

## ASM

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## Introduction to the ASM 2.0 Bytecode Framework

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Java features such as dynamic class loading and reflection make it a dynamic language. However, in many cases, reflection is not sufficient, and developers need to generate bytecode from non-Java source code, such as scripting languages like Groovy ([JSR-241](#)) or BeanShell ([JSR-274](#)), or from metadata such as an OR-mapping configuration. When working with existing classes, and especially when original Java sources are not available, some tools may need to do a static analysis of the interdependencies or even method behavior in order to produce test coverage or metrics, or to detect bugs and anti-patterns. New features added to Java 5, such as annotations and generics, affected bytecode structure and require special attention from bytecode manipulation tools to maintain good performance. This article will give an overview of one of the smallest and fastest bytecode manipulation frameworks available for Java.

## Framework Structure

The [ASM](#) bytecode manipulation framework is written in Java and uses a visitor-based approach to generate bytecode and drive transformations of existing classes. It allows developers to avoid dealing directly with a class constant pool and offsets within method bytecode, thus hiding bytecode complexity from the developer and providing better performance, compared to other tools such as [BCEL](#), [SERP](#), or [Javassist](#).

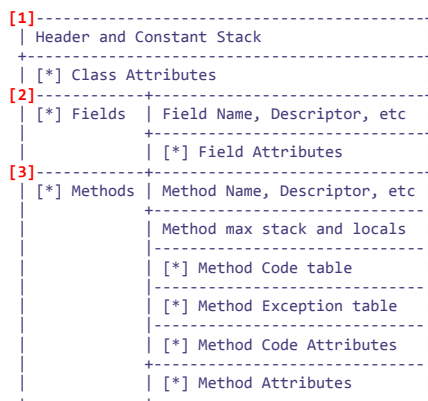
ASM is divided into several packages that allow flexible bundling. The packaging arrangement is shown in Figure 1.



Figure 1. Arrangement of ASM packages

- The **Core** package provides an API to read, write, and transform Java bytecode and defines a foundation for the other packages. This package is sufficient to generate Java bytecode and to implement the majority of bytecode transformations.
- The **Tree** package provides in-memory representation of Java bytecode.
- The **Analysis** package provides basic data-flow analyses and type-checking algorithms for Java method bytecode stored in structures from the tree package.
- The **Commons** package (added in ASM 2.0) provides several commonly used bytecode transformations and adapters to simplify bytecode generation.
- The **Util** package contains several helper classes and simple bytecode verifiers that can help in development or testing.
- The **XML** package provides an adapter to convert bytecode structures to and from XML, and SAX-compliant adapters that allow the use of XSLT to define bytecode transformations.

The next few sections will give an introduction to the Core package of the ASM framework. To get a better understanding of the organization of this package, you have to have some basic understanding of the bytecode structures that are defined in the [JVM specification](#). Here is a high-level diagram of the class file format ([\*] marks repeatable structures).



Here are a few things to notice:

- All descriptors, string literals, and any other constants used in class structures are stored in a *Constant Stack* at the beginning of the class file and then referenced from all other structures by its indexes.
- Each class must contain headers (including class name, super class, interfaces, etc.) and the Constant Stack. Other elements, such as the list of fields, list of methods, and all attributes, are optional and may or may not be present.
- Each Field section includes field info such as name, access flags (public, private, etc.), descriptor and field Attributes.
- Each Method section contains similar header info and information about max stack and max local variable numbers, which are used to verify bytecode. For non-abstract and non-native methods, there is a table of method instructions (method body), an exceptions table, and code attributes. Besides these, there can be other method attributes.
- Each Attribute for Class, Field, Method, and Method Code has its own name, which is also documented in the Class File format section of the JVM specification. These attributes represent various pieces of information about bytecode, such as source file name, inner classes, signature (used to store generics info), line number, and local variable tables and annotations. The JVM specification also allows the definition of custom attributes that will be ignored by the standard VM, but may contain additional information. *Note that Java 5 annotations practically made these custom attributes obsolete, because annotation semantics allow you to express pretty much anything.*
- The Method Code table contains a list of instructions for the Java Virtual Machine. Some of these instructions (as well as the exception, line number, and local variable tables) use offsets within the code table and the values of all of these offsets may need to be adjusted when instructions are inserted or removed from the method code table.

