

**JET:**  
**An Application of Partial Evaluation in**  
**Dynamic Code Generation for Java**

by

**Tony Chao**

Submitted to the Department of Electrical Engineering and Computer Science  
in Partial Fulfillment of the Requirements for the Degree of  
Master of Engineering in Electrical Engineering and Computer Science  
at the Massachusetts Institute of Technology.

May 26, 2000

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## **Abstract**

Java is a popular new language with enormous potential; however, its lack of speed is a major drawback. Staged compilation and runtime specialization through procedure cloning are techniques used to improve code generation and execution performance. The research described in this paper applies these techniques in the design and implementation of a runtime system to improve Java performance. Analyses indicate that staged compilation results in a major improvement in performance. In this current implementation, runtime specialization and constant propagation provides a smaller incremental benefit, but with more aggressive and new forms of specialization, the benefits of dynamic specialization will likely increase.

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# 1 Introduction

Staged compilation and runtime specializations are techniques used to improve code generation and execution performance. This research applies such techniques in a system designed to improve Java performance. This thesis summarizes the work done in design and implementation of this architecture. Preliminary performance data and analysis of design are presented at the end of this paper, and specifications of the implementation as well as algorithms used are found in the appendices.

Java<sup>1</sup> is a programming language developed in recent years by Sun Microsystems. Java was created as a language for the future: a secure, readily extensible, platform independent, portable language. Its objected-oriented nature, strong type verification, automatic memory management, and portability have helped Java spread in popularity. While originally designed for embedded systems, Java has found overwhelming acceptance among Web applications. Virtually everything, from e-commerce applications to traditional standalone applications to computationally intensive numerical analysis tools, is now being developed in Java. As the world becomes more and more immersed in the Internet, Java will continue to grow in importance.

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<sup>1</sup> Java™ is a registered trademark of Sun Microsystems, Inc.

Java does, however, have its shortcomings. Current technology is limited, and the very characteristics that make Java an appealing language for the future are the ones that make Java slow and intolerable in today's applications. Java programs are typically compiled into bytecodes and then interpreted by a virtual machine. Newer Java Virtual Machines (JVM) incorporate a lightweight compiler that is able to dynamically compile the bytecodes into machine code to speed up execution. This is known as Just-In-Time compilation (JIT). Because compilation is performed at execution time, the compilation overhead must be kept to a minimum. As a result, JIT is usually not capable of intensive optimizations. Some developments have also been made to allow bytecodes to statically be compiled into machine code before actual execution takes place. In contrast to JIT, this is known as Ahead-of-Time compilation (AOT). AOT is very much identical to traditional compilers except that it is applied to Java. Since compilation time is not part of performance, AOT is able to perform more intensive optimizations. While AOT is able to offers faster execution, AOT is limited in its flexibility. Java allows dynamically loaded classes, and unless the AOT produces code to duplicate JVM functionalities, AOT programs will be limited in capabilities as well as portability. While JIT and AOT are both good approaches, neither is entirely satisfactory.

Traditional programs are typically compiled at the end of development. No additional analysis or compilation is performed at runtime because runtime information cannot be calculated during static compilation. AOT also follows this process like any other traditional compiler. On the other hand, JIT is compiled at runtime and has access to runtime information to allow customization and optimization, but because such analysis

can be intensive, JIT generally avoids almost all types of optimization and analysis at runtime. There are many advantages to runtime code analysis and compilation. If programs could be analyzed during runtime and modified, programs could be specialized according to the calling context and offer additional efficiency in execution. When programs are compiled statically, the compiled programs must be generic, and optimizations for specialized arguments and calling contexts cannot be incorporated without assuming a specific application or use. To specialize programs for various calling contexts, machine codes must be dynamically generated, and some compilation must be delayed. However, it is not practical to delay all of the compilation until runtime in the manner of JIT; compilation is a computationally intensive process and incurs significant performance degradation. Therefore, this research has chosen to stage the compilation. Programs are statically analyzed and partially evaluated, similar to compilation, but the actual machine code will not be generated until runtime. By making use of knowledge learned during static analysis, dynamic runtime code generation can efficiently generate machine code with little overhead. Java Execution-time Transformations (JET) is an alternative JVM architecture that allows staged compilation analysis and performs efficient code generation and specialization through procedure cloning at runtime.

## **2 Background**

In recent years, many research projects have focused on improving Java performance; JIT's have been developed on most major architectures and JVM's. The most interesting JIT approach is Sun's HotSpot. HotSpot dynamically analyzes "hotspots" or critical areas in the program, and adaptively optimizes the executed code. JET is similar to HotSpot in



that optimizations are made automatically and dynamically, but instead of delaying all analysis and compilation until runtime, JET divides the work into two phases and minimizes the amount of computation involved at runtime. Although not a JIT, JET works closely with the JIT to extend the capabilities of the JVM.

AOT's have also had great success in improving Java performance. Some researchers approach AOT by translating Java to C (or C++ or Fortran) and then using a robust C compiler to generate efficient machine code. This includes Java source to C source translators such as JCC (Shaylor), and Java bytecode to C source converters such as Toba (Proebsting et al.) and Harissa (Muller et al.). Another approach is to generate machine code directly from Java bytecodes. Some examples of this approach include Marmot (Microsoft Research) and TowerJ (Tower Technologies). Since Java programs are able to dynamically load classes, it is not possible for an AOT to statically analyze all possible paths of execution and produce a single executable for every program. Some of these approaches solve the limitations of AOT by providing and linking libraries to provide JVM functionalities; others simply limit the types of programs that can be compiled or translated. Unlike AOT's, JET is an extension to the JVM and does not produce machine code that can be executed without a JVM.

