

# JRes: A Resource Accounting Interface for Java

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## Abstract

In order to better support the Internet the computing model on server systems is undergoing several important changes. First, recent research ideas concerning dynamic operating system extensibility are finding their way into the commercial domain, resulting in designs of extensible databases and Web servers. Second, both ordinary users and service providers must deal with untrusted downloadable executable code of unknown origin and intentions. Across the board, Java has emerged as the language of choice for Internet-oriented software. We argue that, in order to realize its full potential in applications dealing with untrusted code, Java needs a flexible resource accounting interface.

The design and prototype implementation of such an interface – JRes - is presented in this paper. The interface allows to account for heap memory, CPU time, and network resources consumed by individual threads or collections of threads. JRes allows limits to be set on resources available to threads and it can invoke callbacks when these limits are exceeded. The JRes prototype described in this paper is implemented on top of standard Java virtual machines and requires only a small amount of native code.

## 1 Introduction

The spreading use of active content on the Internet makes the use of untrusted code a fact of life for connected users as well as for providers of Internet-based services. On the client side, downloadable executable content, like Java applets and Active X technology, serves to increase the attractiveness of Web pages. On the server side, dynamic server extensibility promises full customizability of various tasks, from information retrieval to accessing proprietary databases to dynamically uploading services. These tasks can be accomplished via a concept of *servlets* [14] - untrusted code executed on the server. The programming language Java is currently a premier tool for implementing such uploadable content.

Despite the attention and publicity given to Java, most notably to its security features, there are still areas where Java either cannot be applied or applying the language is cumbersome and requires non-portable native code support. The language has been extended in various ways and its performance has been continuously improving. However, the current definition of Java (version 1.2) does not have an interface for resource management. The application domains that would benefit from providing such an interface as a standard and integral part of the language specification include both well known paradigms, such as application-controlled load balancing and preventing denial-of-service attacks, as well as emerging concepts, such as extensible servers.

Not addressing the issue of resource management may in fact be an adequate decision when designing a “plain” programming language. This is not so in the case of Java, which is both a language and a runtime environment and includes many features of an extensible operating system (a Java-enabled browser is in essence an operating system running applets). Server-side environments running untrusted code are being developed and will inevitably become common [11,14]. The fact that Java provides neither a model nor mechanisms for controlling resource consumption of applications (apart from changing thread priorities) is a problem in all these systems for two reasons: malicious code cannot be prevented from using too many resources and code cannot be charged for the resources it is consuming. Both issues represent a significant obstacle to deploying commercial extensible servers, even though potential revenue generating abilities of such systems appear to be considerable.

Some ad-hoc resource controlling solutions are possible. For example, using native code it is possible to monitor CPU time consumed by each thread. Such approaches tie an otherwise portable Java environment to an underlying operating system, which results in loss of portability and maintenance problems. Enforcing appropriate resource consumption patterns is also possible for applications where one has full control over the sources and can “make the code behave”. However, in the case of untrusted and unknown code, like applets and servlets, no assumptions can be made about resource consumption.

In this paper we propose JRes — a Java interface which allows per-thread accounting of heap memory, CPU time, and the number of bytes sent and received. In addition to tracking resource consumption, applications can be informed when new threads are created. JRes provides mechanisms for setting limits on the resources available to particular threads and associate *overuse callbacks* to be invoked whenever any such resource limit is exceeded. Although the interface is simple, it is flexible enough to support a variety of resource consumption enforcement policies. For instance, a policy which ensures that no thread gets more than 100 milliseconds of CPU time out of every second is easily expressible, as will be shown later. Similarly, a few lines of code suffice to create a policy in which no thread group can send more than 2MB of data, or in which no thread can allocate more than 1MB worth of objects at any given point in the program.

The contribution of this paper is twofold. First, it motivates considering incorporating a resource management interface in the language specification. By describing several applications of JRes we aim at making a convincing argument that future extensions of Java with resource management support should provide at least the functionality included in JRes. The second goal is to demonstrate that even though it was possible to implement JRes in its current form without modifying the underlying JVM, it comes at a price of certain functionality limitations and performance overheads. The lessons learned in the course of developing JRes can be important guidelines in future work on resource management infrastructure for Java, possibly through changing the implementation of JVMs. Although the JRes project is carried out in the context of Java, it is applicable to other languages with features similar to Java. To date we are not aware of any other work providing the functionality of JRes in a general purpose programming language.

The rest of the paper is structured as follows. The next section motivates extending Java with resource management capabilities. Section 3 describes the JRes interface. The implementation and performance of JRes are presented in Section 4. Section 5 contains a discussion of the design and its limitations. Related work is presented in Section 6. The status of the system and planned future directions are discussed in Section 7. The last section summarizes the paper.