As you can see, bytecode tweaking isn't easy. However, the ASM framework reduces the complexity of the underlying structures and provides a simplified API that still allows for access to all bytecode information and enables complex transformations.

## Event-Based Bytecode Processing

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The Core package uses a push approach (similar to the "[Visitor](#)" design pattern, which is also used in the [SAX API](#) for XML processing) to walk through complex bytecode structures. ASM defines several interfaces, such as [ClassVisitor](#) (section [1] in the class file format diagram above), [FieldVisitor](#) (section [2]), [MethodVisitor](#) (section [3]), and [AnnotationVisitor](#). [AnnotationVisitor](#) is a special interface that allows you to express hierarchical annotation structures. The next few paragraphs will show how these interfaces interact with each other and how they can be used together to implement bytecode transformations and/or capture information from the bytecode.

The Core package can be logically divided into two major parts:

- Bytecode producers, such as a [ClassReader](#) or a custom class that can fire the proper sequence of calls to the methods of the above visitor classes.
- Bytecode consumers, such as writers ([ClassWriter](#), [FieldWriter](#), [MethodWriter](#), and [AnnotationWriter](#)), adapters ([ClassAdapter](#) and [MethodAdapter](#)), or any other classes implementing the above visitor interfaces.

Figure 2 shows the sequence diagram for the common producer-consumer interaction.