Compiler research projects involving staged compilation, deferred code generation, partial evaluation, and runtime specializations are also closely related to this project. Runtime code generation in the form of self-modifying code was actually widely used in early systems when memory was expensive. Fast executables could be generated from a

compact representation. While portability, complexity, and changing technologies caused runtime code generation to fall from favor, runtime code generation is still a valuable and useful technique (Keppel, Eggers, and Henry).

Many staged compilation and runtime code generation architectures have been developed. To perform dynamic code generation and specialization, a design must be able to determine which variables and functions to specialize. A popular approach is to augment the source language with annotations to aid and direct runtime specializations and code generation. Examples of this declarative approach include Fabius for ML (Leone and Lee), and Tempo (Consel et al.) and DyC (Grant et al.) for C. Fabius is a dynamic code generator for a functional subset of ML and is one of the earliest examples of dynamic code generation. Fabius uses function currying to determine what variables and functions to specialize. DyC's code generation process is very similar to the code generation process of JET. Given an annotated C program as input, DyC produces an executable program consisting of a static code portion and a generating extensions (GE) portion. This executable program is the intermediate representation (IR) between the static analysis and the dynamic generation phase. In the JET system, the IR is not a piece of machine code. The JET IR is a binary data structure wrapped in a Java classfile attribute. The GE, DyC's dynamic specializer, is custom produced for each function and included in the IR. The JET specializer, on the other hand, is part of the system architecture and is not generated during static analysis. Both DyC and JET specializers are invoked during runtime to produce dynamically specialized machine code.

Even further on the user involvement spectrum is ``C` and `tcc` (Poletto et al.) ``C` is an extension of `C` that was designed specifically for dynamic compilation; `tcc` is the compiler for ``C` (Poletto et al.). ``C` programmers must explicitly design and declare functions and variables to be specialized. The biggest distinction between these existing systems and JET is that JET does not require any form of user specification. All annotation required by the JET runtime system are generated automatically during static analysis. Once a classfile has been statically analyzed and appended, the entire code generation and specialization process is transparent to the user.

### **3 Motivation**

This thesis project is funded by Compaq Computer Corporation as part of the MIT VI-A internship program. Since the work is funded by a corporate organization, the project must not only satisfy an academic, research interest but also provide economic value to the company.

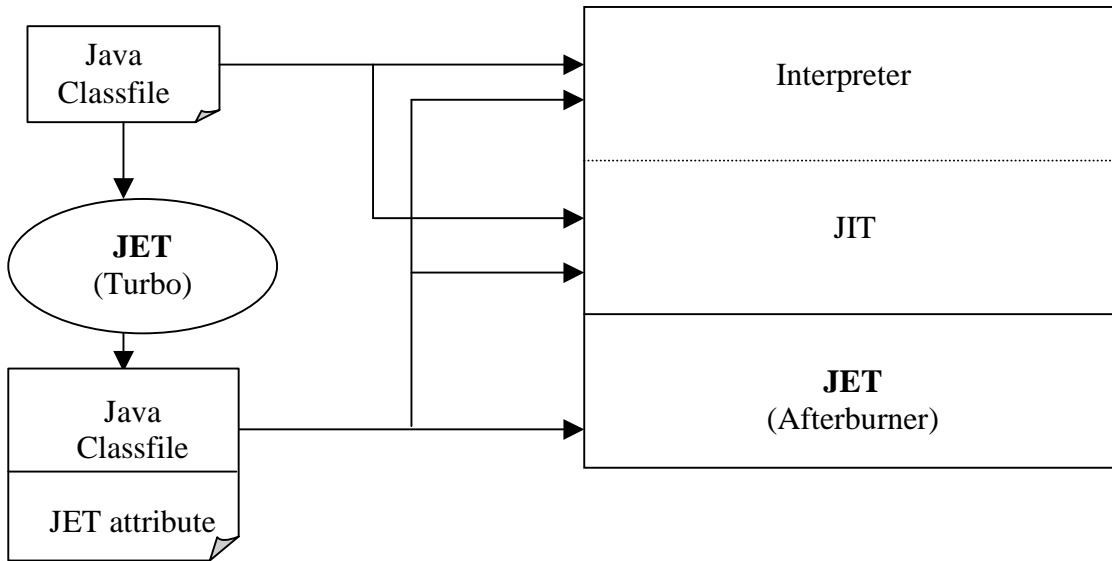
Compaq is interested in this project to help promote sales of its servers. Java is becoming an important means of developing server applications, and to be able to sell servers, especially web and e-commerce servers, the servers must be capable of running Java. By exploring alternative approaches to Java execution and possibly improving speed and performance of Java programs on its servers, this work can give Compaq an edge in promoting and marketing their servers.

From an academic perspective, runtime code generation and automatic specialization through procedure cloning is an interesting compiler research topic. Ideas and understanding gained through this project can help improve general compiler technology. When applied to Java, this is especially interesting because it seeks to fully optimize Java and allow Java to compete in performance with other classical languages such as C/C++ and Fortran.

