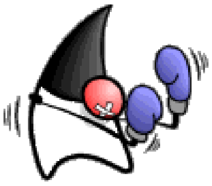
 HotJava(tm): The Security Story

HotJava(tm) is a world wide web (WWW) browser, built using a new language called Java. Perhaps the most significant new facility that HotJava implements is the ability to import code fragments across the net and execute them. One of the most important technical challenges in building a system like HotJava is to make it safe. Importing code fragments across the network, installing, and running them is an open invitation to security problems.

The question of how to provide a secure environment for code to execute in doesn't have a single answer. HotJava has layers of interlocking facilities that provide defenses against a variety of attacks. These layers are:

- The JavaTM language, which was designed to be a safe language and the Java compiler which ensures that source code doesn't violate the safety rules.
- A verification of the byte codes imported into the runtime to ensure that they obey the language's safety rules. This layer guards against an altered compiler producing code that violates the safety rules.
- A class loader which ensures that classes don't violate name space or access restrictions when they are loaded.
- Interface-specific security that prevents applets from doing destructive things. It depends on the security guarantees of the previous layers. This layer depends on the integrity guarantees from the other three layers.

Security layer one: the language and compiler

The Java language and the compiler comprise the first line of security for HotJava. Java was designed to be a safe language.

Initially, the development team thought that by adding safety features to an existing language such as C++, the safety goals could be achieved. However, as work progressed it became clear that this strategy would not succeed without putting some restrictions on C++.

C++ has a series of facilities to control access to objects, but it also has ways to forge access to objects and to sub-parts of objects that defeat the access controls. The C++ facilities that allow forging have either been eliminated in Java or changed to make them safe. Most importantly, you can't do pointer arithmetic; in fact you can't modify pointers in any way. However, Java has true arrays instead of pointer arithmetic. And because the primary use of pointer arithmetic in C and C++ is to access arrays, programmers often don’t notice the change. Another example is the "cast" operator: the Java compiler checks that a cast is legal, whereas C and C++ do not.

Security layer two: verifying the bytecodes

A trustworthy compiler ensures that Java source code doesn’t violate the safety rules, but someone could alter the compiler to produce code that violates them. HotJava, which can import code fragments from anywhere, doesn’t know whether a code fragment comes from a trustworthy compiler or not. So, before executing any code fragment, the runtime system subjects it to a series of tests.

The tests range from verification that the format of the fragment is correct, to passing it through a simple theorem prover to establish that the code plays by the rules. The code is checked to ensure:

- that it doesn’t forge pointers
- that it doesn’t violate access restrictions
- that it accesses objects as what they are. (For example, the tests ensure that "InputStream" objects are always used as "InputStreams" and never as anything else.)
- that it calls methods with appropriate arguments of the appropriate type
- that there are no stack overflows

The representation of code fragments loaded into the runtime is a byte coded machine-independent instruction set that bears a resemblance to representations like the UCSD Pascal P-Codes[Bowles78], i.e., it is stack based.

Consider the following Java code sample:

```
class vector {
    int arr[];
    int sum() {
        int la[] = arr;
        int S = 0;
        for (int i=la.length; --i>=0;)
            S += la[i];
        return S;
    }
}
```

The byte codes generated when the above code is compiled look like the following:

```
    aload_0           Load this
    getfield #10      Load this.arr
    astore_1          Store in la
    iconst_0
    istore_2          Store 0 in S
    aload_1           Load la
    arraylength       Get its length
    istore_3          Store in i
A:  iinc 3 -1         Subtract 1 from i
    iload_3           Load i
    iflt B            Exit loop if <0
    iload_2           Load S
    aload_1           Load la
    iload_3           Load i
    iaload            Load la[i]
    iadd              add in S
    istore_2          store to S
    goto A            do it again
B:  iload_2           Load S
    ireturn           Return it
```

Type information

Java bytecodes contain more type information than is strictly necessary for the interpreter. For example, both the aload and iload opcodes have identical implementations, however, aload is used to load a pointer and iload is used to load an integer. Similarly, the getfield opcode has a symbol table reference; the symbol table has type information. This "extra" type information allows the runtime system to perform checks that guarantee that type information isn’t being illegally manipulated.