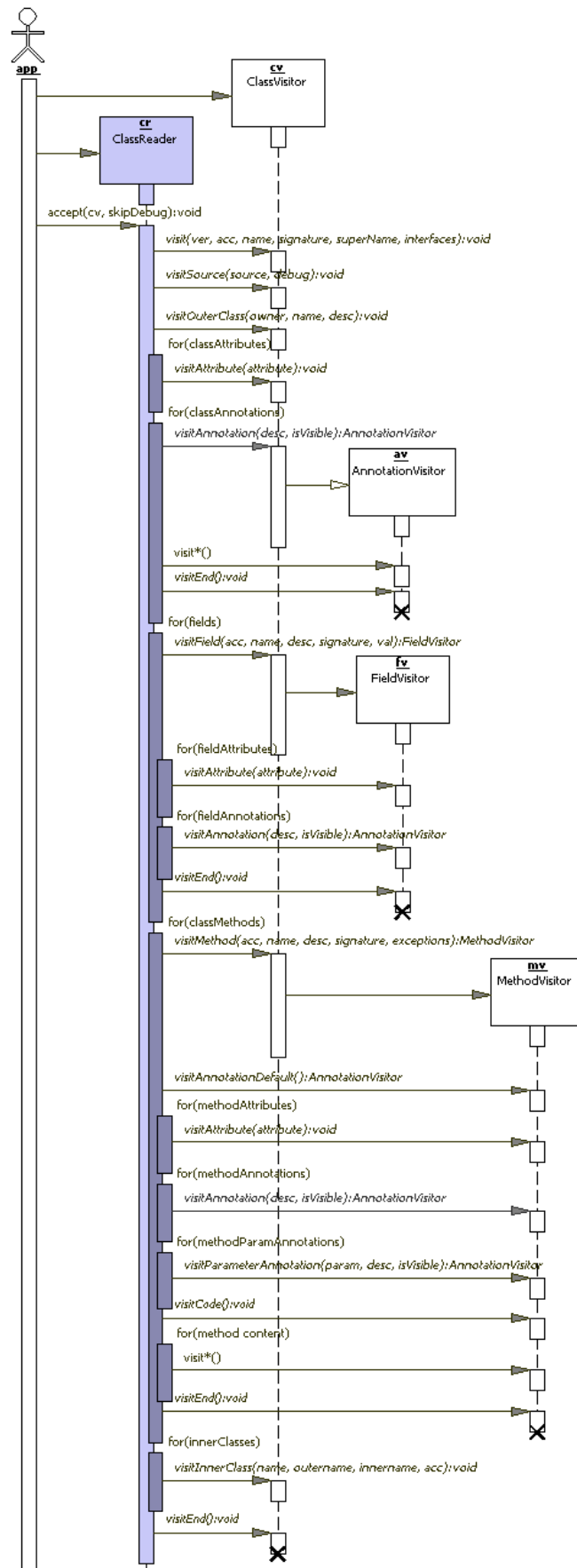


Figure 2. Sequence diagram for producer-consumer interaction

In this interaction, a client application creates `ClassReader` and calls the `accept()` method, passing a concrete `ClassVisitor` instance as a parameter. Then `ClassReader` parses the class and fires "visit" events to `ClassVisitor` for each bytecode fragment. For repeated contexts, such as fields, methods, or annotations, a `ClassVisitor` may create child visitors derived from the corresponding interface (`FieldVisitor`, `MethodVisitor`, or `AnnotationVisitor`) and return them to the producer. When a producer receives a null value for `FieldVisitor` or `MethodVisitor`, it skips that fragment of the class (e.g., a `ClassReader` wouldn't even parse the corresponding bytecode section in such a case, which leads to a sort of "lazy loading" feature driven by the visitors). Otherwise, the corresponding subcontext events are delegated to the child visitor instance. At the end of each subcontext, the producer calls the `visitEnd()` method and then moves on to the next section (e.g., the next field, method, etc.).

Bytecode consumers can be linked together in a "Chain of responsibility" pattern by either manually delegating events to the next visitor in the chain, or with using visitors derived from `ClassAdapter` and/or `MethodAdapter` that delegate all visit methods to their underlying visitors. Those delegators act as bytecode consumers from one side and as bytecode producers from the other. They can decide to modify natural delegation in order to implement specific bytecode transformation:

- Visit call delegation can be omitted in order to remove class fields, methods, method instructions, etc.
- Visit call parameters can be modified in order to rename classes, methods, types, etc.
- New visit calls can be added in order to introduce new fields or methods, or to inject new code into existing methods.

The chain can be ended by a `ClassWriter` visitor, which will produce the resulting bytecode. For example:

```
ClassWriter cw = new ClassWriter(computeMax);
ClassVisitor cc = new CheckClassAdapter(cw);
ClassVisitor tv =
    new TraceClassVisitor(cc, new PrintWriter(System.out));
ClassVisitor cv = new TransformingClassAdapter(tv);
ClassReader cr = new ClassReader(bytecode);
cr.accept(cv, skipDebug);
byte[] newBytecode = cw.toByteArray();
```

In the above code, the `TransformingClassAdapter` implements custom class transformations and sends the results to the `TraceClassVisitor` passed to its constructor. `TraceClassVisitor` prints the transformed class and delegates the same events to `CheckClassAdapter`, which does simple bytecode verification and then passes the event to the `ClassWriter`.

Most of the visit methods receive simple parameters such as `int`, `boolean`, and `String`. In all visit methods where `String` parameters refer to constants within the bytecode, ASM uses the same representation as used by the JVM. For instance, all class names (e.g. super class, interfaces, exceptions, owner classes for the field, and methods referenced from method code) should be specified in the [Internal Form](#). Field and method descriptors (usually the `desc` parameter) also should be in [JVM representation](#). The same approach is taken for `signature` parameters used to represent generics information, so they should follow the grammar defined in Section 4.4.4 of the [Revised Class File Format](#) (PDF). This approach helps avoid unnecessary calculations when no transformation is required. To help construct and parse such descriptors, there is a `Type` class that provides several static methods:

- `String getMethodDescriptor(Type returnType, Type[] argumentTypes)`
- `String getInternalName(Class c)`
- `String getDescriptor(Class c)`
- `String getMethodDescriptor(Method m)`
- `Type getType(String typeDescriptor)`
- `Type getType(Class c)`
- `Type getReturnType(String methodDescriptor)`
- `Type getReturnType(Method m)`
- `Type[] getArgumentTypes(String methodDescriptor)`
- `Type[] getArgumentTypes(Method m)`