## 4 Design

The goal of this research was to develop a Java environment that is capable of dynamically generating and optimizing code. From initial evaluations explained previously, the staged compilation approach was chosen. Staged compilation combines the best of both worlds. Heavy computation overheads are accounted for during a static analysis phase, and the runtime dependent optimizations are performed at runtime to allow the fullest range of possible optimizations. In compliance with the JET nomenclature, the static analysis phase is known as Turbo, and the runtime optimization phase is known as Afterburner. A graphical representation of the design can be found in Figure 1.

Once the decision of using staged compilation has been made, the next step is to design a means to integrate the two phases. The JVM specifications allow for implementations to extend functionality by attaching attributes to the Java classfile. By wrapping the JET information in a classfile attribute, the JET system can modularize the phases and allow classfiles that have been put through the static analysis phase (classfiles that have been



**Figure 1 JET Stages and Integration**

JET-ified) to be usable on JVM environments that do not support the JET architecture. System that do support the JET architecture and have an implementation of Afterburner will be able to make use of the JET information and provide better performance. This approach helps keep the Java classfiles platform independent while extending the functionality to include JET optimizations.

In designing the intermediate representation to encompass the information required for JET optimizations, a modified static single assignment (SSA) value graph and control flow graph (CFG) was chosen. The SSA and CFG are data representations commonly used in developing classic compilers. The CFG seeks to summarize the execution paths and sequences that are possible through a program, and the SSA represents the use and definition of values that make up the program and the instructions to be generated. Together the CFG and the SSA help create a compact flexible representation of the program that allows easy manipulation and optimizations to happen. A complete view of

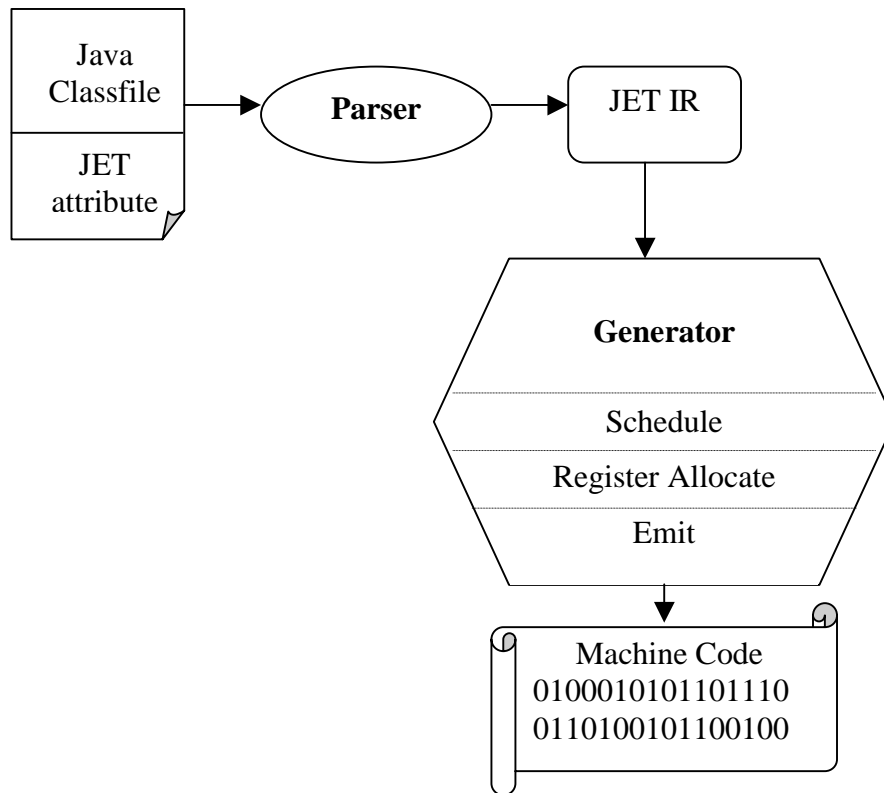
the JET IR can be found in appendix A. The JET IR extends the classic SSA and CFG with the addition of specific optimization information used in JET.

## **4.1 Turbo**

The static analysis portion of JET is codenamed Turbo. Jeremy Lueck, another student in the MIT VI-A program, worked on this portion of JET as his Master of Engineering thesis. Turbo was adapted from an AOT currently under development by Compaq's System Research Center called Swift. Turbo takes in Java classfiles, performs analysis, and outputs a new Java classfile. The new Java classfile contains a JET classfile attribute following the JET IR specifications and containing all the information required to help runtime JET optimizations to be performed efficiently and with minimal overhead.

## **4.2 Afterburner**

The Afterburner represents the dynamic code generation, optimization, and specialization phase of the JET architecture. Afterburner extends the JVM to support the JET architecture. Afterburner performs efficient runtime code generation and analyzes execution of methods in order to perform specialization and optimization where possible. The Afterburner itself can be broken up into three stages: parser, generator, and specializer. When the JVM loads classfiles with a JET attribute, the JET parser will be invoked to load the JET IR. Following successful retrieval, a non-specialized code generation is created. Future execution of JET generated code will trigger specialization and optimization analysis. If specialized optimization is possible and worthwhile, a new



**Figure 2 JET Code Generation Process**

specialized version of the method will be generated. Figure 2 is a graphical representation of this architecture.

