A System Supporting High-Performance Communication and I/O in Java

by

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Abstract

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Implementing efficient communication and I/O mechanisms in Java requires both fast access to low-level system resources (such as network and raw disk interfaces) and direct manipulation of memory regions external to the Java heap (such as communication and I/O buffers). Java native methods are typically too expensive to perform these operations and raise serious protection concerns. We present *Jaguar*, a new mechanism that provides Java applications with efficient access to system resources while retaining the protection of the Java environment. This is accomplished through compile-time translation of certain Java bytecodes to inlined machine code segments.

We demonstrate the use of Jaguar through a Java interface to the VIA communications layer that achieves nearly identical performance to that of C, and *Pre-Serialized Objects*, a mechanism that greatly reduces the cost of Java object serialization. In addition, we present *Tigris*, a cluster-based I/O system which allows applications to automatically balance resource consumption across cluster nodes and achieve high performance even in the face of resource perturbations. To show the feasibility of building high-performance cluster applications in Java, we present performance results for *TigrisSort*, a parallel, disk-to-disk sorting benchmark which rivals that of previous systems built in C and C++.

‘Thank God I am not a genius —

for a genius has nobody in whom he can confide.’

Lawrence Durrell

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1 Introduction

The Java programming environment [11] has made significant headway in support of a wide array of application areas, including mobile agent systems [27], distributed programming models [24], enterprise-wide information processing [21], and scientific and numerical computing [28]. As Java's popularity grows, so will the demands placed upon it to support even more diverse computing platforms, from embedded systems [25] to workstation clusters [34]. If we wish to bring Java to bear on large problems, it seems natural that Java should take advantage of the resources of large-scale servers, including multiprocessors, high-speed networks, and fast I/O.

A great deal of previous work has addressed problems with Java processor performance, namely, efficiency of compiled code, thread synchronization, and garbage collection algorithms [22, 26]. Java compilers, including both static and "just-in-time" (JIT) compilers, are now capable of generating code which rivals lower-level languages such as C++ in performance [18]. However, in a large server environment, high-performance communication and I/O play a dominant role. These aspects of Java performance remain largely unaddressed.

Implementing efficient communication and I/O generally requires the application to invoke operating system calls, perform direct manipulation of memory (e.g., use pointers) to access memory-mapped I/O and network devices, and so forth. Unfortunately, these operations are inexpressible as machine-independent Java bytecodes. Rather than exposing low-level (and hence unsafe) machine operations directly to the Java application, it is desirable to abstract away the *access mechanisms* required for communication and I/O as a Java object replete with type-safe methods and fields. Operations on these Java objects should translate into efficient and direct (as much as possible) access to the low-level machine resources they represent, while retaining the protection of the Java environment.

Java provides so-called "native methods" which enable code implemented in another language (such as C) to be invoked from Java. This is typically used to abstract O/S calls and other functions as Java classes. However, native methods incur a high overhead, requiring that data be copied between Java and native code; in addition, implementing native methods in a low-level language is error-prone and potentially negates the safety guarantees of the Java sandbox. Considering these performance and safety limitations, we believe native methods are ill-suited to enable high-performance communication and I/O in Java.

We present an alternate approach, *Jaguar*,[1] which enables direct, protected access to system resources represented as Java objects. This is accomplished through compile-time code transformation which maps certain Java bytecodes to short, inlined machine code segments. This approach retains the type-safety and protection of the Java environment while allowing applications to directly leverage server resources such as memory-mapped network interfaces, raw disk I/O, and so forth. We demonstrate Jaguar through two examples: *JaguarVIA*, a Java binding to the VIA [29] fast communications substrate, and *Pre-Serialized Objects*, a mechanism which greatly reduces the cost of rendering Java objects in an externalized form for communication or I/O.

In addition, we present *Tigris*, a cluster-based I/O system implemented in Java using Jaguar facilities for fast communication and I/O. Tigris employs a dataflow programming model allowing cluster resources to be automatically balanced across an application, resulting in high performance even in the presence of resource perturbations. We believe that the approach taken in Jaguar is general enough to capture a large range of additional uses.

This thesis makes four major contributions. First, we present a novel approach to enabling efficient and safe utilization of server hardware resources from Java. Second, we present *JaguarVIA*, which obtains the same VIA communications performance as C. Third,

[1] Jaguar is an acronym for *Java Access to Generic Underlying Architectural Resources.*

we present Pre-Serialized Objects, and demonstrate how their use, as enabled by Jaguar, can eliminate the high overhead of Java object serialization. Fourth, we present Tigris, which allows Java-based cluster applications to take full advantage of cluster resources by automatically balancing performance heterogeneity across multiple nodes.

The organization of the rest of this thesis is as follows. Section 2 provides background on the issues faced by Jaguar and related work. Section 3 describes the design and implementation of Jaguar, and Section 4 demonstrates its use through a fast Java binding to VIA. Section 5 describes Pre-Serialized Objects. Section 6 presents the Tigris system, and Section 7 presents *TigrisSort*, a sample Tigris application. Section 8 discusses directions for future work and Section 9 concludes.

2 Motivation and Background

In this section, we motivate the approach taken by Tigris by looking more closely at the problems which it addresses.

A number of performance issues arise when one considers implementing large-scale server applications in Java. These can be roughly divided into two categories: CPU-related issues and I/O-related issues. In terms of the CPU, performance of compiled Java code is the paramount concern, but other factors — including garbage collection and thread synchronization — must be considered as well. Fortunately, a great deal of previous work has investigated this problem domain, for Java [22, 26] as well as other object-oriented languages [5, 8].

Java I/O performance remains largely uninvestigated. A primary goal is to give Java applications efficient access to low-level system resources (such as fast network interfaces, I/O and RAID controllers, and so forth); such access is necessary for implementing high-performance communication and I/O. It is this set of problems which Jaguar intends to solve.

Traditionally, the operating system is responsible for providing applications access to hardware, either through high-level interfaces (such as filesystems and sockets) or lower-level mechanisms (such as raw disk I/O calls). However, in many cases it is desirable to circumvent the operating system to obtain higher performance. In the case of fast networking, user-level network interfaces provide low-overhead communication while allowing multiple processes to safely share the network interface (NI). Applications circumvent the operating system kernel and directly access network interface resources, such as memory-mapped data structures or "protected" NI registers. Doing so eliminates context switch overhead and the cost of copying data between user and kernel space. A large number of of user-level network interface prototypes have demonstrated this principle, such as Active Messages [7] and U-Net [32]; VIA [29] is a recent effort to standardize these interfaces.

A related requirement for communication and I/O is the use of explicitly-managed memory regions. For example, user-level network interfaces often require that communication buffers be pinned to physical memory for direct access by the NI hardware; these pages must be allocated from a special pool or pinned dynamically by the O/S or NI [33]. Memory-mapped files are often used for I/O, and raw disk interfaces usually have special requirements for buffer allocation. However, this requirement runs counter to the existing Java model in which all objects and arrays are allocated from a single heap, managed by the JVM's garbage collector.

2.1 Related Work

Efficient I/O and communication in Java has been investigated through two primary avenues: implementing fast object serialization, and binding fast network interfaces to the Java environment. In terms of serialization, [20] describes an optimized implementation of Java remote method invocation (RMI) which is based on careful coding and a new serialization algorithm, coded entirely in Java. Manta [15] takes the more extreme approach of translating the entire Java application to C, generating specialized per-class serialization code. While this approach moves much of the run-time overhead of communication to compile time, it necessitates a reengineering of the Java run-time, and the resultant environment is arguably something other than “true” Java.

Several projects have attempted to bind fast communication layers into the Java environment through the use of native methods. Native method bindings to MPI [10] and PVM [30] have been described, however, neither of these have considered performance issues with respect to obtaining low latency or high bandwidth. The approach taken by Javia [6] is closest to that in Jaguar. It involves modifications to a static Java compiler to enable efficient bindings to a commercial VIA implementation. In Javia, native methods are used to invoke the C-based VIA library, while communication buffers are exposed to Java through specially-generated code from a modified compiler. While this addresses most of the performance issues with implementing a fast Java VIA interface, the approach does not support efficient access to hardware resources in general.

2.2 Are native methods adequate?

Java native methods can provide access to low-level system functions, albeit at high cost: the overhead of invoking native methods, and transferring data between Java and native code, often outweighs their utility. This is of particular concern for fine-grained operations such as manipulation of network interface data structures. Such operations are performance-critical and should incur as little overhead as possible. Additionally, native code requires that data be copied between specially-managed memory regions (such as network buffers) and the Java heap, again resulting in high overhead.