Note that these descriptors are using an "erased" representation, which does not contain generics information. Generics info is actually stored as a separate bytecode attribute, but ASM takes care of this attribute and passes the generic signature string in a `signature` parameter of the appropriate visit methods. The value of the `signature` string also uses the JVM representation (see Section 4.4.4 in the ["Class File Format"](#) (PDF) as revised for Java 5), which uniquely maps from the generic declarations in Java code, but presents an additional challenge for tools that need to retrieve details from generic types. To handle signatures, ASM provides `SignatureVisitor`, `SignatureReader`, and `SignatureWriter` classes modelled in a way similar to other ASM visitors, as illustrated in Figure 3.

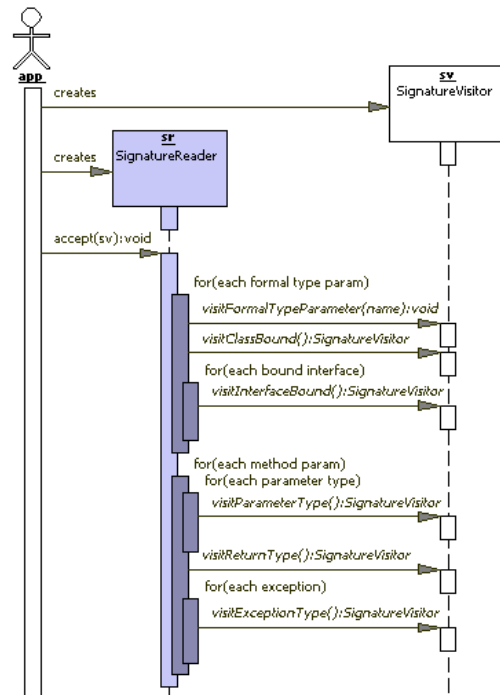


Figure 3. Sequence diagram for Signature classes

The `Util` package contains `TraceSignatureVisitor`, which implements `SignatureVisitor` and allows you to convert a `signature` value into a Java declaration with generic types. The following example converts a method signature into a Java method declaration.

```
TraceSignatureVisitor v =
    new TraceSignatureVisitor(access);
SignatureReader r = new SignatureReader(sign);
r.accept(v);
String genericDecl = v.getDeclaration();
String genericReturn = v.getReturnType();
String genericExceptions = v.getExceptions();

String methodDecl = genericReturn + " " +
    methodName + genericDecl;
if(genericExceptions!=null) {
    methodDecl += " throws " + genericExceptions;
}
```

Up to this point, we have talked about the general design of the ASM framework and manipulating class structure. However, the most interesting part is how ASM handles method code.