## 2 Motivating applications

Several motivating examples are described below in order to clarify why it is crucial that Java (and any other language of similar scope) provide a resource management interface. Such an interface should at least allow the resources consumed by applications (be it applets or servlets) to be monitored and limits on the consumption of particular resources to be enforced.

The first group of applications that can readily benefit from JRes are extensible Web servers, which allow service extensions to be uploaded by clients to the server. Consider image processing services created for profit by an independent developer. An architecture of an extensible Web server makes it possible for the developer to upload the code of the service. This makes the service available to a large group of potential users. Clients access the services either via standard Web browser interface or, in case of more sophisticated or special demands, are able to upload their own code accessing the image-rendering services. A trusted module of this extensible Web server mediates in credit-card purchases of services by clients. Similarly, the service itself has to pay for the computing resources it consumes.

The J-Server, a practical application of the J-Kernel, is an example of a dynamically extensible Web server [11], adequate for implementing such scenarios. Both the system core and the uploaded code execute in a single Java Virtual Machine (JVM). Constructing a server as a single JVM has two considerable advantages. First, the performance of cross-domain calls between the core and extensions is much better than when relying on traditional OS protection mechanisms (e.g. separate processes encapsulating extensions and the core). Second, the security restrictions under which bytecode is run can be finely

controlled and Java provides adequate mechanisms for extensibility and implementing protection domains [11,8].

While the issues of dynamic extensibility and protection are well understood in the context of Java, the lack of support for resource accounting has two serious consequences. First, in a single-address space environment described above, it is difficult to identify servlets that consume too many resources. Malicious servlets can easily mount denial-of-service attacks. Second, one of the main incentives behind attractive, high quality, extensible Internet servers is the revenue they may potentially bring. Lack of support for resource accounting leaves only one alternative for billing users: flat, undifferentiated fees. Although in principle flat rates are not bad, there needs to be several levels of them and a way to force clients to use up only as much resources as purchased.

The second motivating example is the technology of extensible database servers. The functionality of such systems can be augmented by user-defined functions (UDFs) [7]. For example, consider a database of stock market data that is accessible through a Web site. A potential user is any investor with a Web browser, a credit card, and an investment formula `InvestVal`. The following SQL query would then find technology stocks of interest to the user:

```
SELECT *
FROM Stocks S
WHERE S.type = "tech" and InvestVal(S.history) > 5
```

Here, `InvestVal` is a user-defined function. It should be possible (and relatively straightforward) for a large number of such users in a Web environment to create their own UDFs and use them within queries. The motivation for facilitating such database extensions is the next generation of database systems that will be deployed over the Web. In such applications, a large number of physically distributed end-users working on diverse platforms interact with the database through their Web browsers. Because of the large size and diversity of the user community, the utility of UDFs increases. Java is ideally suited for the implementation of such extensible databases because of its security and portability features as long as the resource management concerns are resolved.

Active Networks [4] is yet another example of an extensible environment for which portability and safety features of Java are desirable. The goal of Active Networks is to associate executable content with network packets and execute such programs on hosts and routers of the Internet. This can result in easier management of networks. However, using Java-based environments as an infrastructure for implementing Active Networks is possible only when the programs are trusted because malicious network programs can simply consume enough resources to halt routers, for instance. Extending Java with resource management facilities is very desirable in this context.

A standardized resource management interface has obvious benefits. Portable "Pure Java" programs can be deployed that take advantage of well-known programming techniques previously solved mostly in ad-hoc ways and with the help of non-portable and unsafe native code. Examples include load balancing of distributed applications, gathering execution statistics, and reflective system profiling.

The final motivation for JRes is preventing denial-of-service attacks aimed at Web browsers. An applet is mounting a denial-of-service attack when it is consuming excessive amounts of resources and thereby prevents other applications on the local host from performing as expected. In severe cases, a hostile applet can completely take over a particular resource and crash other applications as well as prevent new applications from being started. It is important to point out that applets may hog resources not only because of malicious intentions, but also because of programming errors. Even though denial-of-service attacks are classified as proper (although not severe) security attacks, to date this issue has not been addressed by Java implementations.

### 3 The proposed interface

The purpose of JRes is to add resource accounting and limiting facilities to Java. The main motivation is the creation of portable and extensible Web environments. This motivation is reflected in the design of JRes. One part of the interface is accessible to both trusted and untrusted code; this part of JRes allows

extensions to learn about resource limits and usage. The purpose of the other part of JRes is to manage and enforce resource limits and is designed to be used by privileged system modules only.

Through JRes, the trusted core of Java-based environments can (i) be informed of all new thread creations, (ii) state an upper limit on memory used by all live objects allocated by a particular thread, (iii) limit how many bytes of data a thread can send and receive, (iv) limit how much CPU time a thread can consume, and (v) register *overuse callbacks*, that is, actions to be executed whenever any of the limits is exceeded.