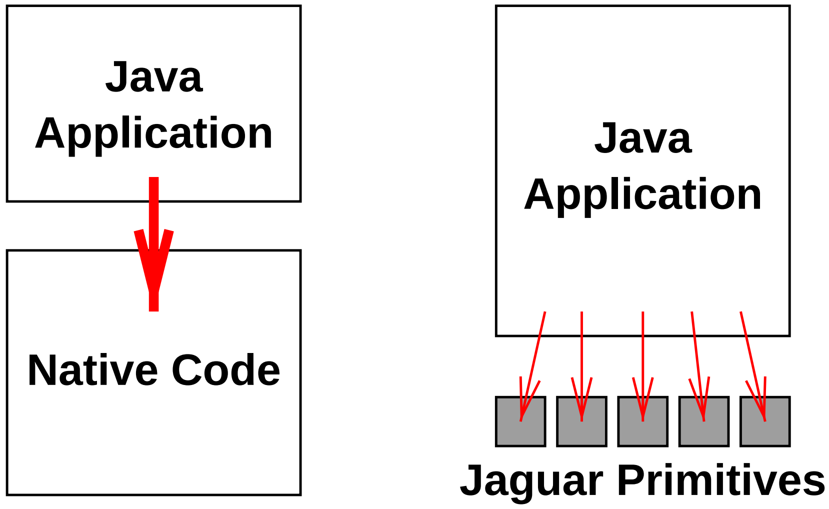
Figure 1 details the overhead of native code invocation from Java. These measurements were performed on a 350 MHz Pentium II running Linux 2.2.5 using Sun JVM 1.1.7. Here, the standard Java Native Interface (JNI) [23] was employed, which abstracts

Benchmark	**JNI**	**C**	**Slowdown**
void arg, void return native method call	.909 μsec	0.038 μsec	23.9
void arg, `int` return native method call	.932 μsec	0.042 μsec	22.2
`int` arg, `int` return native method call	.985 μsec	0.049 μsec	20.1
4-`int` arg, `int` return native method call	1.31 μsec	0.072 μsec	18.2
10-byte C-to-Java array copy	3.0 μsec	0.354 μsec (`memcpy`)	8.47
1024-byte C-to-Java array copy	18.0 μsec	1.68 μsec (`memcpy`)	10.7
102400-byte C-to-Java array copy	1706.0 μsec	432.5 μsec (`memcpy`)	3.94
10-byte Java-to-C array copy	7.0 μsec	0.354 μsec (`memcpy`)	19.8
1024-byte Java-to-C array copy	272.0 μsec	1.68 μsec (`memcpy`)	161.9
102400-byte Java-to-C array copy	27274.0 μsec	432.5 μsec (`memcpy`)	63.1

Figure 1: *A comparison between Java Native Interface and C overheads.*

away details of the JVM structure from native code; the intent is to allow native code to be ported across different JVM architectures. For comparison, similar tests conducted in C are shown; all compiler optimizations were disabled for the C benchmark. As the results show, use of JNI is quite expensive, requiring nearly a microsecond just to perform a native method call and return. More serious is the array-copy overhead which would surely limit the performance of any fast communication or I/O system implemented using native methods.

Regardless of performance, however, native code is a blunt instrument with which to enable low-level operations in Java. Native code must be as trustworthy as the JVM and compiler, yet its power is effectively unlimited: a native method can spin in an infinite loop, access any memory location, and crash the virtual machine. It is up to programmers to exercise proper discipline when implementing native methods, but this discipline cannot be enforced by the system in any way. Likewise, because native code is generally implemented in a low-level language such as C, it is both error-prone and non-portable; it is difficult to convince oneself that a piece of native code will work as advertised. The problem is exacerbated by the fact that native methods must generally do a large amount of work to amortize the cost of their invocation. This concern is a serious one, as it is the robustness



(a) Using Native Code (b) Using Jaguar

Figure 2: *Native code and Jaguar compared.*

of the Java environment which makes the language attractive in the first place.

The Jaguar approach is motivated by the observation that the sort of low-level operations required for enabling high-performance communication and I/O are generally short and easily expressed as a sequence of simple instructions (e.g., accessing a particular memory address, or invoking a system call). This suggests that such operations can be *inlined* into the compiled Java bytecode stream for performance, and that some form of static analysis could be performed to guarantee safety or type-exactness. Such an approach is tantamount to extending the Java runtime with new, safe primitives which perform specialized operations on behalf of an application.

This situation is depicted in Figure 2. Rather than binding a large amount of native code to Java, Jaguar allows the Java runtime to be extended with a set of new, simple primitives. Because use of these primitives is inexpensive, nearly all functionality, including complex system software, can be implemented in Java, leading to more robust applications. The use of Jaguar lends itself to a programming style which uses mostly Java and a small amount of native code, rather than the converse.

3 Jaguar Design and Implementation

Jaguar allows the Java runtime to be extended with new primitive operations which enable efficient access to hardware resources. These primitives are specified as short machine code segments which are directly inlined into the Java bytecode as it is compiled. The fundamental operation of a Java compiler is to translate sequences of Java bytecodes (which manipulate Java objects) into native machine code (which manipulate analogues of those objects on the actual hardware). Jaguar builds upon this concept by introducing an additional set of bytecode-to-machine code translation rules into the compiler, transforming certain bytecode sequences directly to operations on low-level hardware resources.

There are two primary concepts embodied in Jaguar: *code mappings* and *External Objects*.

3.1 Code mappings

Specifying new Java bytecodes to represent low-level machine operations would necessitate modifications to the `javac` bytecode compiler and perhaps to the Java language itself. Rather, we have chosen to apply the concept of *code mappings* which describe transformations from Java bytecode sequences to inlined machine code. In this way, pre-existing bytecodes (say, method calls or field accesses) are translated to specialized operations at compile time. This approach affords a very natural programming model: low-level machine operations are expressed as operations on regular Java objects. Accessing a field or calling a method may transparently trigger an alternative sequence of machine events.

While Jaguar code mappings are similar in nature to native methods, there are two major differences:

- Jaguar code mappings may be applied to virtually any bytecode sequence (such as field accesses, operators, and so forth) while native code is limited to method invocation. As such, Jaguar enables much greater expressiveness: machine resources can be represented by Java objects, with methods, fields, or operators being used as appropriate to describe low-level operations.

- Jaguar primitives consist of short, limited sequences of machine code rather than C functions of arbitrary complexity. This property makes it easier to verify that the implementation of a Jaguar primitive is correct. It also inherently limits Jaguar code mappings to provide basic, low-level operations rather than extensive functionality. In this way, applications can be written almost entirely in Java, aided by a few simple primitives provided by Jaguar.

3.2 External Objects

Jaguar allows Java applications to directly manipulate memory outside of the Java heap, such as specially-allocated buffers for communication and I/O. Jaguar code mappings are used to rewrite field accesses on certain Java objects to directly manipulate this "external" memory; we call the result *External Objects*. External Objects are treated by the application as regular Java objects, the memory storage for which happens to be located outside of the Java heap. This eliminates the expense of copying data between Java and external memory as required by native code.

External Objects have numerous uses. They can be used to map Java object references onto shared-memory segments, memory-mapped files, communication and I/O buffers, and even memory-mapped hardware devices. Because field accesses are processed by Jaguar using knowledge of both field name and type, different behaviors can be implemented for different fields. For example, one field in an object may reference a communication buffer while another references the network interface with which it is associated.

3.3 Implementation

Our prototype of Jaguar is implemented as a Java just-in-time compiler which has been augmented with a set of transformation rules implementing Jaguar code mappings. Each such mapping describes a particular bytecode sequence and a corresponding machine code sequence which should be generated when this bytecode is encountered during compilation. An example of such a mapping might be to transform the bytecode `invokevirtual SomeClass.someMethod()` into a specialized machine code fragment which directly manipulates a hardware resource in some way.

Our prototype JIT compiles Java bytecode to machine code by performing a straightforward translation from each bytecode to a particular machine code template. Jaguar code mappings are implemented by rewriting certain Java bytecodes as Jaguar-specific "meta-bytecodes" during the first pass of the compiler; machine code templates for each such meta-bytecode are provided which implement new Jaguar primitives. For example, the operation `invokevirtual SomeClass.someMethod` might be translated to the meta-bytecode `opc_do_somemethod`, and the machine code template for `opc_do_somemethod` will be inlined into the compiled code sequence during the compiler's second pass.

Jaguar code mappings can be applied to virtually any bytecode sequence; however, they are limited in two fundamental ways:

- The system must have enough information to determine whether the mapping should be applied at compile time. This has an impact on the use of bytecode transformation for virtual methods (see below).

- Recognizing the application of certain mappings is easier than others. For example, mapping a complex sequence of `arrayref` and `add` bytecodes to, say, a fast vector-add instruction would certainly be more difficult than recognizing a method call to a particular object.

In our current prototype, these transformation rules must be compiled into the JIT compiler itself; however, we are currently working on a new implementation (based on the OpenJIT [17] compiler) which allows new code mappings to be specified at runtime. Such an approach presents numerous opportunities for dynamic code specialization beyond the scope of this thesis.

Jaguar runs on the Intel x86 platform under Linux 2.2.5 and Sun JDK 1.1.7.

3.4 Discussion

Apart from the mechanisms employed by Jaguar, by far the most important aspect of this approach is the programming model which it enables. By extending the Java environment with the minimal set of necessary primitives, it is possible to implement complex system software entirely in Java. For example, high-level messaging protocols or disk buffer allocation strategies can be implemented in Java, with only the lowest-level system functions aided by Jaguar code mappings. This helps to ensure the safety and robustness of such system software, and is preferable to wrapping a complex, unwieldy piece of C code up as a set of Java native methods.