The Afterburner is designed to be an extension of the basic JVM. Thus, to accomplish the implementation and design of this system, a working commercial JVM and source code must be available. As this research is part of the MIT VI-A internship, Compaq was kind enough to provide this project with Srcjava. Srcjava is a Java 2 compliant JVM (Java 2 SDK Documentation) currently under development by Compaq's System Research Center in Palo Alto, California. Srcjava is written in C and Assembly, and is developed for Compaq's Tru64 Unix operating system on the Alpha architecture.

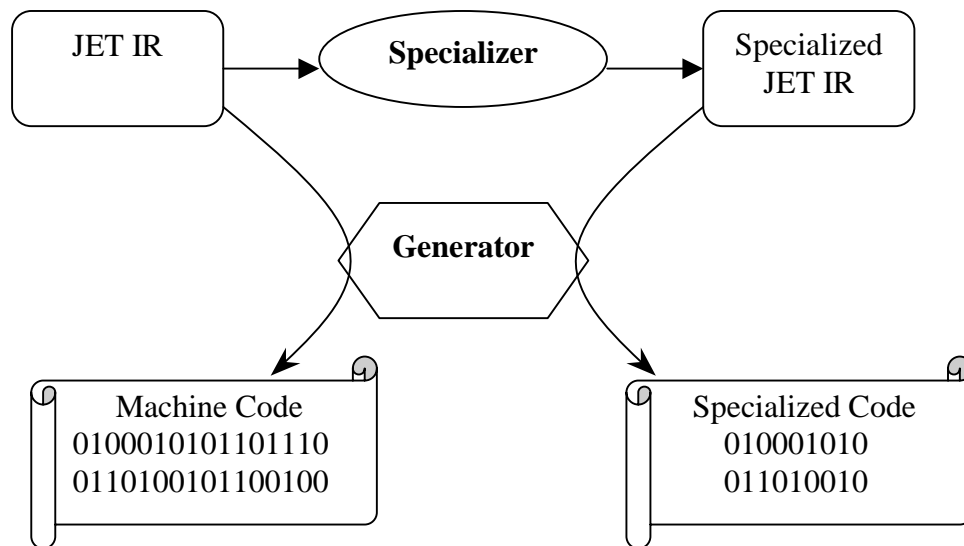
### 4.2.1 Parser

The parser reads in the JET attribute and creates JET objects and METHOD objects. The JET attribute is a binary file structure that represents the JET IR. The JET attribute was designed so that it would be easy to load, and the JET IR was designed so that it would be flexible.

The JET attribute is laid out in a manner that allows the parser to read in the attribute as an array of bytes and cast the region of memory into a JET structure. The pointers in the attribute are made so that they are relative offsets from the beginning of the attribute. After the parser casts the region of memory as a JET structure, it then walks through the JET IR converting relative pointers to absolute pointers.

While this process allows quick and easy loading, some assumptions are inherent and should be taken into consideration for future implementations. This implementation was developed on the Alpha architecture, which uses a little-endian byte-order. The Java classfiles are written using a big-endian byte order because the Sun architecture is big-endian. While the choice of big- versus little-endian is not important, consistency is important. Choosing a byte ordering that is consistent with the underlying processor architecture will allow the parser to load more efficiently; however, to widely deploy JET, all implementations must conform to a byte-ordering standard regardless of the underlying architecture.





**Figure 3 JET Specialized Generation Process**

#### 4.2.2 Generator

Once the JET IR has been created, it is kept for future reference. Copies are made and passed to the generator and the specializer. The generator and specializer operate by modifying the JET IR; making copies allows the generator and specializer to modify the IR as needed without requiring the parser to reload the JET attribute. This specialized generation process is summarized in figure 3. The generator has to perform three tasks: code scheduling, register allocation and code emission. The output from the generator is a standard piece of machine code that can be executed like any other program. The initial code generation for a method will produce machine code that is not specialized. This machine code is registered with the JVM in exactly the same manner as JIT generated machine codes.

#### **4.2.2.1 Scheduler**

The current implementation implements a dummy no-op scheduler. Turbo, the preprocessing stage, has performed scheduling prior to this point; thus it is unnecessary to again perform scheduling during code generation to obtain well-scheduled code. The design does, however, suggest that a more sophisticated runtime scheduler may further improve the performance of some types of code. It is not clear at this point, how the trade off between extra scheduling overhead and further optimized machine code compare. Runtime scheduling is likely to be most beneficial in code that is specialized heavily. A specialized code generation will have fewer instructions compared to the non-specialized code generation, and certain constraints may be removed so that instructions may be rescheduled and further improved. The time constraints for this project did not allow design and implementation of a code scheduler.

#### **4.2.2.2 Register Allocation**

Register allocation is divided into 2 phases: there are variables that are global to the entire method and used across code blocks as well as variables that are local to code blocks. The global variables include variables that must be allocated in designated locations to comply with calling standards such as arguments to procedure calls and return values. Local variables without restriction on locations may be allocated in between global variables or in another free registers. Local variables that do not conflict with each other can share the same register. The JET system takes advantage of this distinction between global and local variables by splitting up the allocation so that the majority of the computationally intensive tasks are performed during the Turbo phase.

In general, a two phased register allocation is somewhat inefficient in its use of registers; however, the JET system is designed so that Turbo performs a Limit phase where Turbo tries to maintain that the register pressure, the number of live registers needed at any point in the code, is at or below the number of register available. This property allows JET to efficiently break up register allocation into a global and a local phase. Turbo is responsible for allocating the global variables and procedure arguments according to the JET calling standard. Turbo is also responsible for grouping of local variables that do not conflict and can potentially share the same register. This is known as symbolic allocation, where each symbolic register is a color that is assigned to that group of variables.