The interface is presented in Figure 1. Despite the fact that the interface is simple, it is flexible enough to build rather complex and diverse resource management policies, involving resource limits for arbitrarily defined collections of threads and imposing periodic limits on resources.

The `Resources` class defines constants identifying resources and exports six public methods. The first one, `initialize(cookie)`, handles an authenticating object (a *cookie*; it can be any object) to the resource accounting subsystem. The purpose of this method is twofold. First, it ensures that only one party can manipulate resource management. This is analogous to Java's requirement that at most one security manager is installed in the system. Second, it prevents untrusted code from interfering with the resource management policies of a given system. For instance, a browser will call `initialize(cookie)`, before any applets are loaded. Since applets cannot get hold of `cookie`, they cannot allocate themselves more resources than granted.

The next method, `setThreadRegistrationCallback(cookie, tCallback)`, hands an object implementing the `ThreadRegistrationCallback` interface to the resource management subsystem. The effect of this operation is that whenever a new Java thread `t` is created, `tCallback.threadRegistrationNotification(t)` will be invoked. This callback is meant to work in conjunction with the method `setLimits(cookie, resType, t, limit, oCallback)` which can be invoked each time a new thread creation is detected and has the effect of

```
public interface ThreadRegistrationCallback {
    public void threadRegistrationNotification(Thread t);
}

public interface OveruseCallback {
    public void resourceUseExceeded(int resType, Thread t, int resValue);
}

public final class Resources {

    public static final int RES_CPU;
    public static final int RES_MEM;
    public static final int RES_NET_RECV;
    public static final int RES_NET_SEND;

    public static boolean initialize(Object cookie);
    public static boolean setThreadRegistrationCallback(Object cookie,
        ThreadRegistrationCallback callback);

    public static boolean setLimits(Object cookie, int resType,
        Thread t, long limit, OveruseCallback c);
    public static boolean clearLimits(Object cookie, int resType, Thread t);

    public static long getResourceUsage(int resType, Thread t);
    public static long getResourceLimit(int resType, Thread t);
}
```

Figure 1. The JRes interface.

setting a limit of `limit` units of a resource `resType` for a thread `t`. Whenever this limit is exceeded, the method `resourceUseExceeded(resType, t, resValue)` will be invoked on the object `oCallback` (note that `oCallback` must implement the `OveruseCallback` interface). The parameter `resValue` passed to the callback provides information about current resource consumption.

The method `getResourceUsage(resType, t)` queries the resource management subsystem about resource usage of a particular thread `t` and `getResourceLimit(resType, t)` can be used to query resource limits. No authentication is necessary in order to invoke “get” methods, which makes it possible for untrusted code to monitor its resource consumption and limits.

The values in which resource limits are expressed and usage values are reported are as follows: memory and network are expressed in bytes and CPU time in milliseconds. As will be explained later, the current implementation of `JRes` allows for exact *pre-accounting* for memory and network resources — that is, an overuse callback is generated before a thread can execute an action leading to exceeding a limit. This is especially desirable when dealing with memory, since once it is allocated it cannot be reclaimed unless the offending thread is killed and there are no other references to the new objects. Enforcing CPU limits is done by a periodic polling thread, which results in a certain small and configurable delay in “reaction time”.

### 3.1 Example use of `JRes`

Figure 2 shows two classes taking advantage of the proposed interface. The code is meant as a resource management module of an extensible server. After being initialized, the code is informed of every thread creation and sets resource limits for newly created threads. In case any limit is exceeded, the code is informed of this and acts according to the particular policy of this server. The policy is as follows: a thread cannot have more than 3MB of memory allocated at any given point of time, it can use only 300 ms of CPU time and can send at most 200 KB of data. No limits are imposed on the amount of data a thread can receive.

The first four lines of `main()` install a custom resource management policy. Specifically, an object of type `CustomResourceMgmt` is registered with the resource management subsystem. This object will be receiving both the upcalls generated by new thread creations, handled by the method `threadRegistrationNotification()` and the upcalls caused by exceeding resource limits, handled by the method `resourceUseExceeded()`.

If any thread exceeds heap memory limits (first `case` statement) a procedure is invoked to terminate the offending thread in an application-specific way. If any thread exceeds the limit on the amount of data sent (last `case` statement), a note is being made of the excess, possibly for later decisions concerning system expansion, as well as charging the offending thread’s group. This demonstrates how thread groups that collections of threads can be held accountable in an aggregate way for the resources they consume.

`JRes` can be used to implement periodic limits on resources, as demonstrated in handling exceeding a limit on CPU (second `case` statement). The intention of the code is to detect threads that consume more than 300 milliseconds of CPU time during one second periods. Each time a thread exceeds its current CPU time limit, the check is made over what period it happened. If the thread received more than 300 milliseconds of CPU time during a second of a wall-clock time this information is recorded. Regardless of the outcome of the check, the new limit is set, equal to the current usage plus 300. This effectively implements the policy that every thread that receives more than 300 milliseconds of CPU time during a second of a wall-clock time is detected and recorded.