Because our prototype specifies code mappings as machine code segments, it is necessary to trust these code mappings as one would trust the compiler or JVM. In some sense, this is more viable than trusting native methods; it is far easier to convince oneself that a short piece of machine code will behave correctly and maintain protection than a complex set of functions coded in C. Using machine code also has the beneficial side-effect that it is difficult for programmers to implement overly complex functionality as a single Jaguar primitive. We are currently investigating the use of a higher-level language in which to represent code mappings, which may allow automatic type-checking and verification.

There is an issue with respect to applying code mappings to virtual method invocations. Normally, the Java runtime resolves virtual method calls at run time, dispatching them to the correct implementation based on the type of the object being invoked. Jaguar currently does not perform any run-time type checks for virtual method code mappings, meaning that an "incorrect" code transformation may be applied to an object if it is cast to one of its superclasses at runtime. While it is feasible to incorporate code transformations into the run-time "jump table" used by the JVM for virtual method resolution, a workaround in the current prototype is to limit transformations to virtual methods which are marked as `private` or `final`, which prohibit overloading. Use of static methods is unproblematic.

Quite similar to Jaguar code mappings is *semantic inlining* [35], a technique which extends the compiler to treat certain operators and method calls as new Java primitives which are inlined. Semantic inlining has been used to implement fast complex arithmetic (by inlining operators on objects of type `Complex`) as well as efficient multidimensional arrays. While the mechanism has much in common with Jaguar, its focus has been on the needs of numerical computing rather than enabling fast communication and I/O. As such, Jaguar raises issues with safely exposing low-level resources to Java applications which semantic inlining alone does not address.

The next two sections evaluate Jaguar through two applications: a fast Java binding to the VIA communications architecture, as well as Pre-Serialized Objects, a mechanism which eliminates Java object serialization overhead for communication and I/O.

4 JaguarVIA

As an example use of Jaguar enabling efficient access to low-level resources, we have implemented *JaguarVIA*, a Java interface to the Berkeley Virtual Interface Architecture (VIA) communications layer [3]. VIA [29] is an emerging standard for user-level network interfaces which enable high-bandwidth and low-latency communication for workstation clusters over both specialized and commodity interconnects. This is accomplished

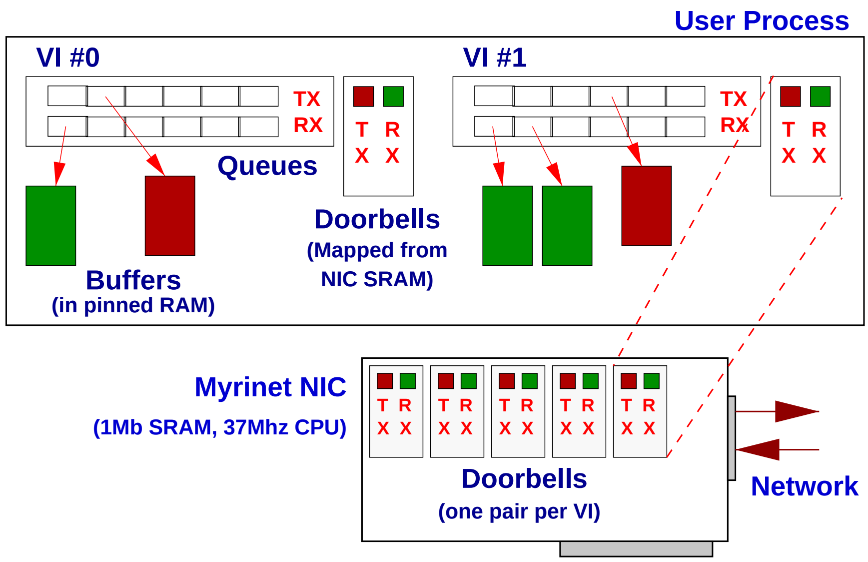


Figure 3: *Berkeley VIA Architecture.*

by eliminating data copies on the critical path and circumventing the operating system for direct access to the network interface hardware; VIA defines a standard API for applications to interact with the network layer. Berkeley VIA is implemented over the Myrinet system area network, which provides raw link speeds of 1.2 Gbps; generally, the effective bandwidth to applications is limited by I/O bus bandwidth. The Myrinet network interface used in Berkeley VIA has a programmable on-board controller, the LanAI, and 1 megabyte of SRAM which is used for program storage and packet staging. The implementation described here employs the PCI Myrinet interface board on dual 450 MHz Pentium II systems running Linux 2.2.5.

4.1 The Berkeley VIA architecture

The Berkeley VIA architecture is shown in Figure 3. Each user process may contain a number of Virtual Interfaces (VIs), each of which corresponds to a peer-to-peer communications link. Each VI has a pair of transmit and receive descriptor queues as well as a transmit and receive *doorbell* corresponding to each queue.

To transmit data, the user builds a descriptor on the appropriate transmit queue, indicating the location and size of the message to send, and “rings” the transmit doorbell by writing a pointer to the new transmit queue entry. In order to receive data, the user pushes a descriptor to a free buffer in host memory onto the receive queue and similarly rings the receive doorbell.

The LanAI processor on the NI is responsible for polling the doorbells and taking appropriate action to transmit or receive data on behalf of the (potentially) multiple user processes sharing the network interface.

Transmit and free packet buffers must be first *registered* with the network interface before they are used; this operation, performed by a kernel system call, pins them to physical memory. The network interface performs virtual-to-physical address translation by consulting page maps in host memory, using an on-board translation lookaside buffer to cache address mappings.

The C API provided by VIA includes routines such as the following:

- `VipPostSend()`, post a buffer on the transmit queue;
- `VipPostRecv()`, post a buffer on the receive queue;
- `VipSendWait()`, wait for a packet to be sent;
- `VipRecvWait()`, wait for a packet to be received;

as well as routines to handle VI setup/teardown, memory registration, and so forth.

4.2 JaguarVIA Implementation

Implementing an efficient Java binding to VIA, then, relies upon two major requirements:

1. The ability to efficiently manipulate VIA doorbells and queues; and

2. The ability to directly access registered VIA data buffers, without a copy.

Exposing the JaguarVIA API to Java could be implemented through the Java native code interface, however, copying data between C and Java is expensive, and the high overhead of native method invocation would dominate the cost of issuing VIA API calls; most of these functions do little more than manipulate a couple of pointers, or write small values to the doorbells. Because CPU overhead can be the dominant factor when considering application sensitivity to network interface performance [16], maintaining minimal host overhead for VIA operations is desirable.

JaguarVIA is implemented using two components: first, a Java library duplicating the functionality of the C-based library which provides the VIA API; and second, a set of Jaguar code mappings which translate low-level operations on VIA descriptor queues, doorbells, and data buffers into fast machine code segments. Thus, the majority of JaguarVIA is implemented in Java itself, and only the barest essentials are handled through Jaguar code transformations.

Let us consider the operation of the `VipPostSend` method, contained in the `VIA_VI` class. Here is the Java source code:

```
public int VipPostSend(VIA_Descr descr) {
  /* Queue management omitted ... */
  while (TxDoorbell.isBusy()) /* spin */;
  TxDoorbell.set(descr);  return VIP_SUCCESS;
}
```

Its essential function is to poll the transmit doorbell until it is ready to be written, and then set its value to point to the transmit descriptor specifying the data to be sent.[2] Here, `TxDoorbell` is a private field in the `VIA_VI` class representing the transmit doorbell for this VI, and `Descr` is an object of the type `VIA_Descr` representing the descriptor-queue entry for the packet to be sent.

[2] Additional code to maintain a linked list of outstanding transmit descriptors has been omitted for space reasons.

```
package Jaguar.JaguarVia;

public class VIA_Doorbell {
  /* Address of doorbell in memory */
  private int vaddr;

  public boolean isBusy() {
    /* No body; implemented by Jaguar */
    return false;
  }

  public void set(VIA_Descr descr) {
    /* No body; implemented by Jaguar */
  }
}
```

Figure 4: *Source code for the* `VIA_Doorbell` *class.*

The layout of the doorbell structure, as mapped from the SRAM of the network interface, is two 32-bit words: the first is a pointer to the transmit descriptor itself, and the second is a *memory handle*, an opaque value which is associated with the registered memory region in which the descriptor is contained. To poll the doorbell it is sufficient to test whether the first word is non-zero. To update the doorbell, both values must be written (first the memory handle, then the descriptor pointer) as virtual addresses in the process address space; however, the Java application has no means by which to generate or use virtual addresses directly. In fact, we wish to prevent the application from specifying an arbitrary address as a transmit or receive descriptor (say), as this would allow the application to access or corrupt any virtual memory address, including memory internal to the JVM.

