String classname;

  public MethodLoggerAdapter(ClassVisitor cv) { super(cv); }

  public void visit(int ver, int access, String name, String sig,
      String superName, String[] interfaces) {
    this.classname = name;
    super.visit(ver, access, name, sig, superName, interfaces);
  }

  public MethodVisitor visitMethod(int acc, final String name,
      final String desc, String sig, String[] ex) {
    return new MethodAdapter(super.visitMethod(acc, name, desc, sig, ex)) {
      public void visitCode() {
        mv.visitFieldInsn(GETSTATIC, "java/lang/System", "out",
                          "Ljava/io/PrintStream;");
        mv.visitLdcInsn(classname + "." + name + desc);
        mv.visitMethodInsn(INVOKEVIRTUAL, "java/io/PrintStream", "println",
                           "(Ljava/lang/String;)V");
        super.visitCode();
      }
    };
  }
}
```

Tools make your life easy

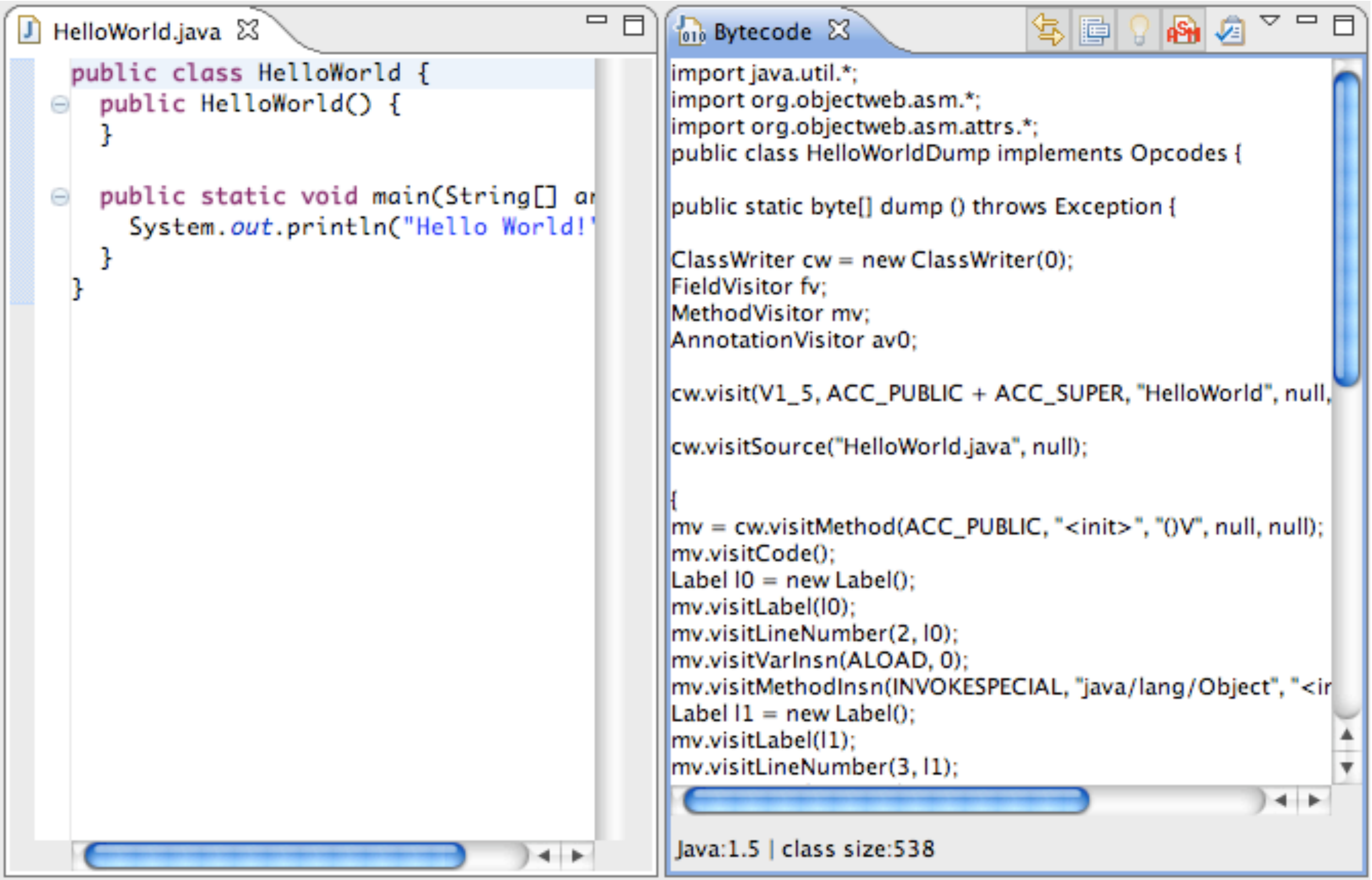
JDK's javap command

- Class file disassembler
- By default print out the structure of a class based on accessibility modifiers (`package`, `protected`, `public`, `private`)
- Using the `verbose` option, the bytecode of methods is displayed

ASM tools

- `TraceClassVisitor`
  – Prints out a readable trace of the bytecode that is actually generated
  – Hooked up in your code's visitor chain
- `CheckClassAdapter`
  – Detect errors that wouldn't pass the verifier
  – Hooked up in your code's visitor chain
- `ASMifierClassVisitor`
  – Prints the Java source code to generate a particular class with ASM
  – Used from the command line

Eclipse Bytecode Outline Plug-in



Eclipse Bytecode Outline Plug-in

- Automatically convert Java source code to readable bytecode
- Alternatively convert to ASM API instructions that generate the bytecode
- Bytecode analysis pane that shows local variable array and operand stack
- Contains a bytecode reference for each instruction

Jad - fast Java decompiler

- Generates Java source from bytecode
- Handy when looking at classes whose bytecode has already been manipulated
- Used on the command line, for example: `jad HelloWorld.class`
- Generates HelloWorld.jad

Jad - HelloWorld.jad