In this particular extensible server, some threads may implement an interface `EarlyWarning`. If the CPU limit has been exceeded by a such thread, the `exceeded()` method of this interface is invoked and the thread is informed of the fact. By setting the limits to slightly lower values than the actual limits, this simple example can be extended to warning threads when they are within, for instance, 5% of exceeding the limit.

## 4 JRes Implementation

This section contains a discussion of specific implementation issues and decisions as well as performance data. CPU accounting and accounting for memory used by allocated arrays requires native code support, that is, a set of six routines written in C and called from within a Java program as native methods. All

```
public class ExampleOfResourceMgmt {

    public static void main(String[] args) {
        // initialization
        Object cookie = new Object();
        Resources.initialize(cookie);
        CustomResourceMgmt rmgmt = new CustomResourceMgmt(cookie);
        Resources.setThreadRegistrationCallback(cookie, rmgmt);
        // Start the proper computation ...
    }

    class CustomResourceMgmt
        implements ThreadRegistrationCallback, OveruseCallback {

        private Object ck;
        CustomResourceManagementClass(Object cookie) { ck = cookie; }

        // Invoked by JRes whenever a new thread is created.
        public void threadRegistrationNotification(Thread t) {
            Resources.setLimits(ck, Resources.RES_MEM, t, 3000, this);
            Resources.setLimits(ck, Resources.RES_CPU, t, 300, this);
            Resources.setLimits(ck, Resources.RES_NET_SEND, t, 200000, this);
        }

        // Invoked by JRes whenever a resource limit has been exceeded.
        // The terminateThread(), intervalSinceLastCPUOveruseCallback()
        // chargeThreadGroup() and log() functions are not defined here.
        public void resourceUseExceeded(int resType, Thread t, long value) {
            switch (resType) {

                case Resources.RES_MEM:
                    // Application specific thread termination, not defined here.
                    terminateThread(t);
                    break;

                case Resources.RES_CPU:
                    if (1000 > intervalSinceLastCPUOveruseCallback(t)) {
                        if (t implements EarlyWarning) { // Thread can be informed.
                            ((EarlyWarning) t).exceeded(resType, value);
                        }
                        log(t + " has exceeded CPU limit: " + value);
                    }
                    Resources.setLimits(cookie, resType, t, value + 300, this);
                    break;

                case ResourceLimits.RES_NET_SEND:
                    log("Need more bandwidth.");
                    chargeThreadGroup(t.getThreadGroup(), Resources.RES_NET_SEND);
                    Resources.clearLimits(cookie, resType, t);
                    break;

            }
        }
    }
}
```

Figure 2. Example resource accounting and limit enforcing with JRes.

other features of JRes are accomplished through bytecode rewriting, that is, inserting appropriate bytecode instructions at selected places in original classes in order to maintain information about resource consumption.

The experimental setup, to which some implementation details and all performance results refer, consists of a 300 MHz Pentium II PC with 128 MB of RAM. Microsoft's Visual J++ version 1.1 was used, with the Java SDK 2.0.

#### **4.1 Rewriting Java bytecode for JRes**

Java is an ideal environment for load-time code transformations, a powerful tool in which details of class implementations are changed. Java has a number of properties which assist load-time transformation: (i) classes retain enough symbolic information to enable members to be inserted or renamed, (ii) the JVM is a stack machine, which allows simple code fragments to be inserted into methods, and most importantly, (iii) the JVM uses a user-extensible class loader to locate and add new classes on demand. The class loader's method `loadClass()` is called by the JVM whenever it encounters a reference to a class not yet loaded. Typical class loaders implement `loadClass()` by searching for the class file (possibly over the network) and then calling `defineClass()`, which converts an array of bytes into an instance of `java.lang.Class`. This instance of `Class` is verified to ensure that the class is semantically valid and that all operations are used with appropriate types before is ready for execution.

In JRes, classes can be either rewritten during class loading or off-line, which avoids runtime performance overheads. On-line bytecode rewriting occurs in `loadClass()` before calling `defineClass()`. After the rewriting is complete, the resulting byte array is passed to an invocation of `defineClass()` and the resulting `Class` object is passed to the JVM, just as if it were the original code. The JVM core does not even know that any changes were made. The current implementation of JRes uses a bytecode rewriting tool developed in the J-Kernel project [11].

#### **4.2 Thread registration**

The goal of thread registration is to store information about all threads that are or were active in the system. The module responsible for maintaining this information is contacted whenever a user program sets or clears a resource limit of a particular thread and whenever new resource consumption information becomes available. Another responsibility of the thread registration module is to generate upcalls for newly created threads. This happens if such upcalls have been registered by `Resources.setThreadRegistrationCallback()`.