During the runtime Afterburner phase, these symbolic registers are matched up with real physical registers. An attempt is first made to match symbolic registers up with physical registers that were allocated to global variables. This effort reduces the number of free, unrestricted physical registers needed and is possible if the involved variables are not used or not live over the same range of instructions. Symbolic registers that were not matched up with global registers are then allocated into the remaining available physical registers during the final allocation phase. The final allocation phase, whose name is one-pass allocation, takes a linear pass over the remaining unallocated variables and assigns physical registers to these variables.

There is the possibility that not enough physical registers exist to accommodate all the symbolic registers. In this situation, spill code to write variables into stack or memory

locations must be inserted into the generated code to partially relieve the register pressure. The implementation does not actually insert spill code during the register allocation phase but instead marks the values to indicate that their assigned location is on the stack and leaves the spill code insertion for the code emission phase.

The JET IR is designed so that each SSA value node includes a location field. The location field indicates where in the machine this value is stored. For example, the integer constant zero has a location of R31. Global variables are assigned physical register locations during the static phase. The symbolically allocated variables have symbolic register locations. Value nodes that do not emit instructions have a null location because they do not require registers to hold its value. When symbolic registers are matched up with physical registers during register allocation, all value nodes with that symbolic register get their locations updated from the symbolic register location to the allocated physical register location. Value nodes may also be allocated to stack slot locations when the number of available registers have run out.

This division of labor allows runtime register allocation to require only a few passes over the set of instructions. Register allocation is typically computationally intensive and a major bottleneck in dynamic compilation. JET is able to limit the amount of computation necessary at runtime and keep the register allocation overhead to a minimum. A detailed explanation as well pseudo-code related to the register allocation design can be found in Appendix D.

Some assumptions are inherent in the design of the register allocation process. First of all, many of the global variables are assigned according to a JET calling convention, which is the same as the Alpha calling convention. Future implementation of JET will need to also support the same calling convention within the JET architecture but may use its native calling convention for code outside the JET architecture. The next assumption is that there are 32 floating and 32 integer registers available. This is fairly typical among modern architectures. If more or fewer registers are available, then some form of emulation will be necessary. While these assumptions make the design somewhat less generically applicable, some basic assumptions are necessary, and these assumptions are based on fairly common trends in industry. These limitations and assumptions are maintained so that a JET classfile can be created once and executed anywhere an implementation of Afterburner is available.

#### **4.2.2.3 Emitting Code**

The last component of the generator is the code emitter. The code emitter translates JET opcodes into actual machine instructions. The spill codes are inserted and the generated code stubs are registered with the JVM. Most SSA values can be translated directly into machine instructions; however, flow control instructions that require relative offsets such as branches must first be emitted with null offsets as the final code positions may not yet be known. Once all the instructions have been generated, relocations get applied so that the references and offsets are accurate and correct. The complete list of JET opcodes and its descriptions may be found in Appendix B.

Code is emitted by translating the opcode of the value node into an actual machine instruction. If the opcode is an instruction that requires additional arguments, the instruction must be emitted such that the correct registers are used as arguments. These registers are found by looking up the location of the argument value nodes. The output of the instruction must also be placed in the correct register by looking up the location of the current value node. If a value node's location is on the stack, then spill code must be generated and a temporary register must be employed. Since an instruction may require at most two arguments and the output register may reuse one of the input registers, the worst case, a situation in which both arguments as well as the output reside in stack locations, will require at most two temporary registers. The JET calling standard always reserves one temporary register that is not assigned to variables. The other temporary register is formed by using the return address (RA) register. RA register is used to keep track of the return address for a particular subroutine call. RA is saved on the stack whenever a subroutine code segment makes additional, nested subroutine calls. The scheme of using RA as a temporary register adds the constraint that RA will also need to be saved on the stack if there exists an instruction that requires two temporary registers. A detailed explanation of the JET calling standard can be found in Appendix C.

When classfiles are loaded by the JVM, a method table is created to map code stubs to the methods. This is necessary for the correct inheritance of objects. When methods are invoked, the actual executed code must first be looked up in the method table. If the caller method is a piece of generated code, then the process can be streamlined so that the caller method calls the callee code directly. This is possible if the method being invoked

is static or if it is the only one of its type and signature. For example, methods that are not static but have not yet been known to be overridden can be called directly. This optimization requires that each call site be registered so that if the generated code changes or if methods are overridden, these direct call sites can be updated to call the correct new code. This process allows the JVM to switch easily between interpreted code and JIT generated code. JET generated machine code behave similarly to JIT generated code, and must also be registered with the JVM before the JVM can make use of the JET generated code. Registration of JET generated code can be done using the same process as for JIT generated code.

### **4.2.3 Specializer**

Upon the first execution of a JET generated call site, the specializer will be invoked before execution. The call site is set up to call a code stub that executes the specializer instead of the actual method. The specializer analyzes executed methods and the calling conditions to see if specialization is possible and worthwhile. If so, the specializer creates specialized versions of the JET IR and sends the JET IR to the generator. The specializer also registers the newly created specialized code with JET and updates the specialized call site.