The Java source code for the `VIA_Doorbell` class is shown in Figure 4. The methods `VIA_Doorbell.isBusy` and `VIA_Doorbell.set` are implemented through Jaguar code mappings. Jaguar recognizes the bytecode sequence `invokevirtual VIA_Doorbell.isBusy` (as well as for `VIA_Doorbell.set`) and inlines machine code which performs the doorbell

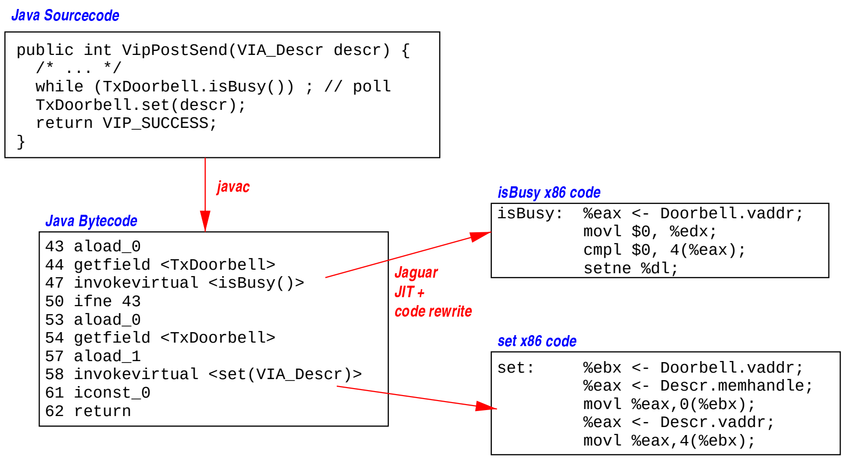


Figure 5: *JaguarVIA Code Transformations.*

polling and write functions, respectively. This process is depicted in Figure 5.

In the case of `isBusy`, the machine code segment simply tests the first word of the doorbell for a non-zero value, and pushes a `true` or `false` value onto the Java stack as appropriate. In the case of `set`, the machine code segment writes the two words of the doorbell in the appropriate order. The address of the doorbell itself (as mapped from the LanAI SRAM) is stored in a private field within the doorbell class, and is extracted from the doorbell object by the generated machine code. Similarly, the address and memory handle of the `VIA_Descriptor` object are stored in private fields of that class. The use of private fields ensures that only trusted code is capable of accessing those values — in this case, constructors which create doorbell and descriptor objects, and the Jaguar code mappings which operate on them.

VIA packet buffers are an example of Jaguar External Objects at work. They are implemented as the class `VIA_Databuffer`, which represents a region of registered virtual memory. The data buffer may be manipulated in a manner similar to a Java array, through the methods `readByte`/`writeByte`, `readInt`/`writeInt`, and so forth. These methods are implemented through Jaguar code mappings which directly manipulate the contents of the

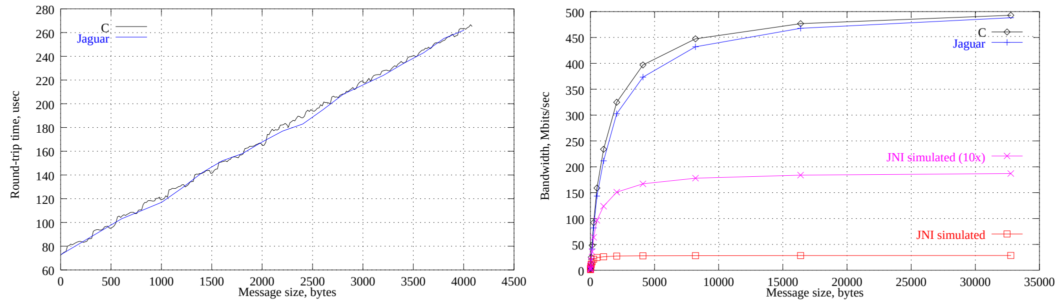


Figure 6: *JaguarVIA performance results. The figure on the left shows round-trip latency as a function of message size for raw VIA, as accessed from C, and JaguarVIA. The figure on the right shows message bandwidth as a function of message size for C-based VIA access, JaguarVIA, and simulated results for accessing VIA through the Java Native Interface.*

buffer in virtual memory. The class contains the private fields `vaddr`, `size`, and `memhandle` which keep track of the buffer's address, size, and VIA memory handle, respectively. A `VIA_Databuffer` is created through a special constructor which allocates a memory region outside of the JVM heap and registers (pins) it through the appropriate system call; this memory is not managed directly by the JVM. The class can also be used as a "container" for Jaguar Pre-Serialized Objects, as described in Section 5.

4.3 JaguarVIA Performance

To demonstrate the efficiency of this approach to mapping VIA resources into Java, we implemented two standard VIA microbenchmarks: `pingpong`, which measures round-trip latency for messages of varying sizes, and `bandwidth`, which measures the bandwidth obtained when streaming packets through the network interfaces at the maximum rate.[3]

The results of these microbenchmarks for C and Java are shown in Figure 6. The Java and C `pingpong` benchmarks obtain identical performance with a minimal round-trip time of 70 microseconds for small messages. `bandwidth` in Java obtains 99% of the

[3]Note that Berkeley VIA itself does not implement flow control or reliable delivery; applications are expected to implement their own protocols over the raw transport mechanisms provided. Therefore, the bandwidth benchmark makes no presumption about the flow-control protocol used, and assumes that data is received as rapidly as it is transmitted.

bandwidth achieved by C, peaking at 488 megabits/sec for 32Kb packets. The lost efficiency is due to higher loop and method-call overheads in Java. More aggressive optimization in the JIT compiler used by Jaguar should be able to overcome these issues.

To highlight the advantage of using Jaguar over the Java native code interface, we have estimated the performance of the `bandwidth` benchmark if the Java Native Interface (JNI) were used to provide VIA functionality in Java. In the estimation, the overhead of using JNI (from Figure 1) was added to the measured per-message cost and the resulting bandwidth recalculated. We assume that each native method call costs 1.0 μsec and that copying data from Java to native code costs 270 μsec per kilobyte. Four native method calls are required per message transmitted. The estimated bandwidth peaks at 28.55 megabits/sec, a factor of 17 smaller than JaguarVIA. Even if the performance of the native interface were a factor of 10 faster than it is currently, the peak bandwidth would be only 187 megabits/sec, far below that obtained with Jaguar.

These results clearly show the performance benefit of the Jaguar approach. VIA communication requires several fine-grained manipulations of NI resources (doorbells and descriptor queues) per message, for which the cost of the native code interface would be prohibitive. Furthermore, the use of Jaguar External Objects provides a thin interface to VIA packet buffers, enabling zero-copy communication.

5 Pre-Serialized Objects

JaguarVIA allows arbitrary sequences of bytes to be transferred over the network, using the `VIA_Databuffer` class to represent a registered communication buffer. The methods on this class treat the buffer as a simple array; however, it is desirable to allow more structured Java objects to be communicated over VIA.

The traditional approach to communicating or storing Java objects is to use Java object serialization, which writes out the state of a set of Java objects as a string of bytes.

```
public class MyObject extends PSO {
  public static int getPSOSize() {
    /* Jaguar redirected */
  }
  /* Fields */
  public int someInt;
  public byte someByte;
  public MyObject someRef;
}
```

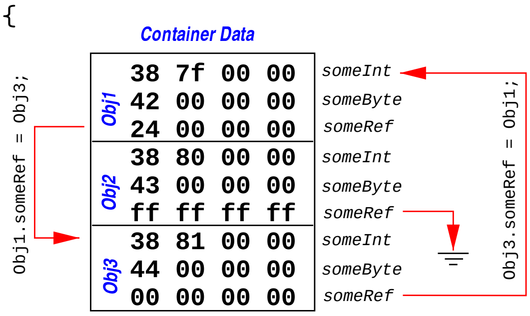


Figure 7: *An example PSO and its memory layout.*

Java objects may be later *recovered* from this string of bytes, meaning that the bytes are retrieved from the disk or network and converted into a set of new Java objects.

Standard implementations of Java serialization are quite costly, although alternatives have been developed [20]. These alternatives, however, rely upon making a copy of the data contained within a Java object and all objects referred to by it. Efficient serialization is the key problem to overcome in implementing high-performance communication and persistence models in Java, such as Remote Method Invocation [15].

A special use of Jaguar code mappings is to implement *Pre-serialized Objects*, or PSOs. Abstractly, a PSO can be thought of a Java object for which the memory representation is already serialized. PSOs eliminate the copy and reference-traversal steps in serialization and de-serialization by requiring that the object be stored in a "pre-packaged" form, ready for storage or communication. Sending the PSO over a communications link, therefore, requires nothing more than directly transmitting the pre-serialized object buffer in memory. On the receiver, the buffer into which data was received need only be pointed to by a new PSO reference.

5.1 PSO Implementation

PSOs are implemented through specialized Jaguar code mappings which recognize `putfield` and `getfield` accesses to the object in question, marshalling object data into and out of its pre-serialized form. Atomic fields (`byte`, `long`, and so forth) are stored using a simple machine-independent representation. The position of each field within the PSO buffer region is determined in a manner similar to that of a C `struct`: each field is stored at a location which maintains alignment constraints on common architectures (for example, that a 32-bit value must be stored on a 32-bit word boundary).

Figure 7 shows code for a simple user-defined PSO type and the memory layout of three such PSOs with references between them.

Object references are handled by requiring that each PSO have an associated *container*, which is a Jaguar External Object acting as the backing store for the object's pre-serialized form. Multiple PSOs may share the same container, and containers can be nested. (The JaguarVIA `VIA_Databuffer` class implements a PSO container, allowing PSOs to be stored within VIA communication buffers.) Each PSO can be thought of as occupying a certain location in its container, with an associated offset and size. The PSO's container and offset are stored as private fields in the PSO itself, and are accessed by the Jaguar code mappings which implement PSOs.