Thread registration is accomplished via injecting a few bytecode instructions at the end of one of the initializing methods of the class `java.lang.Thread`. The goal of these instructions is to replace a reference to a `Runnable` object (procedure to be executed by this thread) by a reference to a JRes object. When the thread is started, it will invoke the `run()` method of the JRes object, which in turn will register the thread before invoking the `run()` method of the original `Runnable` object.

#### **4.3 Accounting for network resources**

JRes tracks the amount of data transferred by a thread. Implementing this was relatively straightforward. There are only a handful of native methods in classes belonging the `java.net` package which can access the network directly. The methods are either private or protected and are located in non-public classes. This means that they cannot be called by any code outside of `java.net`. Thus, the only action necessary to account for network usage was to rewrite the `java.net` package. The rewriting ensures that whenever one of these native methods is called, an appropriate information is recorded and an upcall informing of exceeding resource limits is generated, if necessary.

A simple ping-pong program was run between two computers connected by Fast Ethernet in order to estimate the overhead of JRes-instrumented bytecode. The round-trip time increased by a fraction of one percent (for messages larger than 50 KB) to 4.5% (for very small message sizes). This result is encouraging and made us resign from further experimenting with an alternative approach to tracking network usage, such as a native code on top of sockets layer.

## 4.4 Accounting for CPU time

In the current implementation of JRes, CPU time is accounted for through a mixture of bytecode rewriting and native code. During thread registration a native code routine is invoked in order to create an operating-system level handle to the new thread. This handle is used later to query the system for information on the CPU time usage by the thread.

As a part of the CPU accounting module startup, a new thread is created. This thread wakes up periodically and, using the stored thread handles, queries the operating system for CPU consumption. When necessary, appropriate overuse callbacks are generated. Except for the overhead of waking up the polling thread and querying the OS, there are no other runtime overheads.

In principle, gauging per-thread consumption of CPU time can be accomplished via bytecode rewriting. Inserting appropriate instructions at well-chosen points of methods can result in statistical information on per-thread CPU usage. We did not experiment with this approach, because the resulting execution time seems to be prohibitive when a reasonable degree of accuracy is to be achieved.

## 4.5 Accounting for heap memory

The goal of memory accounting is to know, at any point of program's execution, how much memory is used by objects belonging to every thread. This is accomplished by bytecode rewriting. Constructors of non-array objects are modified to record information about the allocating thread and finalizers are either modified or generated so that JRes can detect when the garbage collector frees an object. The code of every method is changed such that appropriate bytecode is inserted whenever an object allocating instruction occurs in the original method code. When an object (array or non-array) is allocated, a method invocation is inserted just before the allocating instruction. The method will increment a counter by the new object's size and verify that the memory limit has not been exceeded. If the limit is exceeded, the overuse callback is invoked.

When an array allocation instruction is encountered, code computing the number of entries in the array is inserted into the original bytecode. Computing the number of entries takes advantage of the fact that at runtime, just before an array is allocated, the size of every dimension is stored on top of the operand stack. In the case of multidimensional arrays these stack entries must be multiplied out.

In order to detect array deallocation a *weak pointer* to the newly allocated array is obtained after allocation. Weak pointers are available in Java native code interfaces to reference objects that are moved by the garbage collector without preventing deallocation. If the referenced object is deallocated, the weak pointer is changed to null. JRes stores weak pointers to all arrays allocated by a thread in a per-thread vector. Whenever an object allocation causes a thread to exceed its memory limit, an appropriate list of weak pointers is scanned and sizes of all recently garbage-collected arrays are subtracted from the memory usage counter.

### 4.5.1 Performance of JRes memory accounting

Four diverse, substantial Java applications were run in order to evaluate the overheads of JRes memory accounting. The test suite consists of (i) running JavaCC, a parser generator from SunTest [23], on a C++ grammar; (ii) executing a set of sorting and list manipulating functions in a Lisp interpreter [13]; (iii) running the embedded version of Caffeine Mark suite of tests [20]; and (iv) serving a set of Web pages with the Jigsaw Web server [15]. Classes of all the benchmarks programs were rewritten off-line for memory accounting. Memory limits were set to values that were never exceeded; thus, no overuse callbacks were invoked.

Figure 3 shows the overheads caused by JRes as a percentage of the total execution time of rewritten programs. This percentage is split up into three components. The first component reports the overhead of invoking empty finalizers on objects of modified classes and the increase in the duration of garbage collection. Since most Java objects do not have finalizers, garbage collectors optimize for that; however, in JRes-modified programs every non-array object has a finalizer. The second component is the overhead of accounting for memory usage, i.e. the cost of executing JRes routines maintaining memory usage statistics. The last component reports the overhead of checking for resource limits. The total overheads caused by the memory accounting subsystem of JRes do not exceed 18% on any of the benchmarks.