```
// Decompiled by Jad v1.5.8g.
// Copyright 2001 Pavel Kouznetsov.
// Jad home page: http://www.kpdus.com/jad.html
// Decompiler options: packimports(3)

import java.io.PrintStream;

public class HelloWorld
{
    public HelloWorld()
    {
    }

    public static void main(String args[])
    {
        System.out.println("Hello World!");
    }
}
```

Agenda

- What is bytecode manipulation?
- Some popular projects using it
- **Don't be afraid**
- Plug in the manipulation
- Best practices
- Q & A

Agenda

- What is bytecode manipulation?
- Some popular projects using it
- Don't be afraid
- **Plug in the manipulation**
- Best practices
- Q & A

Different options

- Compiler
- Static transformer
- JDK instrumentation agent
- Classloader

Compiler

- Generate class files by parsing source
- Used by Java, Groovy, Scala, ...
- Unless you're writing your own language you'll probably never use this option
- Don't de facto dismiss it though
- For example, RIFE's template engine uses a simple parser and writing a compiler for it was trivial

Static transformer (pre-processor)

- Class files can be read as byte arrays
- This can be provided as an argument to ASM's visitors
- Resulting in another byte array
- Can be written to another file

- This can be easily integrated with an existing build process

JDK instrumentation agent

- Available since JDK 1.5
- Can register transformers that are called when classes are defined or re-defined
- Class' byte array is provided by JDK
- Cleanly separates the class definition phase from the class loading phase
- Activated through JVM command-line option `-javaagent`
- JDK 1.6 adds support for self-activating agents through jar manifest option

Classloader

- Last resort when:
  - JDK 1.4 support is needed
  - JDK 1.5 support is needed and JVM command-line can't be modified
  - manipulation requires state of running system
- Writing your own classloader is difficult
- Have to respect the classloader hierarchy
- Classpath has to be correctly setup
- Difficult to debug class compatibility issues
- Not trivial to obtain byte arrays quickly

Agenda

- What is bytecode manipulation?
- Some popular projects using it
- Don't be afraid
- **Plug in the manipulation**
- Best practices
- Q & A

Agenda

- What is bytecode manipulation?
- Some popular projects using it
- Don't be afraid
- Plug in the manipulation
- **Best practices**
- Q & A

The trivial ones

Trivial best practices

- Use the available tools and libraries
- Prefer agents over classloaders
- Start from Java to know which opcodes you need, don't write them from scratch

Document the purpose of your opcodes

Document the purpose of your opcodes

- Even more important than Java source code comments since there's a lot of noise
- Structure blocks in logical sections
- Generating opcodes is easy, understanding what really goes on after the fact is much harder
- Non trivial instrumentations require a lot of effort to comprehend without context

Document the purpose of your opcodes

- For example, look at the following trivial snippet and imagine something difficult:

```
int hashEntryLocal = newLocal(Type.getObjectType(
  "java/util/concurrent/ConcurrentHashMap$HashEntry"));
mv.visitVarInsn(ASTORE, hashEntryLocal);
Label labelStart = new Label();
Label labelEnd = new Label();
Label labelFinally = new Label();
mv.visitTryCatchBlock(labelStart, labelEnd, labelFinally, null);
mv.visitVarInsn(ALOAD, hashEntryLocal);
mv.visitInsn(MONITORENTER);
mv.visitLabel(labelStart);
mv.visitVarInsn(ALOAD, hashEntryLocal);
super.visitFieldInsn(opcode, owner, name, desc);
int valueLocal = newLocal(Type.getObjectType("java/lang/
Object"));
mv.visitVarInsn(ASTORE, valueLocal);
```

```java
// store the hash entry in a local variable
int hashEntryLocal = newLocal(Type.getObjectType(
  "java/util/concurrent/ConcurrentHashMap$HashEntry"));
mv.visitVarInsn(ASTORE, hashEntryLocal);

// setup try catch with finally to release the monitor
// on the hash entry that will be entered below
Label labelStart = new Label();
Label labelEnd = new Label();
Label labelFinally = new Label();
mv.visitTryCatchBlock(labelStart, labelEnd, labelFinally, null);

// enter a monitor on the hash entry
mv.visitVarInsn(ALOAD, hashEntryLocal);
mv.visitInsn(MONITORENTER);

// start try catch block
mv.visitLabel(labelStart);

// obtain the value of the entry
mv.visitVarInsn(ALOAD, hashEntryLocal);
super.visitFieldInsn(opcode, owner, name, desc);
int valueLocal = newLocal(Type.getObjectType("java/lang/Object"));
mv.visitVarInsn(ASTORE, valueLocal);
```

Prefer visitor API over tree API

Prefer visitor API over tree API

- Compare to XML
  - visitor API == SAX
    - event driven, no in memory tree
    - fast
    - less memory
  - tree API == DOM
    - in memory tree of the entire class
    - can be easier when doing class transformations

Visitor API excerpt

```
public interface ClassVisitor {

  void visit(int version, int access, String name, String sig,
      String superName, String[] interfaces);

  void visitSource(String source, String debug);

  void visitOuterClass(String owner, String name, String desc);

  AnnotationVisitor visitAnnotation(String desc, boolean visible);

  void visitAttribute(Attribute attr);

  void visitInnerClass(String name, String outerName,
      String innerName, int access);

  FieldVisitor visitField(int access, String name, String desc,
      String sig, Object value);

  MethodVisitor visitMethod(int access, String name, String desc,
      String sig, String[] exceptions);

  void visitEnd();
}
```

Tree API excerpt

```
public class ClassNode {
  public int version;
  public int access;
  public String name;
  public String signature;
  public String superName;
  public List<String> interfaces;
  public String sourceFile;
  public String sourceDebug;
  public String outerClass;
  public String outerMethod;
  public String outerMethodDesc;
  public List<AnnotationNode> visibleAnnotations;
  public List<AnnotationNode> invisibleAnnotations;
  public List<Attribute> attrs;
  public List<InnerClassNode> innerClasses;
  public List<FieldNode> fields;
  public List<MethodNode> methods;
}
```

Use `LocalVariablesSorter` ASM method adapter

LocalVariableSorter method adapter

- In bytecode, local variables are referred to as indexes in an array
- All opcodes within the same method use those numeric indexes
- If you introduce local variables, all later ones need to be renumbered everywhere

- `LocalVariableSorter` does this for you

Prefer delegating to real Java code

Prefer delegating to real Java code

- Don't forget that you can call your own classes and methods from within bytecode
- In-lining functionality as opcodes is less readable and less maintainable
- For example, in the method logging example consider this helper method:

```
public static class ByteCodeUtil {
  public static void systemOutPrintln(MethodVisitor mv, String msg) {
    mv.visitFieldInsn(GETSTATIC, "java/lang/System", "out",
                      "Ljava/io/PrintStream;");
    mv.visitLdcInsn(msg);
    mv.visitMethodInsn(INVOKEVIRTUAL, "java/io/PrintStream",
                       "println", "(Ljava/lang/String;)V");
  }
}
```

Prefer delegating to real Java code

- Now the adapter can be simplified to:

```
public class MethodLoggerAdapter extends ClassAdapter implements Opcodes {
  private String classname;

  public MethodLoggerAdapter(ClassVisitor cv) { super(cv); }

  public void visit(int ver, int access, String name, String sig,
      String superName, String[] interfaces) {
    this.classname = name;
    super.visit(ver, access, name, sig, superName, interfaces);
  }

  public MethodVisitor visitMethod(int acc, final String name,
      final String desc, String sig, String[] ex) {
    return new MethodAdapter(super.visitMethod(acc, name, desc, sig, ex)) {
      public void visitCode() {
        ByteCodeUtil.systemOutPrintln(mv, classname + "." + name + desc);
        super.visitCode();
      }
    };
  }
}
```

Don't copy and modify, inspect and instrument

Don't copy and modify

- Let's say that you want to modify a method of an existing library class
- The wrong approach is:
  - Generate the ASM calls from existing method
  - Modify the calls
  - Replace the entire method
- Why?
  - Licensing and copyright
  - Not resilient to class changes
  - Very unmaintainable

Inspect and instrument

- The correct approach is:
  - Generate the ASM calls from existing method
  - Look for patterns that need modification
  - Write the ASM visitors to check for these
  - Insert or omit bytecode when the patterns are detected
- Advantages:
  - You copy none of the existing code
  - You instrument one particular behavior
  - The rest of the original method can change

Remove unnecessary opcodes

Remove unnecessary opcodes

- Using the Eclipse plugin or the `ASMifierClassVisitor`, it's very easy to obtain bytecode generation instructions
- Read through the results carefully
- Some opcodes might have to be removed
- For example:
  - line numbers
  - unnecessary labels
  - local variable table
  - max stack and max locals

Remove unnecessary opcodes

- Imagine the bytecode of this code has to be added to an existing method:

```
StringBuilder msg = new StringBuilder(
  new Date().toString());
msg.append(" : Hello World!");
System.out.println(msg);
```

This is the generated bytecode

```
L0
 LINENUMBER 8 L0
 NEW StringBuilder
 DUP
 NEW Date
 DUP
 INVOKESPECIAL Date.<init>() : void
 INVOKEVIRTUAL Date.toString() : String
 INVOKESPECIAL StringBuilder.<init>(String) : void
 ASTORE 1
L1
 LINENUMBER 9 L1
 ALOAD 1: msg
 LDC " : Hello World!"
 INVOKEVIRTUAL StringBuilder.append(String) : StringBuilder
 POP
L2
 LINENUMBER 10 L2
 GETSTATIC System.out : PrintStream
 ALOAD 1: msg
 INVOKEVIRTUAL PrintStream.println(Object) : void
L3
 LINENUMBER 11 L3
 RETURN
L4
 LOCALVARIABLE args String[] L0 L4 0
 LOCALVARIABLE msg StringBuilder L1 L4 1
 MAXSTACK = 4
 MAXLOCALS = 2
```

This is what you should remove

```
   L0
    LINENUMBER 8 L0
    NEW StringBuilder
    DUP
    NEW Date
    DUP
    INVOKESPECIAL Date.<init>() : void
    INVOKEVIRTUAL Date.toString() : String
    INVOKESPECIAL StringBuilder.<init>(String) : void
    ASTORE 1
   L1
    LINENUMBER 9 L1
    ALOAD 1: msg
    LDC " : Hello World!"
    INVOKEVIRTUAL StringBuilder.append(String) : StringBuilder
    POP
   L2
    LINENUMBER 10 L2
    GETSTATIC System.out : PrintStream
    ALOAD 1: msg
    INVOKEVIRTUAL PrintStream.println(Object) : void
   L3
    LINENUMBER 11 L3
    RETURN
   L4
    LOCALVARIABLE args String[] L0 L4 0
    LOCALVARIABLE msg StringBuilder L1 L4 1
    MAXSTACK = 4
    MAXLOCALS = 2
```

Modularize by chaining visitors

Modularize by chaining visitors

- Do not write one big visitor with every manipulation
- The visitor pattern is perfect for delegation (for example, `ClassAdapter` ASM class)
- Create independent visitors for single, well-defined tasks
- Chain them together

‣ Easier to comprehend, easier to maintain and often even easier to implement

Agenda

- What is bytecode manipulation?
- Some popular projects using it
- Don't be afraid
- Plug in the manipulation
- **Best practices**
- Q & A

Q & A

TERRACOTTA

Cluster your JVM

http://terracotta.org