The generator emits indirect subroutine calls. An intermediate specializer invocation code stub is called before the subroutine code is executed. The specializer stub determines whether specialization is possible, and if so, whether a specialized generation of this instance exists already or a new specialized generation must be created.

For each method, Turbo is responsible for determining what input arguments would be helpful as constants. Turbo also marks certain SSA values as constants if they're known as constants. During the specializing phase, the specialized determines which input arguments are constants for each executed subroutine call. The specialized then computes the intersection of the set of arguments that the method wants to have as constants and the ones that actually are constants. IF the resulting set is null then specialization is not possible and the indirect call through the specialized is replaced with a direct call to the callee. If the resulting set is not null, then specialization is possible. This intersection set will be known as specialization set.

Specializations with the same specialization set are considered the same category or type of specialization, as they will have similar specialization effects. If the specialized determines that specialization is possible, it searches through a linked list of existing specialization categories for that method. If one exists, then it continues by looking for a specialization instance with identical arguments. If such an instance exists, this particular specialization has been performed in the past and the specialized code can be reused. If no such instance exists, then a new specialization must be performed. The newly generated instance is registered under the appropriate category following generation. If no such specialization category exists, then a new category is created and a new specialization instance is generated. The categorization makes it easier to determine if a particular specialization instance exists already. This cataloging and registration process is similar to the code registration process of the JIT and the JVM.



While a number of various optimizations are possible during runtime specialization, this research focused on constant propagation and procedure cloning. When a call stubs invokes the specializer and the specializer determines that specializations are possible and needed, constant propagation is performed. Using an algorithm similar to constant propagation algorithms in classic compilers, the specializer generates specialized clones of the procedure being invoked. Because this specialization is performed at runtime, the system knows the values of the arguments. The specialization category determines which arguments are considered as constants in the function being specialized. For each argument that is considered a constant, the specializer propagates the constant by finding descendent values that use constants as inputs. If all arguments to an instruction are constants, the output of that instruction is also a constant and its value can be evaluated and stored as a constant. Constant values do not require code to be emitted unless the constant values are used by instructions that do not have constant values. Branches in the code can be eliminated if the condition variable can be determined to be a constant. A more detailed overview of the constant propagation algorithm used can be found in Appendix E.

This research limited the effects of specialization to strictly elimination of code. This limitation was put in place to minimize the complexity of implementation. While techniques such as loop unrolling are typically used in conjunction with constant propagation, such techniques were not utilized. In defense of this decision, loop unrolling is performed during Turbo for loops that benefit from unrolling. Obviously, additional

and more precise loop unrolling can be performed during runtime specialization and should be considered for the next iteration of this design.

Once the specialized code has been generated, the execution must resume seamlessly. The specializer has already generated the specialized code and registered it as a specialization instance under the appropriate specialization category. The original call site has also been patched so that future execution of that call site will no longer invoke the specializer call stub but instead invoke the appropriate specialized code. The specializer needs to execute the specialized code and return control to the JVM. Instead of having the specializer handle the execution and deal with all the possible exception scenarios, the easiest approach is to modify the call stack return address from the instruction after the call site to the call site itself. Now the specializer can simply return control to the JVM and be confident that the JVM will be fooled into re-execution of the now updated call site. This re-execution will now invoke the newly generated specialized code, and all will appear normal to the JVM and the user.

## **5 Analysis**

Constant propagation is achieved by disseminating knowledge and assuming certain input arguments are constants. Computational instructions that do not involve I/O and memory access benefit from constant propagation because their results can be saved as constants and do not need to be calculated again in future executions. Appendix F illustrates some typical code generations and specializations starting from the Java source files.

To determine the benefit of JET system, a number of relative performance measurements were assessed. Factors considered in performance measurements include file size, code size, and execution speed. A detailed summary of the performance measurements can be found in Appendix G.

JET classfiles are normal Java classfiles with an added attribute. This JET attribute contains all the information required to efficiently generate code and perform specializations. This additional information comes at a price; the JET classfiles are on average thirty-two times as large as a regular Java classfile. For this reason, JET should not be implemented on a system that is constrained by disk storage space.

Benchmark performance tests were executed to evaluate JET performance. The Embedded Caffeine Mark 3.0 benchmark suite was chosen for this purpose. Each scenario is executed multiple times and the average performance values compared. The following five scenarios were executed: classic Java JVM using interpretation on normal classfiles, JIT enabled JVM on normal classfiles, classic Java JVM using interpretation on JET classfiles, JET enabled JVM with dynamic code generation but no specialization, and JET enabled JVM with dynamic code generation and specialization.

While JET classfiles are much larger than classic Java classfiles, the size does not affect the execution performance. In most benchmarks the performance is nearly identical. The Sieve benchmark actually benefited from a 30% improvement due to the larger JET classfile. It is not clear why the sieve benchmark benefits from a larger input file size.

JIT provide an average 300% performance improvement compared to classic, interpreted Java. The JET enabled JVM without specializations showed an additional 180% performance improvement over the JIT, and a 550% improvement over classic, interpreted Java. This analysis suggests that the larger file sizes of staged compilation have paid off handsomely in performance improvements. JET with specializations had only an insignificant advantage over the JET without specializations. In fact, on the Floating benchmark, JET with specialization was actually slightly worse than the JET without specialization. All JET performance numbers include dynamic compilation and specialization overhead.