When a reference to another PSO is stored using the `putfield` bytecode, if the two PSOs are within the same container, then the referenced object's offset into that container is stored. Otherwise, a special null value is stored, indicating that the object reference cannot be recovered externally to this JVM. Note, however, that references to PSOs outside of the container and to non-PSO objects are permitted; such references are stored within the field slot of the Java object corresponding to the PSO. However, these references are unrecoverable outside of this JVM (e.g., by the receiver of a PSO sent over a communications channel).

The first time an object reference is read (using the `getfield` bytecode), a new Java PSO object is created which maps onto the container at the given offset. If the stored offset is null or outside of the range of the container, the special Java `null` value is returned. Subsequent `getfield` accesses will yield the PSO reference created during the original access, which is stored in the actual Java object corresponding to the PSO. Thus, object references within a PSO are resolved "lazily," that is, only upon their first use. This has the advantage that if a reference within a received PSO container is never traversed, a Java object reference will never be created for it.

5.2 Limitations

Pre-serialized Objects have several limitations. The first is that arbitrary Java objects cannot be represented as PSOs; the implementation depends upon the use of Jaguar code mappings for `putfield`/`getfield` operations on particular classes (in this case, any subclasses of `Jaguar.PSO`). It would be possible, however, to integrate the use of a standard Java object serializer with PSOs, allowing those portions of the object not pre-serialized by Jaguar to be serialized and deserialized in the standard way (albeit at higher cost).

A second limitation is that only atomic types and references to other PSOs within the same container are recoverable from a PSO's memory representation. This is not as limiting as it might seem. Java arrays are simulated through a generic `PSOArray` class which permits array-like operations on a container using method calls such as `readByte` and `writeInt`.

Further, we believe that the efficiency afforded by PSOs will make it worthwhile for programmers to manage PSO cross-references within the same container. Finding the right balance of programming generality and efficiency in this case is an open research issue.[4]

[4]Supporting cross-container PSO references is feasible, but unsupported by our current prototype. We have decided to retain the simplicity and performance of this design rather than building a more general, and less efficient, implementation.

Benchmark	**Time**
Create PSO object	9.24 μsec
Recover PSO reference	8.9 μsec
Follow recovered PSO reference	0.305 μsec
Assign PSO `int` field	0.033 μsec
Assign Java `int` field	0.023 μsec
Write `int PSOArray` element	0.053 μsec
Read `int PSOArray` element	0.049 μsec
Write `int` array element	0.041 μsec
Read `int` array element	0.043 μsec

Figure 8: *Pre-Serialized Object microbenchmarks.*

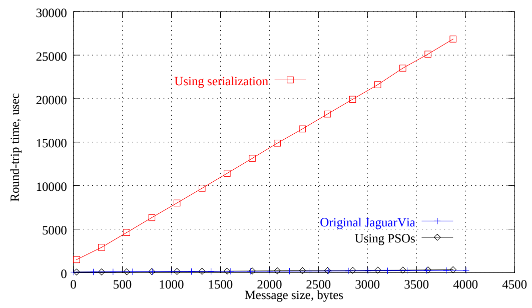
5.3 PSO Performance

We measure the performance of Pre-Serialized Objects in three ways: a set of microbenchmarks showing basic performance, a benchmark comparing PSOs to object serialization for communication over VIA, and a benchmark demonstrating the use of PSOs for high-performance disk I/O.

Figure 8 shows results for a simple microbenchmark of Pre-serialized Object performance. This benchmark creates a linked list of objects, with the same structure as `MyObject` shown in Figure 7, filling a one-megabyte container.

First, the benchmark creates each object in the list and fills in each field in the object. Next, recovery of the list from the pre-serialized buffer is simulated by "forgetting" the original list head and mapping a new PSO onto the beginning of the buffer. Each list entry is traversed by following the `someRef` reference to the next list element; this requires that the next list element be recovered, creating a new PSO instance mapping onto the container at the appropriate offset.Next, the benchmark traverses each list element a second time, which uses the cached PSO references created during the first traversal.

Times are shown for creating a PSO, for recovering a PSO from its pre-serialized form, and for reading a pre-recovered PSO reference. Also shown is the time to write a



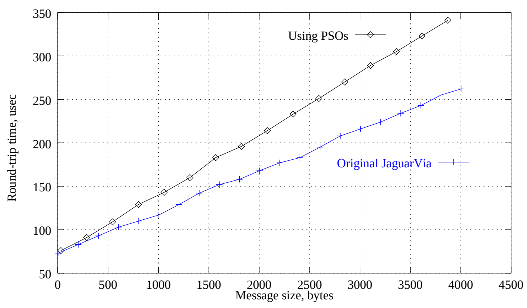


Figure 9: *PSO-over-VIA message latency results. The figure on the left compares the use of PSOs and JaguarVIA with Java object serialization; the figure on the right compares the use of PSOs over JaguarVIA with raw JaguarVIA communication times.*

PSO field of type `int`, which is compared to writing an `int` field to a regular Java object.

Also shown in Figure 8 are timings for reading and writing every element of the one-megabyte container as a `PSOArray`, which treats the container as a simple array of `int`. These values are compared to accessing elements of a Java `int` array. `PSOArrays` are only slightly more expensive than regular Java arrays, due to higher bounds-checking cost in the Jaguar code mappings implementing `PSOArrays`.

Pre-Serialized Objects eliminate the high cost of Java object serialization for communication and I/O. To demonstrate this, we have augmented the original JaguarVIA `pingpong` benchmark (from Figure 6) to transmit a linked list of simple Java objects consisting of nine fields: four `bytes`, four `ints`, and a reference to the next object in the list.

There are two variations on this benchmark shown. The first uses Pre-Serialized Objects to store object data directly into a VIA communications buffer. The second uses standard Java object serialization to write the linked list into the buffer. This was accomplished by implementing a simple class, `ViaOutputStream`, which writes bytes into a VIA communications buffer. A standard Java `ObjectOutputStream`, which performs object serialization, is created which writes serialized data to the `ViaOutputStream`.

To simplify both benchmarks, serialization is performed only by the transmitter;

no de-serialization (or mapping of PSO objects onto the received packet) is performed by the receiver. In the PSO version of the benchmark, the time to assign values to each field of each PSO in the linked list is included in the measurement, which represents the worst-case performance: a real application may be able to eliminate this overhead by re-using a PSO multiple times. In the object serialization benchmark, only the time to create a new `ObjectOutputStream`, and call `writeObject` with the head of the linked list as an argument, are included. This is the minimum amount of work required to serialize a set of objects.[5]

Figure 9 shows the round-trip time as a function of the message size for the use of PSOs over VIA, object serialization over VIA, and the raw JaguarVIA timings(from Figure 6). The right-hand plot does not include the object serialization times, as these dwarf the PSO and raw VIA measurements. It is clear that Pre-Serialized Objects eliminate the high overhead of object serialization: transmitting a linked list of 128 PSOs filling a four-kilobyte buffer has a round-trip latency of 341 μsec, while using Java object serialization costs 26843 μsec, a factor of 78 higher.

For comparison, transmitting an empty 4 Kb buffer using JaguarVIA has a round-trip latency of 262 μsec; filling the buffer using PSOs adds only 39.5 μsec each way, or (39.5 μsec / 128 objects) = 0.30 μsec per object. If the buffer were filled using the `PSOArray` mechanism described above, the cost would be (0.053 μsec per word / 1024 words) = 54.2 μsec. Note that accessing fields of a PSO does not require any bounds-checking to be done: the check is performed when the PSO is created (and mapped onto an underlying container). However, the `PSOArray` must bounds-check each access.

To evaluate the use of Pre-Serialized Object arrays to implement efficient disk I/O in Java, Figure 10 shows results for a simple benchmark which scans a one-megabyte file of random integers for the maximum value. This not only stresses the I/O component of the

[5] It is necessary to create a new `ObjectOutputStream` for each message; otherwise, the stream will serialize the linked list just once, for the first packet, and for subsequent packets will store a reference to the previously-serialized state. Because each packet is independent, this is unacceptable.

Benchmark	**Time**	**MByte/sec**
`DataInputStream`	4910 ms	0.203
`DataInputStream` (buffered)	488 ms	0.672
Jaguar `PSOArray`	28 ms	35.71
C (unbuffered `read`)	771 ms	1.32
C (`mmap`)	23 ms	43.47

Figure 10: *PSO File-scan benchmarks.*

system but brings the data into the application to perform simple analysis.

There are several variations on the benchmark. The first two use the standard Java `DataInputStream` class, both with and without an underlying `BufferedInputStream`. The third uses the Jaguar `PSOArray` class to treat a memory-mapped file as an array of bytes or integers. The final two results show the same benchmark in C, using unbuffered `read` system calls as well as `mmap` to access the file.

As the results show, only the Jaguar `PSOArray` and C-based `mmap` benchmarks obtain good performance (23 and 28 milliseconds, respectively). Both of these operate on memory-mapped files, so we should expect performance to be higher than the use of file I/O. The additional cost of the `PSOArray` over direct use of `mmap` from C is due to several factors: the `PSOArray` methods perform bounds-checking while the C code does not, and the optimizations in our prototype JIT compiler are not as advanced as in the C compiler.