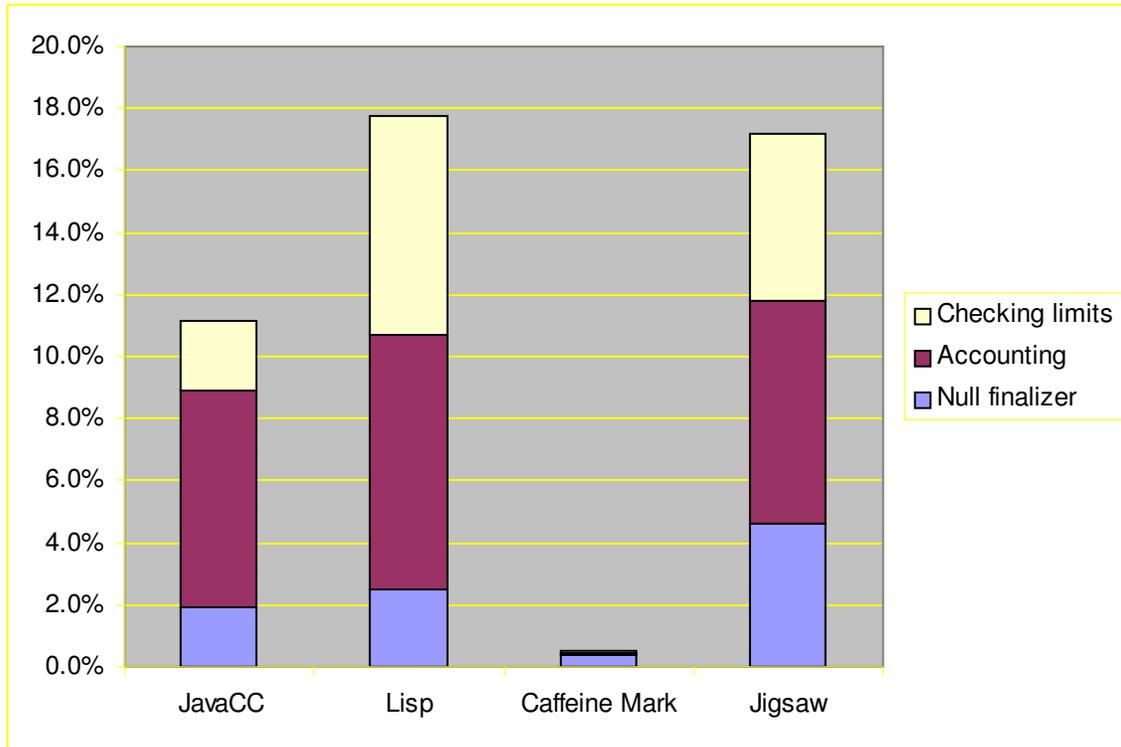


Figure 3. Overheads of JRes memory accounting.

The left side of Table 1 provides several run-time statistics of the benchmarks which help understand the results from Figure 3. As might be expected, the number of objects has a direct impact on the cost of memory accounting. Lisp and Jigsaw allocate an object roughly every 250 bytecode instructions and they suffer the highest overheads. Across all four programs arrays are allocated much less frequently than non-array objects, which indicates that future JRes optimizations should be targeted towards improving the handling of the latter. The overhead caused by introducing finalizers is the smallest one.

Program	Runtime statistics			Compile-time statistics				
	Bytecode instructions	Object creations	Array creations	Bytecode instructions	Object creations	Array creations	Classes	Rewrite time (s)
JavaCC	134763243	85750	10749	154113	1885	193	62	15.3
Lisp	73620868	288842	0	5429	155	0	40	2.5
Caffeine	14108912	1011	10	1801	38	5	13	0.6
Jigsaw	1830860	6775	1079	30919	598	98	47	1.9

Table 1. Runtime and compile-time statistics of the benchmark programs.

Compile-time statistics (right-hand side of Table 1) provide information on bytecode-rewriting costs. The *Classes* column reports the number of classes actually used in the particular run of the program, i.e. not all of the classes in a given program. With our current rewriting system, the costs of rewriting classes are substantial (last column in Table 1), even on the programs that contain very few object allocation instructions. It is not clear what the overheads of other bytecode rewriting systems [5,16] are. In the environments JRes is primarily aimed at, it may be necessary to rewrite classes on-the-fly - for instance, in extensible Web servers. Thus, rewriting will enter the critical path between the remote client issuing the request and obtaining the results. Fortunately typically extensions are small. For instance, it took about 2.4 seconds to rewrite *all* 134 example applet classes from the JDK 1.1.1 distribution. The average size of these classes is 350 bytecode instructions.