## **6 Conclusion and Future Work**

It appears that specializations were not extremely effective. A possible explanation is that the amount of analysis carried out was insufficient or not widely applicable. Perhaps a more ambitious specialization policy would allow more methods to be specialized and a broader effect and performance improvement can be observed. Deeper analysis of how and why programs benefit from specialization will help pave the way to new and more in-depth types of specialization. Currently, the only specialization performed is constant propagation. Without dynamic loop unrolling, it is difficult for constant propagation to produce dramatic performance improvements.

If a more relaxed specialization policy is implemented, more arguments can be treated as constants and more specialization would be possible. This new design could attempt to

specialized on variables that are not guaranteed to be constants. If a variable is seen frequently with the same value, it could be treated as a constant and used to specialize. This approach allows more specialization to occur but incur the additional complexity that a verifier code stub must be produced to ensure that a variable that is assumed to be constant does not change value. While it is not clear that specialization will provide much more benefit, using a more relaxed specialization policy will allow more specialization to occur and a more definitive answer on the benefits of specialization can be obtained.

Further constant propagation can be achieved if procedure calls can be eliminated through constant propagation. This would require support from the static analysis phase. If a method can be determined to have predictable results given constant arguments, then that method can be executed during specialization and its result can be stored as a constant in the caller. Since the analysis to determine if a method is predictable will likely be highly involved, it is most suited for the Turbo stage. Even without Turbo support, there exist a few common runtime procedures that are currently known to be predictable and can be dynamically resolved into constants with only a few minor modifications to Afterburner.

Another idea for specialization is to eliminate unnecessary synchronization overhead. If a synchronized object is referenced by only one object, then there is no need to lock the synchronized object. Only one reference of the synchronized object exists and no possible race condition exists.

Java is a powerful but young language. There is lots of room for improvement. This research applied new approaches to execution of Java programs. The combination of static compilation and dynamic optimization combine to make a powerful staged compilation process that lends itself easily to optimization, specialization, constant propagation, and procedure cloning. These techniques were united to create JET. Dynamic code generation through staged compilation proved to be an excellent technique to improve Java performance; however, the types runtime specialization implemented were not extensive enough to produce definitive performance improvements. Insights gained from this experience can help refine the next iteration of JET and perhaps lead to further increases in performance.

## Appendix A: JET IR Specification

The following document contains the specification for the current version of the JET internal representation binary output (JET IR).

JET files are essentially Java class files with an added class attribute. This attribute is called "JET" and contains the JET structure that will be described below.

JET attributes can be outputted in either *little-endian* or *big-endian* order. Since the initial implementation was development on the Alpha architecture, and the Alpha architecture is little-endian, the little-endian byte-order was chosen. The choice is not important; however consistency across various implementations is important.

The bytes in a JET IR are laid out in an order that is very similar to how these structs would be laid out in program memory using a memory-manipulation language such as C. This should look exactly like the automatic memory alignment for structs that is performed by the C compiler. A relative "pointer" in a JET attribute is the file offset of the structure within the file.

The process for reading in a JET attribute:

1. Find the JET attribute from the class file parser in the JVM.
2. Grab the offset to the beginning of the JET attribute
3. Iterate through the different structures of the JET attribute casting file offsets into the structs and fixing pointers.

Since relative pointers are file offsets, they have to be converted into absolute pointers using the following calculation:

```
ptr = (T *)((long)starting_memory_location + (long)ptr)
```

T\* is a pointer to some JET structure type and `starting_memory_location` is the memory address of the beginning to the JET structure (or the pointer address of the `malloc`-ed memory in step 2 above). The *long* data type is used for pointer calculations since the Alpha architecture uses 64-bit addressing.

### ***JET***

Each JET attribute contains the following structure:

```
JET {
    u2          methodCount;
    MethodInfo[] methods;
}
```

The items in the `JET` structure are as follows:

### **methodCount**

This item holds the number of methods that are contained within this `JET` attribute. Should be the same as the number of methods contained in the classfile.

### **methods**

The method item is a table of methods that contain the intermediate representations (IR's). The format of a method and its IR are defined by the `MethodInfo` structure. The size of this table is defined by `methodCount` item.

## *Method Information*

Every method has an intermediate representation structure contained within `JET`. This IR consists of two separate structures with pointers between them. The first structure is the control flow graph (CFG) and the second is the value graph generated for static single assignment (SSA) form. The CFG is made up of basic blocks connected by successor and predecessor pointers. The SSA form is made up of value nodes that represent instructions and connected by pointers to other value nodes that make up the parameters of that instruction.

Each `MethodInfo` item must have the following structure:

```
MethodInfo {
    u2          blocksCount;
    u2          valueCount;
    u2          paramCount;
    value**     params;
    bitvec*     rtConstArgs;
    blockInfo[] blocks;
    valueInfo[] values;
}
```

The items in the `MethodInfo` structure are as follows:

### **blocksCount**

This item contains the number of basic blocks contained within the CFG for this method.

### **valueCount**



This item contains the number of individual values that make up the SSA value graph for this method.

### **paramCount**

This item contains the number of parameters to this method. This number includes the object references for instance methods (pointer to *this* object).

### **params**

This item contains a list of values that are the parameters to this method. The length of this list is specified by the `paramCount` item.

### **rtConstArgs**

This item contains a `bitvec` of size equal to the number of arguments to this method. Item `n` in `rtConstArgs` will be set if knowing that the `n`-th argument to this method is a runtime constant will help in specializing this method.