External Objects and PSOs are a powerful means of enabling efficient I/O in Java. They provide direct access to memory-mapped files and a means to reduce the cost of object serialization. We believe these results indicate that higher-level I/O and communication mechanisms (such as persistent data structures and RPC) can be efficiently implemented using Jaguar.

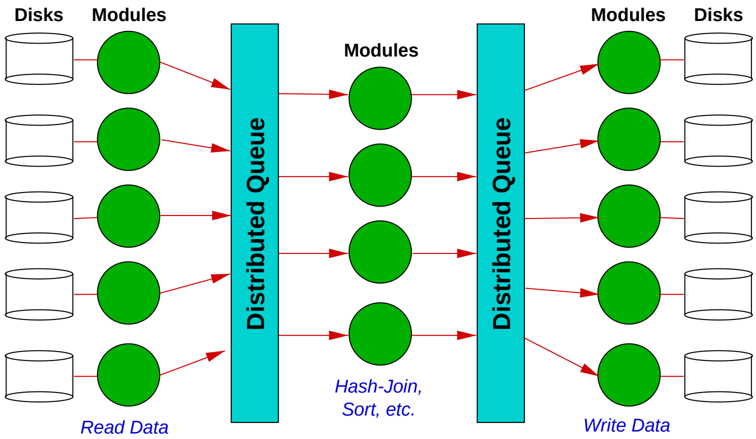


Figure 11: *A sample River application.*

6 The Tigris System

To demonstrate the high-level application benefits of Jaguar, we have implemented *Tigris*, a system supporting scalable, cluster-based applications with large I/O and communication demands. The key ideas in Tigris are borrowed from River [2], a system which automatically balances CPU, network, and disk I/O load across the cluster as a whole. River employs a dataflow programming model wherein applications are expressed as a series of *modules* each supporting a simple input/output interface. Modules communicate through the use of *reservoirs*, channels upon which data packets can be pushed into or pulled out of. A simple data-transformation application might consist of three distinct modules: one which reads data from a disk file and streams it out to a reservoir; one which reads packets from a reservoir and performs some transformation on that data; and one which writes data from a reservoir back onto disk. Figure 11 depicts this scenario. By running multiple copies of these modules across many nodes of a cluster, the overall throughput of the data transformation can be scaled.

The goal of River is to automatically overcome cluster resource imbalance and mask this behavior from the application. For example, if one node in the cluster is more heavily loaded than others, without some form of work redistribution the application may run at the rate of the slowest node. The larger and more heterogeneous a cluster is, the more evident this problem will be; often, performance imbalance is difficult to prevent (for example, the location of bad blocks on a disk can seriously affect its bandwidth). This is especially true of clusters which utilize nodes of varying CPU, network, and disk capabilities. Apart from hardware issues, software can cause performance asymmetry within a cluster as well; for example, "hot spots" may arise based on the data and computation distribution of the application.

River addresses resource imbalance in a cluster through two mechanisms: a *distributed queue* (DQ) which balances work across consumers in the system, and *graduated declustering* (GD), mechanism which adjusts load across producers. The DQ allows data to flow at autonomously adaptive rates from producers to consumers, thereby causing data to "flow to where the computation is." GD is a data layout and access mechanism which allows producers to share the production of data being read from multiple disks. By mirroring data sets on several disks, disk I/O imbalance is automatically managed by the GD implementation.

Tigris is an implementation of the River system in Java. This was motivated for several reasons. First, Java is a natural platform upon which to build cluster-based applications, for reasons described in the introduction. Second, River is attractive as a programming paradigm for cluster-based Internet service architectures being investigated by the Ninja project [31] at UC Berkeley. Because Ninja relies heavily upon the use of the Java runtime environment (as in MultiSpace [12]), mapping the concepts in River to an implementation in Java presented an opportunity to address issues with the use of Java, the Ninja service platform, and the River programming model all at once. Finally, we felt that River could benefit greatly from the integration of Java, both in terms of code simplification and added flexibility. For example, the use of Java Remote Method Invocation (RMI) for

```
public interface ModuleIF {
  public String getName();
  public void init(ModuleConfig config);
  public void destroy();
  public void doOperation(Water inWater,
    Reservoir outRes);
}
```

Figure 12: *Tigris Module interface.*

control of Tigris components is more expressive and simpler to program than a lower-level control mechanism.

6.1 Implementation overview

Here, we focus on the details of the Tigris system as they differ from the original C++ implementation of River (Euphrates) described in [2].

Tigris is implemented entirely in Java. Each cluster node runs a Java Virtual Machine which is bootstrapped with a receptive execution environment called the *iSpace* [12]. iSpace allows new Java classes to be "pushed into" the JVM remotely through Java Remote Method invocation. A Security Manager is loaded into the iSpace to limit the behavior of untrusted Java classes uploaded into the JVM; for example, an untrusted component should not be allowed to access the filesystem directly. This allows a flexible security infrastructure to be constructed wherein Java classes running on cluster nodes can be given more or fewer capabilities to access system resources based on trust.

Tigris modules are implemented as Java classes which implement the `ModuleIF` interface, which is shown in Figure 12. This interface provides a small set of methods which each module must implement. `init` and `destroy` are used for module initialization and cleanup, and `getName` allows a module to provide a unique name for itself. The `doOperation` method is the core of the module's functionality: it is called whenever there is new incoming data for the module to process, and is responsible for generating any outgoing data and pushing it down the dataflow path which the module is on.

Communication is managed by two classes: `Reservoir` and `Water`. The `Reservoir` class represents a communications channel between two or more modules; it provides two methods, `Get` and `Put`, which allow data items to be read from and written to the communications channel. The `Water` class represents the unit of data which can be read from or written to a `Reservoir`; this is the same unit of work which is processed by the module `doOperation` method. A `Water` can be thought of as containing one or more data buffers which can be accessed directly (through the Jaguar `PSOArray` class) or out of which Jaguar Pre-Serialized Objects can be allocated from. This allows the contents of a `Water` to represent a structure with typed fields which have meaning to the Java application, rather than as an untyped collection of bytes or integers.

By subclassing `Reservoir` and `Water`, different communication mechanisms can be implemented in Tigris. A particular `Water` implementation can be associated with a particular `Reservoir`; for example, in case the communications channel requires special handling for the data buffers which can be sent over it. Our prototype implementation includes three reservoir implementations:

- `ViaReservoir` provides reliable communications over Berkeley VIA using the previously-described *JaguarVia* library.

- `MemoryReservoir` implements communications between modules on the same JVM, passing the data through a FIFO queue in memory.

- `FileReservoir` associates the `Get` and `Put` reservoir operations with data read from and written to a file, respectively. This is a convenient way to abstract file I/O.

`Water`s are initially created by a `Spring`, an interface which contains a single method: `createWater(int size)`. Every `Reservoir` has associated with it a `Spring` im-

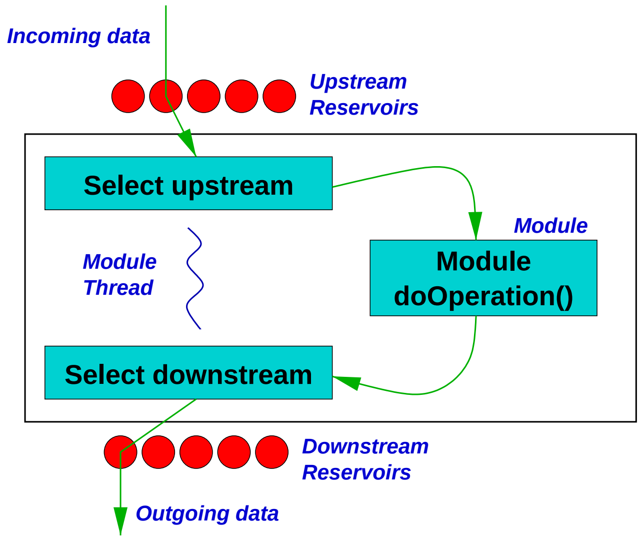


Figure 13: *Tigris* `ModuleThread` *operation.*

plementation which is capable of creating `Water`s which can be sent over that `Reservoir`. This allows a `Reservoir` implementation to manage allocation of `Water`s which will be eventually transmitted over them; for example, a reservoir may wish to initialize data fields in the `Water` to implement a particular communications protocol (e.g., sequence numbers). The implementation of `Water` can ensure that a module is unable to modify these "hidden" fields once the `Water` is created, by limiting the range of data items which can be accessed by the application.

Each `Module` has an associated `ModuleThread` which is responsible for repeatedly issuing `Get` from the module's "upstream" reservoir and invoking `doOperation` with two arguments: the input `Water`, and a handle to the "downstream" reservoir to which any new data should be sent. A single `ModuleThread` may have multiple upstream and downstream reservoirs associated with it; for example, to implement one-to-many or many-to-one communication topologies in the dataflow graph of the application. (This is also the cornerstone of the Distributed Queue implementation in Tigris, as we will see later.) Different implementations of ModuleThread can implement different policies for selecting the reservoir which should be used for each invocation of the module's doOperation method. For example, RRModuleThread implements a round-robin scheme for selection of both the upstream and downstream reservoir on each iteration.[6] Figure 13 depicts the operation of the ModuleThread main loop.