## 5 Discussion

The resource accounting interface presented in this paper significantly enhances the functionality of dynamically extensible Internet-oriented environments that subsume the functionality of an operating system for uploaded extensions. JRes enables the construction of such environments with the capability of tracking resource usage of extensions. The interface is small, simple, and allows to build complex policies on top of it.

JRes can be used to control access to other kinds of resources, beyond CPU, heap memory and the network. For instance, thread creation callbacks can impose limits on the number of threads a particular thread group (and its child thread groups) can create. Although not included in the standard interface of JRes, the system can be extended to limit the number of objects of a certain type alive in the system at any given point of time. For instance, the number of windows opened by applets or the number of JDBC queries created by user defined functions in an extensible database can be controlled in this way.

JRes has several limitations. The most severe one is that the actions taken because of exceeding a resource limit are restricted to what Java allows. For instance, it is possible to lower a thread's priority but it is impossible to change the thread scheduling algorithm. Having full control over the scheduler would allow us to provide resource guarantees as well, in addition to enforcing resource limits as JRes currently does. Performance overheads of memory accounting are directly linked to the fact that JRes is not part of the JVM. For instance, being able to tap into the memory allocator and garbage collector would make it unnecessary to rewrite bytecode, which would certainly cut the overheads dramatically. The decision not to modify the JVM was dictated by two reasons. First, JRes is now a Java library with a small native component, and as such can be easily ported to most virtual machines. Second, not tying JRes into a JVM implementation allows for fast experimentation with various ideas. Ultimately, however, we would like to incorporate the functionality of JRes into an industry-strength JVM.

The most serious limitation of JRes is that it does not handle the sharing of objects by threads well. Consider a scenario in which a thread A creates a large object O and hands it off to a thread B. Thread A exits but O cannot be garbage collected and is not counted into B's memory consumption. This problem can be avoided in situations where it is possible to identify cooperating threads and ensure that no data is shared between such groups of threads. In fact, this constraint is not as severe as it may appear. For instance, applet security rules ensure that applets cannot access threads in other thread groups. Another example of architecture where it is easy to define and identify collections of cooperating threads is the J-Kernel [11]. An important decision made in the J-Kernel design was to disallow object sharing between protection domains. Similar designs can be expected in future designs of extensible Java-based environments.

## 6 Related Work

JRes is related to several research areas: resource accounting and enforcing resource limits in traditional and extensible operating systems, safe language technologies, and binary code transformations. In this section we summarize the most important work from these areas influencing our research.

## 6.1 Operating Systems

Enforcing resource limits has long been a responsibility of operating systems. For instance, many UNIX shells export the `limit` command, which sets resource limitations for the current shell and its child processes. Among others, available CPU time and maximum sizes of data segment, stack segment, and virtual memory can be set. Enforcing resource limits in traditional operating systems is coarse-grained in that the unit of control is an entire process. The enforcement relies on kernel-controlled process scheduling and hardware support for detecting memory overuse.

Single address space operating systems take advantage of the radical address space increase available to operating systems and applications with the appearance of 64-bit architectures. An early example of a 64-bit operating system is Opal [3]. Opal provides coarse-grained allocation and reclamation of resources (a set of memory pages, for instance), similar to that used in conventional operating systems. The basic storage management mechanism is explicit reference counting, which applications and support facilities use to allocate and release untyped storage in coarse units. A mechanism of *resource groups* is provided as the basis for a resource control policy, e.g. quotas or billing, to encourage or require users and their applications to limit resource consumption. Each time an application wants to obtain rights to use a particular resource, it has to pass its own resource group capability as a hidden argument on system calls.

Another example of a single-address-space operating system is Mungi [12]. An interesting feature of that system is that it uses an economics-based model to manage backing store management. Applications obtain “bank” accounts from which “rent” is collected for the storage occupied by objects. Rent automatically increases as available storage runs low, forcing users to release unneeded storage. Bank accounts receive regular “income”. In addition, a “taxation system” is used to prevent the excessive buildup of funds by inactive applications.

The architecture of the SPIN extensible operating system allows applications to safely change the operating system’s interface and implementation [2]. SPIN and its extensions are written in Modula-3 and rely on a certifying compiler to guarantee the safety of extensions. The CPU consumption of untrusted extensions can be limited by introducing a time-out. Another example of an extensible operating system concerned with constraining resources consumed by extensions is the VINO kernel [21]. VINO uses software fault isolation as its safety mechanism and a lightweight transaction system to cope with resource hoarding. Timeouts are associated with time-constrained resources. If an extension holds such a resource for too long, it is terminated. The transactional support is used to restore the system to a consistent state after aborting an extension.

The main objective of extensible operating systems is to allow new services to be added to the kernel and for core services to be modified. Their built-in and “hard-coded” support for resource management is adequate for an operating system. In contrast, the main motivation behind JRes is building extensible, safe and efficient Internet environments implemented entirely in a safe language, such as Java. An extension may be an entire application and various billing, accounting and enforcing policies may have to be effective at the same time.