?	visitAnnotationDefault	Visits the default value for annotation interface method
*	visitAnnotation	Visits a method annotation
*	visitParameterAnnotation	Visits a method parameter annotation
*	visitAttribute	Visits a non-standard method attribute
?	visitCode	Starts the visit of the method's code for non-abstract and non-native methods
*	visitInsn	Visits a zero operand instruction: NOP, ACONST_NULL, ICONST_M1, ICONST_0, ICONST_1, ICONST_2, ICONST_3, ICONST_4, ICONST_5, LCONST_0, LCONST_1, FCONST_0, FCONST_1, FCONST_2, DCONST_0, DCONST_1, IALOAD, LALOAD, FALOAD, DALOAD, AALOAD, BALOAD, CALOAD, SALOAD, IASTORE, LASTORE, FASTORE, DASTORE, AASTORE, BASTORE, CASTORE, SASTORE, POP, POP2, DUP, DUP_X1, DUP_X2, DUP2, DUP2_X1, DUP2_X2, SWAP, IADD, LADD, FADD, DADD, ISUB, LSUB, FSUB, DSUB, IMUL, LMUL, FMUL, DMUL, IDIV, LDIV, FDIV, DDIV, IREM, LREM, FREM, DREM, INEG, LNEG, FNEG, DNEG, ISHL, LSHL, ISHR, LSHR, IUSHR, LUSHR, IAND, LAND, IOR, LOR, IXOR, LXR, I2L, I2F, I2D, L2I, L2F, L2D, F2I, F2L, F2D, D2I, D2L, D2F, I2B, I2C, I2S, L2S, L2CMP, F2CMP, D2CMP, DCMP, I2CMP, L2CMP, F2CMP, D2CMP, IRETURN, LRETURN, FRETURN, DRETURN, ARETURN, RETURN, ARRAYLENGTH, ATHROW, MONITORENTER, or MONITOREXIT.
	visitFieldInsn	Visits a field instruction: GETSTATIC, PUTSTATIC, GETFIELD or PUTFIELD.
	visitIntInsn	Visits an instruction with a single int operand: BIPUSH, SIPUSH, or NEWARRAY.
	visitJumpInsn	Visits a jump instruction: IFEQ, IFNE, IFLT, IFGE, IFGT, IFLE, IF_ICMPEQ, IF_ICMPNE, IF_ICMPLT, IF_ICMPGE, IF_ICMPGT, IF_ICMPLE, IF_ACMPEQ, IF_ACMPNE, GOTO, JSR, IFNULL, or IFNONNULL.
	visitTypeInsn	Visits a type instruction: NEW, ANEWARRAY, CHECKCAST, or INSTANCEOF.
	visitVarInsn	Visits a local variable instruction: ILOAD, LLOAD, FLOAD, DLOAD, ALOAD, ISTORE, LSTORE, FSTORE, DSTORE, ASTORE, or RET.
	visitMethodInsn	Visits a method instruction: INVOKEVIRTUAL, INVOKESPECIAL, INVOKESTATIC, or INVOKEINTERFACE.
	visitIincInsn	Visits an IINC instruction.
	visitLdcInsn	Visits an LDC instruction.
	visitMultiANewArrayInsn	Visits a MULTIANEWARRAY instruction.
	visitLookupSwitchInsn	Visits a LOOKUPSWITCH instruction.
	visitTableSwitchInsn	Visits a TABLESWITCH instruction.
	visitLabel	Visits a label.
	visitLocalVariable	Visits a local variable declaration.
	visitLineNumber	Visits a line number declaration.
	visitTryCatchBlock	Visits a try-catch block.
	visitMaxs	Visits the maximum stack size and the maximum number of local variables of the method.
	visitEnd	Visits the end of the method.

Also note that if a method actually has some bytecode (i.e., if it is not abstract and not a native method), then `visitCode` must be called before the first `visit...Insn` call, and the `visitMaxs` method must be called after last `visit...Insn` call.

Another challenge with any kind of bytecode generation or transformation is that offsets within method code can change and should be adjusted when additional instructions are inserted or removed from the method code. This is applicable to parameters of all jump opcodes (*if*, *goto*, *jsr*, and *switch*), as well as to try-catch blocks, line number and local variable declarations, and to some of the special attributes (e.g., *StackMap*, used by CLDC). However, ASM hides this complexity from the developer. In order to specify positions in the method bytecode and not have to use absolute offsets, a unique instance of the *Label* class should be passed to the *visitLabel* method. Other *MethodVisitor* methods such as *visitJumpInsn*, *visitLookupSwitchInsn*, *visitTableSwitchInsn*, *visitTryCatchBlock*, *visitLocalVariable*, and *visitLineNumber* can use these *Label* instances even before the *visitLabel* call, as long as the instance will be called later in a method.

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## Tracking Class Dependencies with ASM Visitors

There are already a few articles that explain how to generate bytecode with ASM (see the [Resources](#) section for some links). For a change, let's see how ASM can be used to analyze existing classes. One interesting application is to capture information about external classes or packages used by any given module or .jar file. For simplicity, this example will only capture outgoing dependencies and won't keep track of the dependency types (e.g., superclass, method parameters, local variable types, etc.).