6.2 Distributed Queue implementation

In Tigris, the DQ is implemented as a subclass of ModuleThread which balances load across multiple downstream reservoirs. In this way, *all* reservoirs in Tigris are maintained by ModuleThreads, and modules themselves are unaware of the connectivity of the dataflow graph.

There are three ModuleThread implementations included in our prototype:

RRModuleThread selects the upstream and downstream reservoir for each iteration in a round-robin fashion.

RandomModuleThread selects the upstream reservoir for each iteration using round-robin, and the downstream reservoir using a randomized scheme. The algorithm maintains a credit count for each downstream reservoir. The credit count is decremented for each Water sent on a reservoir, and is incremented when the Water has been processed by the destination (e.g., through an acknowledgement). On each iteration, a random reservoir R is chosen from the list of downstream reservoirs. If that reservoir has a zero credit count, another reservoir is chosen. This is the DQ implementation used in the original River implementation [2].

LotteryModuleThread selects the upstream reservoir for each iteration using round-

[6]By passing a handle to the current downstream reservoir to doOperation, the module is capable of emitting zero or more Waters on each iteration. Also, this permits the module to obtain a handle to the reservoir's Spring to create new Waters to be transmitted. Note that the module may decide to re-transmit the same Water which it took as input; because a reservoir may not be capable of directly transmitting an arbitrary Water (for example, a ViaReservoir cannot transmit a FileWater), the reservoir is responsible for transforming the Water if necessary, e.g., by making a copy.

robin, and the downstream reservoir using a “lottery” scheme. The algorithm maintains a credit count for each downstream reservoir. On each iteration, a random number r is chosen in the range $(0..N)$ where N is the total number of downstream reservoirs. The choice of r is weighted by the value $w = (c_R/C)$ where c_R is the number of credits belonging to reservoir R and $C = \sum c_R$. The intuition is that reservoirs with more credits are more likely to be chosen, allowing bandwidth to be naturally balanced across multiple reservoirs.

6.3 Initialization and control

A Tigris application is controlled by an external agent which contacts the iSpace of each cluster node through Java RMI, and communicates with the `RiverMgr` service running on that node. `RiverMgr` provides methods to create a `ModuleThread`, to create a reservoir, to add a reservoir as an upstream or downstream reservoir of a given `ModuleThread`, and to start and stop a given `ModuleThread`. In this way the Tigris application and module connectivity graph is “grown” at runtime on top of the receptive iSpace environment rather than hardcoded *a priori*. Each cluster node need only be running iSpace with the `RiverMgr` service preloaded.

Execution begins when the control agent issues the `moduleStart` command to each module, and ends when one of two conditions occur:

- The control agent issues `moduleStop` to every module; or,
- Every module reaches the “End of River” condition.

“End of River” (EOR) is indicated by a module receiving a null `Water` as input. This can be triggered by a producer pushing a null `Water` down a reservoir towards a consumer, or by some other event (such as the `ModuleThread` itself declaring an EOR condition). A module may indicate to its surrounding `ModuleThread` that EOR has been reached by throwing an `EndOfRiverException` from its `doOperation` method; this obviates the need for an additional status value to be passed between a module and its controlling thread.

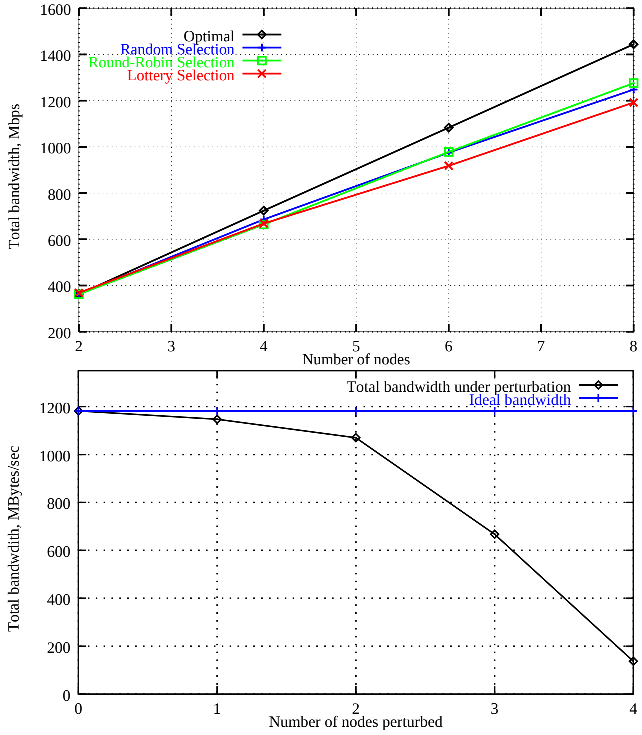


Figure 14: *Tigris Distributed Queue performance.*

6.4 Distributed Queue Performance

Figure 14 shows performance of the Tigris Distributed Queue implementations under scaling and perturbation. The first benchmark demonstrates the three DQ implementations (round-robin, randomized, and lottery) as the number of nodes passing data through the DQ is scaled up. The `ViaReservoir` reservoir type is used, which implements a simple credit-based flow-control scheme over the VIA fast communications layer. End-to-end peak bandwidth through a `ViaReservoir` is 46 MBytes/sec, or 75% of the peak bandwidth of raw JaguarVia (which implements no flow-control or reliability).

In each case an equal number of nodes are sending and receiving data through the DQ. The results show a 12% bandwidth loss (from the optimal case) in the 8-node case. This is partially due to the DQ implementation itself; in each case, the receiving node selects the upstream Reservoir from which to receive data in a round-robin manner. Although the receive operation is non-blocking it does require the receiver to test for incoming data on each upstream Reservoir until a packet arrives. We also believe that a portion of this bandwidth loss is due the VIA implementation being used; as the number of active VIs increases, the network interface must poll additional queues to test for incoming or outgoing packets.

The second benchmark tests the performance of the lottery DQ implementation as receiving nodes are artificially loaded by adding a fixed delay to each iteration of the receiving module's `doOperation()` method. The total bandwidth in the unperturbed case is 1181.58 MByte/second (4 nodes sending 8Kb packets at the maximum rate to 4 receivers through the DQ), or 295.39 MByte/sec per node. Perturbation of a node limits its receive bandwidth to 34.27 MByte/sec. The lottery DQ balances bandwidth automatically to nodes which are receiving at a higher rate, so that when 3 out of 4 nodes are perturbed, 56% of the total bandwidth can be achieved. Over 90% of the total bandwidth is obtained with half of the nodes perturbed.

7 TigrisSort: A Sample Application

In order to evaluate the performance and flexibility of the low-level mechanisms embodied in Jaguar, as well as the design of the Tigris system as a whole, we have implemented *TigrisSort*, a parallel, disk-to-disk sorting benchmark. As with Datamation [9] and NOWSort [1], external sorting is a good way to measure the memory, I/O, and communication performance of the complete system. While the existence of previous sorting results on other systems yields a yardstick by which the Tigris system can be compared, we were also interested in understanding the functional properties of the Tigris and Jaguar mechanisms in the context of a "real application."

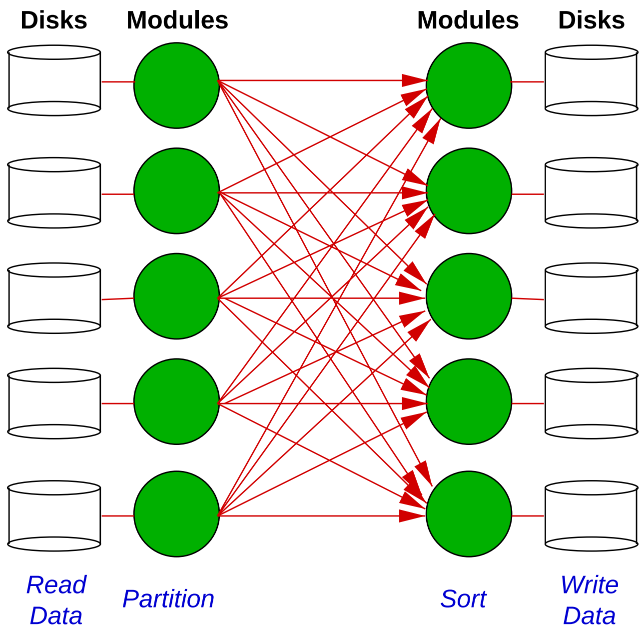


Figure 15: *TigrisSort structure.*

7.1 TigrisSort structure

The structure of TigrisSort is shown in Figure 15. Tigris sort implements a one-pass, disk-to-disk parallel sort of 100-byte records each of which contain a 10-byte key. Data is initially striped across the input disks with 5 megabytes of random data per node. The application consists of two sets of nodes: *partitioners* and *sorters*. Partitioning nodes are responsible for reading data from their local disk and partitioning it based on the record key; the partition "buckets" from each node are transmitted to the sorting nodes which sort the entire data set and write it to the local disk. This results in the sorted dataset being striped by increasing key value across the sorting node disks.