## 6.2 Programming Language Approaches

Except for the ability to manipulate thread priorities and invoke garbage collection, Java programmers are not given any interface to control resource usage of programs. Several extensions to Java attempt to alleviate this problem, but none of them shares the goals of JRes. For instance, the Java Web Server [14] provides an administrator interface which allows to view resource usage in a coarse-grained manner, e.g. the number of running threads can be displayed. PERC (a real-time implementation of Java) [19] provides an API for obtaining guaranteed execution time and assuring resource availability. While the goal of real-time systems is to ensure that applications obtain *at least* as many resources as necessary, the goal of JRes is to ensure that programs do not exceed their resource limits.

A very recent specialized programming language PLAN [10] aims at providing infrastructure for programming Active Networks. PLAN is a strictly functional language based on a dialect of ML. The programs replace packet headers (which are viewed as ‘dumb’ programs) and are executed on Internet hosts and routers. In order to protect network availability PLAN programs must use a bounded amount of space and time on active routers and bandwidth in the network. This is enforced by the language runtime

system. JRes is similar to PLAN in that it limits resources consumed by programs. The main difference is that PLAN pre-computes resources available to programs based on the length of the program. The claim is that resources for an Active Networks program associated with a packet should be bounded by a linear function of the size of the packet's header.

Another approach to constraining resource consumption uses the ideas underlying Proof Carrying Code (PCC) [18]. PCC associates a proof of certain safety properties with a program. The program may contain some runtime checks necessary to allow a proof to be generated (for instance, a proof that no array access exceeds array bounds). After downloading, the proof is verified against the program, which is executed only if the verification is successful. In principle, proofs can be constructed guaranteeing that no more than a certain amount of memory will be allocated or that no more than a specified number of instructions will be executed. However, the feasibility of this approach is still unknown. Currently the size of such resource-constraining proofs exceeds the size of the original code by an order of magnitude. This is a serious problem in extensible Web environments since upload time is on the time-critical path.

The power of Java bytecode transformation has been recognized by other research groups recently. For instance, several recent projects rely on bytecode rewriting to provide increased levels of security [11,24]. Publications on BIT [16] and JOIE [5] utilities contain a detailed list of issues that need to be solved when designing such bytecode rewriting tools. Overheads reported in [16] are an evidence that Java bytecode rewriting is extremely performance sensitive.

## 7 Current Status and Future Work

The system described in this paper is operational and consists of two packages and one native library. Currently it requires Microsoft's JVM but we are porting it to Sun's JDK as well. The design and implementation of JRes demonstrate that many interesting and useful resource management functions can be added to Java without modifying the JVM. We are working on incorporating JRes into the Jaguar extensible database [7] and the J-Kernel [11]. JRes may be extended with several calls facilitating setting resource limits for thread collections. The current version allows for setting per-thread limits; collective limits on thread groups are implemented by adjusting individual threads' limits, which may be cumbersome in some cases.

JRes has been used to alleviate the problem of denial-of-service attacks targeted at browsers. The interface provides enough infrastructure to define a simple policy preventing applets from using more heap memory, CPU time and network resources than a user specifies in a configuration file. As a practical demonstration of usefulness of JRes, the classes implementing JRes and the class implementing the resource consumption policy were added to the core classes of JVM executing inside Microsoft Internet Explorer. It resulted in an enhanced browser in which applets are prevented from mounting denial-of-service attacks through monopolizing the use of any of the three mentioned resources.

In addition to being an enabling technology for a class of software systems, JRes is being used to understand resource management for an emerging model of Internet computing. The main characteristics of this model are high code mobility and large numbers of anonymous users, which result in different kind of resource demands made by applications than in traditional operating system environments. Efficient use of distributed computational resources becomes a must if the model is to be useful. JRes provides an experimental infrastructure to research these issues.

## 8 Summary

This paper presents JRes — an interface extending Java with resource accounting and limiting capabilities. The main motivation behind JRes is facilitating the creation of extensible Internet environments, onto which untrusted code can be uploaded. Currently Java lacks resource management support, which is a severe shortcoming when building such environments. JRes addresses this problem with a small interface that is flexible enough to allow complex resource management policies to be built. The implementation uses a combination of bytecode rewriting and native code to add resource management to off-the-shelf Java virtual machines. The performance overheads are small in the case of accounting for CPU time and

network resources. On a set of four substantial Java applications memory accounting resulted in overheads between 0.5-18%.

The current implementation of JRes did not require modifications of the Java Virtual Machine. The discussion of the usefulness of the interface and its limitations and sources of performance overheads presented in this paper can be important when adding a functionality of JRes to an industry-strength implementation of the JVM.

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