Most stack based instruction sets don’t limit what you can do with the stack and local variables. Conceptually, at any point in the program each slot in the stack and each local variable has a type. This collection of type information, i.e., all the slots and local variables, is called the type state of the execution frame. An important property of the type state is that this type can be determined statically by induction, i.e., before any program code is executed. As the runtime systems reads through a block of instructions, each instruction pops and pushes values of particular types. Instruction definitions are required to have the following inductive property:

> *Given only the type state before the execution of the instruction, the type state afterwards is determined.*

Given a straight-line block of code, i.e., no branches, and starting with a known stack state, the type state of each slot in the stack is known. For example:

```
iload_1 Load integer variable, stack type state=I
iconst 5        Load integer constant, stack type state=II
iadd    Add two integers producing an integer, stack type state=I
```

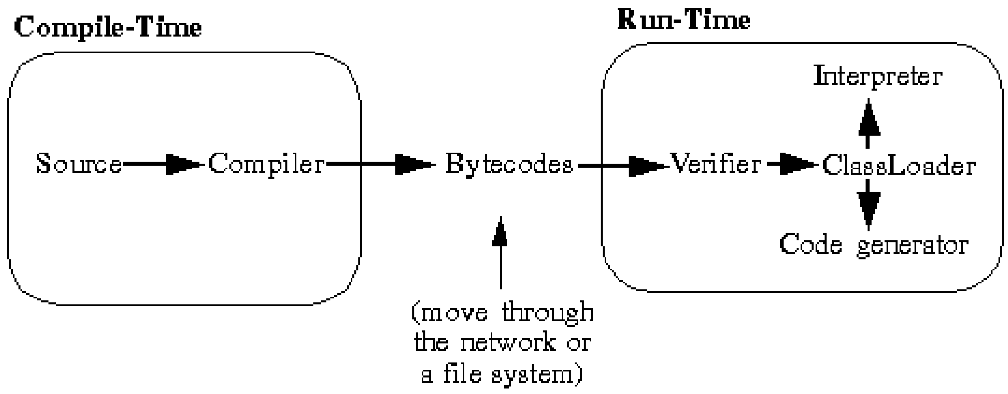
A number of stack-based instruction sets, like Smalltalk [Chambers92] and PostScript [Adobe85] do not have this property. For example, the definition of the PostScript add operator explicitly states "If both operands are integers and the result is within integer range, the result is an integer, otherwise the result is a real." In many situations this dynamic type behavior is considered to be an advantage, but HotJava needs to provide a secure execution environment and it must know the types of objects in order to guarantee a certain level of security.

In conjunction with the inductive property above we require that:

> *When there are two execution paths into the same point, they must arrive there with exactly the same type state.*

This requirement has several implications. For example, compilers cannot write loops that iterate through arrays, loading each element of the array onto the stack, effectively copying the array onto the stack. This behavior is prevented because the flow path into the top of the loop will have a different type state than the branch back to the top. Because all paths to a point are required to arrive with the same type state, the type state from any incoming path can be used to do further manipulations.

Code is checked for compliance with these rules by a part of the loader called the verifier. It traverses the byte codes, constructs the type state information, and verifies the types of the parameters to all the opcodes. The following illustration shows the flow of code from Java source code to execution by the runtime system.



The verifier acts as a gatekeeper by preventing the execution of imported code until it has passed the verifier’s tests. When code verification is complete a number of important properties of the code are known:

- The code causes no operand stack overflows or underflows.
- The types of the parameters to all opcodes are known to always be correct.
- No illegal data conversions are done, like converting integers to pointers.
- Object field accesses are known to be legal (i.e., the verifier checks that the rules for public, private, and protected accesses are obeyed).

Knowing these properties makes the runtime system much faster because it doesn’t have to check anything. There are no operand type checks and no stack overflow checks. The runtime can eliminate these checks without compromising safety.

These properties also provide a foundation for the security of the system:

- pointers can be treated essentially as capabilities
- applications cannot forge pointers, e.g., casting an integer to a pointer
- applications cannot get around pointers
- all the access restrictions are enforced

So, in HotJava, you can trust that a private variable really is private, that no piece of application code is doing some magic with casts to extract information from a private variable, for example, a credit card number from the billing software. This means that implementing security for HotJava against destructive applets is easier to do. HotJava security has to deal with restricting file access and the ability of applets to grab files and throw them over firewalls. The HotJava security implementation doesn't have to worry about threats like hacked bytecodes forging access to private methods or overflowing the stack.