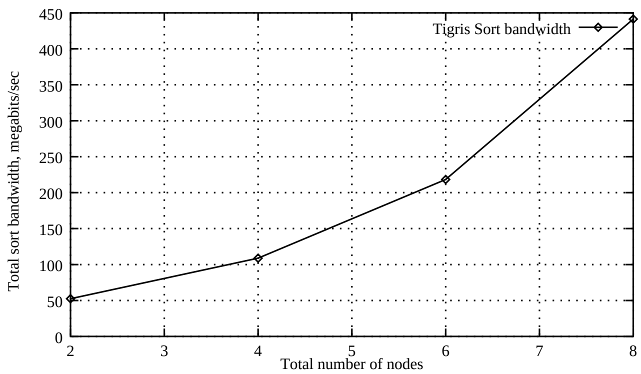
Partitioning is implemented as a `PartitionModuleThread` class which continually reads a buffer of data from a local disk file, partitions the buffer into a number of buckets based on the key, and writes full buckets to the reservoir corresponding to that bucket. All buckets are flushed to the communications channel when file data has been exhausted.

The actual partitioning of records is accomplished through a native method, `bucketize()`, which takes as arguments a Jaguar external object corresponding to the input file buffer and an array of external objects corresponding to each bucket. No data copying between Java and C is necessary as both Java and native code can directly manipulate the contents of the external objects.

Sorting is implemented as a `SortModule` contained within a `LotteryModuleThread`. The module's `doOperation` method saves a copy of each packet received until End-of-River is signalled; at that time it collates every packet into a single buffer, sorts that buffer, and writes the sorted data out to disk. Sorting is accomplished by a native method, `doSort()`, which takes an array of external objects corresponding to the packets received during the lifetime of the module. Again, no data copy between Java and C is necessary.

File I/O is implemented as a class, `FilePSOBuffer`, which causes a file to be memory mapped (through the `mmap` system call) into the address space of the JVM and exposed to the Java application as a PSO container. PSO operations on that container correspond to disk reads and writes through the memory-mapped file. A special method is provided, `flush()`, which causes the contents of the memory-mapped file to be flushed to disk.

This approach has several limitations. One is that the operating system being used (Linux 2.2.5) does not allow the buffer cache to be circumvented using memory-mapped files. Another is that a particular write ordering cannot be enforced. Currently, Linux does not provide a "raw disk" mechanism which provides these features. Rather than concerning ourselves with these details, we assume that performance differences arising because of them will be negligible. This seems to be reasonable: first, disk I/O is just one component of the TigrisSort application, which does not appear to be disk-bandwidth limited. Secondly, double-buffering of sort data in memory is not problematic with the small (5 megabyte) per-node data partitions being dealt with. Third, write ordering is not



# nodes	Amount sorted	Avg time/node	Avg sort bw/node	Total sort bw
2	5 MBytes	762 msec	52.49 Mbps	52.49 Mbps
4	10 MBytes	734.5 msec	51.725 Mbps	108.91 Mbps
6	20 MBytes	733 msec	51.82 Mbps	218.28 Mbps
8	40 MBytes	725 msec	52.40 Mbps	441.37 Mbps

Figure 16: *TigrisSort performance results.*

important for implementing parallel sort; it is sufficient to ensure that all disk writes have completed.

7.2 TigrisSort performance

Figure 16 shows the performance of TigrisSort as the benchmark is scaled up from 2 to 8 nodes. In each case, half of the nodes are configured as partitioners, and half as sorters; 5 megabytes of data are partitioned or sorted per node. The total time to complete the sort averaged 738 milliseconds; this implies that as more nodes are added to the application, more data can be sorted in constant time. Given this result we feel that with careful tuning, TigrisSort can compete with the current world-record holder of the Datamation sort record, Millennium Sort [4], which was implemented on the same hardware platform using Windows NT and C++. However, the dominant cost of Datamation sort on modern systems is application startup; the results above do not include the cost of starting the Tigris system itself. There is some question as to what should be included in the startup measurements (e.g., for traditional implementations, the cost of cold-booting the operating system is not measured).

8 Issues and Future Work

Our initial experience with Jaguar has indicated a number of possible avenues for further research. While our prototype has provided encouraging results, we are interested in the extension of the Jaguar approach to other application areas.

One major concern is protection. Currently, the user must trust Jaguar code extensions (built-in to the JIT compiler as a set of bytecode-to-machine code transformation rules) as much the JVM and the compiler itself. As discussed previously, however, this is perhaps better than the use of arbitrary native methods, which have the same trust requirements but far greater complexity in general.

However, it is still desirable to express extensions to the Java environment in a way which enables certain properties to be verified, such as type-safety, bounded execution time, and limited impact on the Java protection model. One approach would be to use a higher-level language to represent Jaguar code mappings; typed assembly language [19] is one candidate, but other languages are possible. The use of such a language should make it possible to statically verify important properties about Jaguar's code mappings — while this may not permit entirely untrusted Java extensions, the goal is rather to raise the degree of trustworthiness such that new code mappings do not have unexpected behavior.

Use of a limited extension language may have the secondary effect that it inherently limits the set of actions which can be implemented as Jaguar code mappings. For example, loops, unbounded branches, and ill-formed Java stack and object operations may be restricted by the semantics of the language. This is desirable as it prevents the abuse of the Jaguar code mapping technique to inline large amounts of low-level code as a single Java primitive; the philosophy of Jaguar is to build in only the minimal set of extensions needed to provide efficient Java access to some server resource.

Pre-Serialized Objects present several untapped opportunities. The first is to exploit PSOs to implement an efficient RPC and data-persistence mechanism for Java; combining the use of JaguarVIA and PSOs should enable a high-performance RPC mechanism for workstation clusters. We are also investigating the use of PSOs to implement distributed data structures for cluster-based Internet services [13] and databases [14].

The prototype implementation of Pre-Serialized Objects has several important limitations. The fact that cross-PSO references are only recoverable if both PSOs are within the same "container" implies an informed programming model which makes this limitation explicit. Currently, it is up to the programmer to arrange for multiple PSOs to coreside in a single container if their object references are to be recovered. While it is possible to remove this limitation, doing so would involve considerable complexity. We believe that programmers who require the performance afforded by PSOs are willing to go to the trouble to carefully maintain PSO relationships; we intend to test this claim by developing applications which use this feature.

Tigris presented an opportunity to apply Jaguar to higher-level application demands in the context of dynamic resource management in a cluster of workstations. Our test configuration was limited, but we feel that initial results with Tigris and TigrisSort are promising: it is possible to build powerful, system-level abstractions in Java with the aid of Jaguar's efficient I/O and communications primitives. Our future goal is to deploy Tigris on a larger cluster and measure its performance with respect to the original C++ implementation of River. Implementing the River concepts in Java was greatly simplified by the availability of the MultiSpace [12] cluster-management layer and the use RMI for control.

Jaguar is a general solution for efficiently binding Java application code to hardware resources. There are myriad potential uses for this mechanism, of which we have yet explored but a few. Other interesting uses include:

- Fast access to devices such as raw disk I/O, framebuffers, and NUMA-style memory-bus network interfaces;
- Transparent data persistence, using a mechanism similar to Pre-Serialized Objects. Certain Java objects could be tagged as "persistent" — Jaguar code mappings could directly implement retention of such objects' state.
- Use of Jaguar code mappings to access shared memory segments in a multiprocessor machine, or to implement distributed shared objects across a network.

Because Jaguar can be applied so generally, it is important to strike the right balance between development of new Java primitives and applications which utilize those primitives. Our claim is that it is undesirable to extend the Java environment arbitrarily; just what the limits are should be brought out by further experimentation.

9 Conclusion

Jaguar bridges the gap between Java applications and the underlying server resources that they wish to exploit. This is accomplished by translating Java bytecodes to inlined machine code sequences at compile time; this ability to abstract system resources as a Java object in this way provides both safety and high performance. The programming model presented by Jaguar allows low-level system software to be coded almost entirely in Java, aided by the minimal set of additional primitives required for direct access to hardware resources.

Jaguar addresses two primary concerns which are essential for enabling high-performance communications and I/O from Java:

1. Efficient, protected access to low-level system resources; and

2. Direct manipulation of memory regions external to the Java heap.

We have described *JaguarVIA*, an efficient Java binding to the VIA communications architecture using Jaguar code mappings to provide fast access to VIA queues, doorbell registers, and specially-pinned data buffers. JaguarVIA obtains identical communication performance to VIA as accessed from C. Pre-Serialized Objects are another application of Jaguar code mappings which reduce the cost of Java object serialization by rewriting object field references to directly access an externalized form of the object's state.

Tigris is a high-level cluster programming model which relies heavily upon the efficient communication and I/O mechanisms enabled by Jaguar. Tigris allows applications to automatically balance their resource consumption across the cluster, through the use of a dataflow programming model and *Distributed Queues*, a mechanism which balances data movement between producers and consumers. TigrisSort, a sample application of Tigris, demonstrates parallel disk-to-disk sorting performance which is competitive with that of previous systems implemented in C or C++.

We believe that the approach taken by Jaguar can be extended in a number of ways, both in terms of applications (such as applying Pre-Serialized Objects to implement a fast RPC layer) as well as protection (by expressing Jaguar code transformations in a higher-level language). Jaguar is a general solution which covers a wide range of application demands on the Java environment. As such, it is important to consider the performance and complexity tradeoffs of extending Java with new primitive operations in this way.

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