Notice that for analysis purposes, we don't need to create new instances of child visitors for annotations, fields, and methods. All of these visitors, including class and signature visitor, could be implemented in a single class:

```
public class DependencyVisitor implements
    AnnotationVisitor, SignatureVisitor,
    ClassVisitor, FieldVisitor, MethodVisitor {
    ...
}
```

For this example, we will track dependencies between packages, so individual classes should be aggregated by the package name:

```
private String getGroupKey(String name) {
    int n = name.lastIndexOf('/');
    if(n>-1) name = name.substring(0, n);
    packages.add(name);
    return name;
}
```

In order to collect dependencies, visitor interfaces such as `ClassVisitor`, `AnnotationVisitor`, `FieldVisitor`, and `MethodVisitor` should selectively aggregate parameters of their methods. There are several common cases:

First of all, there are class names in [internal form](#) (super class, interfaces, exceptions, field and method owners); e.g., `java/lang/String`:

```
private void addName(String name) {
    if(name==null) return;
    String p = getGroupKey(name);
    if(current.containsKey(p)) {
        current.put(p, current.get(p)+1);
    } else {
        current.put(p, 1);
    }
}
```

In this case, `current` is the current group of dependencies (e.g., package).

Another case is type descriptors (annotations, enum and field types, parameters of the newarray instruction, etc.); e.g., `Ljava/lang/String;`, `J`, and `[[[I`. These can be parsed with `Type.getType(desc)` to obtain the class name in internal form:

```
private void addDesc(String desc) {
    addType(Type.getType(desc));
}

private void addType(Type t) {
    switch(t.getSort()) {
        case Type.ARRAY:
            addType(t.getElementType());
            break;
        case Type.OBJECT:
            addName(t.getClassName().replace('.', '/'));
            break;
    }
}
```

Method descriptors used in method declarations and in invoke instructions describe parameter types and return a type; e.g., `([Ljava/lang/String;II)V`. The helper methods `Type.getReturnType(methodDescriptor)` and `Type.getArgumentTypes(methodDescriptor)` can parse such descriptors and extract parameter and return types.

```
private void addMethodDesc(String desc) {
    addType(Type.getReturnType(desc));
    Type[] types = Type.getArgumentTypes(desc);
    for(int i = 0; i < types.length; i++) {
        addType(types[i]);
    }
}
```

The special case is the `signature` parameter used in many "visit" methods to specify Java 5 generics info. If it is present (i.e., non-null), this parameter overrides the descriptor parameter and contains an encoded form of the generics information. `SignatureReader` class could be used to parse this value. So we can implement a `SignatureVisitor`, which will be called for each signature artifact.

```
private void addSignature(String sign) {
    if(sign!=null) {
        new SignatureReader(sign).accept(this);
    }
}

private void addTypeSignature(String sign) {
    if(sign!=null) {
        new SignatureReader(sign).acceptType(this);
    }
}
```

Methods implementing the `ClassVisitor` interface, such as `visit()`, `visitField()`, `visitMethod()`, and `visitAnnotation()`, can collect information about dependencies on superclasses and interfaces, types used by fields, method parameters, return values, and exceptions, as well as types of the annotations. For example:

```
public void visit(int version, int access,
    String name, String signature,
    String superName, String[] interfaces) {
    String p = getGroupKey(name);
    current = groups.get(p);
    if(current==null) {
        current = new HashMap<String,Integer>();
        groups.put(p, current);
    }

    if(signature==null) {
        addName(superName);
        addNames(interfaces);
    }
}
```

```

    } else {
        addSignature(signature);
    }
}

public FieldVisitor visitField(int access,
    String name, String desc,
    String signature, Object value) {
    if(signature==null) {
        addDesc(desc);
    } else {
        addTypeSignature(signature);
    }
    if(value instanceof Type) {
        addType((Type) value);
    }
    return this;
}

public MethodVisitor visitMethod(int access,
    String name, String desc,
    String signature, String[] exceptions) {
    if(signature==null) {
        addMethodDesc(desc);
    } else {
        addSignature(signature);
    }
    addNames(exceptions);
    return this;
}

public AnnotationVisitor visitAnnotation(
    String desc, boolean visible) {
    addDesc(desc);
    return this;
}