Security level three: the class loader

After the initial runtime environment checks are passed, code encounters a class loader. The environment seen by a thread of execution running Java byte codes can be visualized as a set of classes partitioned into namespaces. The class loader guarantees that a unique namespace exists for classes that come from the local file system (called built-ins), and a unique namespace exists for each network source. When HotJava imports a class across the network the Class Loader places it into the private namespace associated with its origin. Thus, classes imported from different places are partitioned from each other.

When a class references another class, the runtime system first looks for it in the namespace of the built-ins, then in the namespace of the referencing class. There is no way that an imported class can "spoof" a built-in class. Built-ins can never accidentally reference classes in imported namespaces, they can only do it explicitly. Spoofing is prevented because the system always checks built-in classes first.

Security level four: protecting the file system and network access

HotJava enforces security policies confident that its security interfaces are secure. The three lower levels of security guarantee that all local classes, e.g., the file access primitives, are themselves protected from being supplanted, replaced, or extended by imported code.

The file access primitives implement an access control list that controls read and write access to files by imported code (or code invoked by imported code). The defaults for these access control lists are very restrictive. If an attempt is made by a piece of imported code to access a file to which access has not been granted, a dialog box pops up to allow the user to decide whether or not to allow that specific access. These security policies err on the conservative side in order to ensure maximum security. This conservative approach may make writing some applets more difficult or awkward.

For network security, HotJava provides a variety of mechanisms that can provide information about the trustworthiness of imported code. These mechanisms cover a wide range of possibilities. At the simple end the system can check on the origin of a code fragment to determine if it came from inside or outside a firewall. At the sophisticated end of the range a mechanism exists whereby public keys and cryptographic message digests can be securely attached to code fragments that not only identify who originated the code, but guarantee its integrity as well. This latter mechanism will be implemented in future releases.

The security policies implemented by the runtime system can be dynamically adjusted based on the information available concerning the origin of a code fragment. The Socket class provides such an example.

The Socket class implements security policies that are adjusted to reflect the trustworthiness of the code that invoked it, and transitively, the code that invoked the invoker. The information about what code began the chain of execution is available to the class in the form of which namespace contains the invoking code and what parameters are associated with that class. The class loader puts the classes it has loaded in a specific namespace, allowing the Socket class to determine the network host from which a class is loaded.

Knowing the network host allows the HotJava security mechanism to determine whether the class originated inside or outside a firewall. Knowledgable users of HotJava can decide which category of hosts to trust when loading executable code. For example, the Socket class can implement the policy of only allowing new connections to be created that terminate at the host from whence the code was loaded. This restriction means that code loaded from outside a firewall cannot connect to other machines on the net behind the firewall. Code that comes from more trusted sources can be allowed more freedom to make connections to other machines. As an additional defense against untrusted sources HotJava's security can be set to prevent any code from being loaded. The level of security is configurable by HotJava users.

Summary

The security in HotJava provides a safe environment for the execution of imported code. The security is based on interlocking layers of security that range from the design of the Java language at the base to the file and network access protections at the top. In the future HotJava will support network commerce through the inclusion of public key encryption technology.

Bibliography

[Adobe85]
Adobe Systems Incorporated, "PostScript Language Reference Manual", Addison Wesley.
[Aho86]

Aho, Alfred V., Ravi Sethi, Jeffrey D. Ullman, "Compilers: Principles, Techniques and Tools", Addison Wesley.

[Bowles78]

Bowles, Kenneth L, "UCSD Pascal", Byte. 46 (May)

[Chambers92]

Chambers, Craig, David Ungar, and Elgin Lee. An Efficient Implementation of Self, a Dynamically-Typed Object-Oriented Language Based on Prototypes. In OOPSLA ‘89 Conference Proceedings, p. 49-70, New Orleans, LA, October 1989. Published as SIGPLAN Notices 24(10), October 1989. Also published in Lisp and Symbolic Computation 4(3), Kluwer Academic Publishers, June 1991.

[Duetsch84]

Deutsch, L. Peter and Alan Schiffman, "Efficient Implementation of the Smalltalk-80 System." Proceedings of the 11th Symposium on the Principles of Programming Languages, Salt Lake City, UT, 1984

[Goldberg83]

Goldberg, Adele and David Robson, "Smalltalk-80: The Language and its Implementation", Addison Wesley.