```

Methods implementing the `MethodVisitor` interface can collect dependencies on types of the parameter annotations and types used in bytecode instructions that can use object references:

```

public AnnotationVisitor
    visitParameterAnnotation(int parameter,
        String desc, boolean visible) {
    addDesc(desc);
    return this;
}

/**
 * Visits a type instruction
 * NEW, ANEWARRAY, CHECKCAST or INSTANCEOF.
 */
public void visitTypeInsn(int opcode,
    String desc) {
    if(desc.charAt(0)=='[') {
        addDesc(desc);
    } else {
        addName(desc);
    }
}

/**
 * Visits a field instruction
 * GETSTATIC, PUTSTATIC, GETFIELD or PUTFIELD.
 */
public void visitFieldInsn(int opcode,
    String owner, String name, String desc) {
    addName(owner);
    addDesc(desc);
}

/**
 * Visits a method instruction INVOKEVIRTUAL,
 * INVOKESPECIAL, INVOKESTATIC or
 * INVOKEINTERFACE.
 */
public void visitMethodInsn(int opcode,
    String owner, String name, String desc) {
    addName(owner);
    addMethodDesc(desc);
}

/**
 * Visits a LDC instruction.
 */
public void visitLdcInsn(Object cst) {
    if(cst instanceof Type) {
        addType((Type) cst);
    }
}

/**
 * Visits a MULTIANEWARRAY instruction.
 */
public void visitMultiNewArrayInsn(
    String desc, int dims) {
    addDesc(desc);
}

/**
 * Visits a try catch block.
 */
public void visitTryCatchBlock(Label start,
    Label end, Label handler, String type) {
    addName(type);
}

```

Now we can use `DependencyVisitor` to collect dependencies from the entire .jar file. For example:

```
DependencyVisitor v = new DependencyVisitor();
ZipFile f = new ZipFile(jarName);
Enumeration<? extends ZipEntry> en = f.entries();
while(en.hasMoreElements()) {
    ZipEntry e = en.nextElement();
    String name = e.getName();
    if(name.endsWith(".class")) {
        ClassReader cr =
            new ClassReader(f.getInputStream(e));
        cr.accept(v, false);
    }
}
```

The collected information can be represented in many different ways. One can build dependency trees and calculate some metrics, or create some visualizations. For example, Figure 5 shows how *ant-1.6.5.jar* looks in a visualization I built on top of the collected information using some simple Java2D code. The following diagram shows packages from the input .jar on a horizontal axis and external dependencies on a vertical axis. The darker a box's color is, the more times the package is referenced.

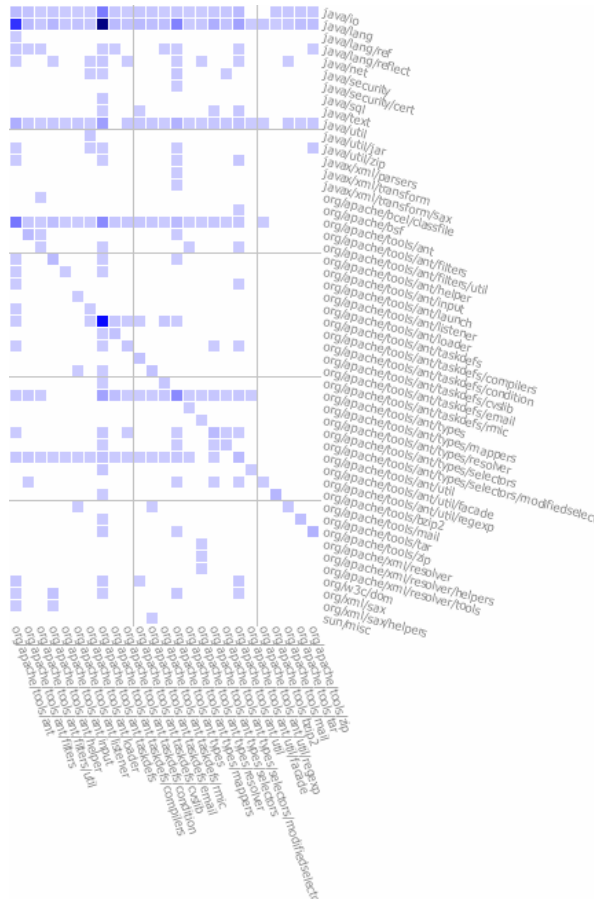


Figure 5. Dependencies in *ant-1.6.5.jar*, as discovered with ASM

The complete code of this tool will be included into the next ASM release. It can be also obtained from [ASM CVS](#).

## Changes in the ASM 2.0 API Since ASM 1.x

You can skip this section if you haven't used ASM 1.x.

The major structural change in ASM 2.0 is that all J2SE 5.0 features are built into the ASM visitor/filter event flow. So the new API allows you to deal with generics and annotations in a much more lightweight and semantically natural way. Instead of explicitly creating annotation attribute instances, we have generics and annotation data within the event flow. For example, in ASM 1.x, the `ClassVisitor` interface used the following method:

```
CodeVisitor visitMethod(int access, String name,
    String desc, String[] exceptions,
    Attribute attrs);
```

This has been split into several methods in ASM 2.0:

```
MethodVisitor visitMethod(int access,
    String name, String desc, String signature,
    String[] exceptions)

AnnotationVisitor visitAnnotation(String desc,
    boolean visible)

void visitAttribute(Attribute attr)
```

In the 1.x API, in order to define generics info, you'd have to create specific instances of the `SignatureAttribute`, and to define annotations, you'd need instances of the `RuntimeInvisibleAnnotations`, `RuntimeInvisibleParameterAnnotations`, `RuntimeVisibleAnnotations`, `RuntimeVisibleParameterAnnotations`, and `AnnotationDefault`. Then you'd put these instances into the `attrs` parameter of the appropriate visit method.

In ASM 2.0, a new `signature` parameter has been added to represent generics info. The new `AnnotationVisitor` interface is used to handle all annotations. There is no need to create an `attrs` collection, and annotation data is more strictly typed. However, when migrating existing code, especially when "adapter" classes have been used; it is necessary to be careful and make sure that all methods overwritten from the adapter are updated to new signatures, because the compiler will raise no warnings.

There are several other changes introduced in ASM 2.0.

- Introduced the new interfaces `FieldVisitor` and `AnnotationVisitor`.



- `CodeVisitor` into `MethodVisitor`.
- New `visitCode()` method added to the `MethodVisitor` to easily detect first instruction.
- `Constants` interface renamed into `Opcodes`.
- Almost all attributes from the `attrs` package are incorporated into ASM's event model.
- `TreeClassAdapter` and `TreeCodeAdapter` are incorporated into the `ClassNode` and `MethodNode`.
- Introduced the `LabelNode` class to make elements of `instructions` collection common type of `AbstractInsnNode`.

In general, it would be a good idea to run tool like [JDiff](#) and review the differences between the ASM 1.x and 2.0 APIs.

## Conclusion

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ASM 2.0 hides many bytecode complexities from the developer and allows one to efficiently work with Java features on a bytecode level. The framework allows you not only to transform and generate bytecode, but also to pull out significant details about existing classes. The API is being constantly improved--version 2.0 incorporates the generics and annotations introduced in J2SE 5.0. Since then, support for the new features introduced in Mustang (see "[Java SE 6 Snapshot Releases](#)") have been added to the ASM framework.

## Resources

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- [Java Virtual Machine Specification](#)
- "[Revised Class File Format](#)" (Chapter 4 of the JVM specification; PDF). Includes modifications for J2SE 5.0 to support changes mandated by JSR-14, JSR-175, and JSR-201, as well as minor corrections and adjustments.
- "[Using the ASM Toolkit for Bytecode Manipulation](#)"
- "[Create and Read J2SE 5.0 Annotations with the ASM Bytecode Toolkit](#)"
- [Bytecode Instrumentation \(BCI\)](#). Kelly O'Hair discusses challenges in bytecode instrumentation.

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