**NOTE:** The size of this set will be equal to `paramCount`. This includes the instance object for instance methods. The size of this set will not be the same as the number of inputs to a method call value.

### **blocks**

The `blocks` item contains a table of basic block information for a CFG. The format of these blocks is defined by the `blockInfo` structure. The length of this table is established by the `blockCount` item. The `blocks` array is ordered in the way that they should be written out during code generation.

### **values**

The `values` item contains a table of values within the SSA value graph. The format of these values is defined by the `valueInfo` structure. The length of this table is established by the `valueCount` item.

## ***Block Information***

Each basic block within the CFG contains information regarding the type of control within the block, the successor blocks, pointers to values used in this block, and liveness information to aid in the allocation of registers. Some block types need special added information in order to generate code for that block. Thus, there are three types of block output: `blockInfo`, `excBlockInfo`, and `multiBlockInfo`. The default basic block follows this structure:

```

blocksInfo {
    u1      type;
    u1      controlType;
    u2      valueCount;
    u2      predecessorCount;
    u2      successorCount;
    u2      index;
    u1      isLoopHead;
    valueInfo* valueRoot;
    valueInfo** values;
    blockInfo** predecessors;
    blockInfo** successors;
    bitvec*   liveOut;
    bitvec*   liveStart;
    bitvec*   liveEnd;
    bitvec*   liveThrough;
    bitvec*   liveTransparent;
    auxInfo*  aux;
}

```

The items in the `blockInfo` structure are as follows:

### **type/control\_type**

The `type` and `control_type` items contain two sets of type information. This information is created when the CFG is created inside of the Swift compiler.

The tags for the `type` and the `controlType` of the block are listed in the following table:

<i>Type</i>	<i>Value</i>	<i>ControlType</i>	<i>Value</i>
NORMAL	0	SIMPLE	0
HANDLER	1	IF	1
EXTRA	2	SWITCH	2
ENTRY	3	THROW	3
NORM_EXIT	4	FAULT	4
EXC_EXIT	5	JSR	5
GRAPH_EXIT	6	RET	6

### **valueCount**

This item contains the number of values that make up the instructions for this basic block.

### **index**

This is the numerical identifier of this `blockInfo` among the `blocks[]` of the `MethodInfo` that holds this `blockInfo`.

**valueRoot**

This item contains a pointer to the value that decides the control flow out of this block.

**values**

This item contains a table of pointers to pointer to the values from the SSA value graph used in this basic block. The size of this table is determined by the `valueCount` item.

**successorsCount**

This item contains the number of successor blocks to this block within the CFG.

**successors**

This item contains a table of pointers to successors to this block. This table consists of a list of pointers to `blockInfo` structures that contain the basic block successors. The size of this table is determined by the `successorCount` item.

**NOTE:** In the case of IF blocks, the successors are ordered such that the fall-through block is the first successor, and the branch-to block is the second successor.

**liveOut / liveStart / liveEnd / liveThrough / liveTransparent**

These items contain bit vectors that represent the values that are live in the various categories for a block.

## *Value Information*

Each node in the value graph represents an operation and a value. Nodes are connected if a node is used as parameters in another node. Each method contains an array of values. The structures of these values have the following format:

```
valueInfo {
    u1      op;
    u1      type;
    u2      pc;
    u2      index;
    u2      paramCount;
    u2      useCount;
    u1      locationType;
    u1      locationFlags;
    u2      location;
    u1      isSpilled;
    u1      isRTConst;
    bitvec* unavailRegs;
    valueInfo** uses;
```

```

    valueInfo** params;
    blockInfo*  container;
    auxInfo*    aux;
}

```

The items in the `valueInfo` structure are as follows:

### **op**

The `op` item contains a number that represents a particular operation within an IR stage. These ops are defined in Appendix B.

### **type**

The `type` item contains a number that represents a type for a value. These types are listed in the table below.

<b>type</b>	<b>value</b>
VOID	0
CC	1
FCC	2
TUPLE	3
BOOLEAN	4
BYTE	5
CHAR	6
SHORT	7
INT	8
LONG	9
FLOAT	10
DOUBLE	11
ARRAY	12
STORE	13
NULL	14
OBJECT	15

### **pc**

The `pc` item contains the program counter for this particular instruction. This information is saved for use by the exception handling mechanism.

### **index**

This is the numerical identifier of this `valueInfo` within the `values[ ]` item of the `MethodInfo` that holds this `valueInfo`.

### **locationType**

The `locationType` item contains place where the memory for this value should live. The following table describes the different `locationTypes`.

<b>locationType</b>	<b>value</b>
VOID_LOCATION	255
INT_REG	0
FLOAT_REG	1
STACK_TMP	2
STACK_IN_ARG	3

### **locationFlags**

Contains added information about the memory location of this value, such as whether it is assigned to a symbolic or physical register. The following table describes the different `locationFlags`. The value of a `locationFlags` item is a bit mask of the values in the table.

<b>locationFlags</b>	<b>value</b>
IS_REGISTER	1
IS_CALLEE_SAVE	2
IS_RESERVED	4
IS_SYMBOLIC	8
IS_LOCAL	0

### **location**

The number associated with the physical register, or symbolic register, or the stack location that holds this value. This item along with `locationType` and `locationFlags` gives all the possible memory locations for a value within a method.

### **isSpilled**

This item is set to 1 if this variable is spilled during global or local allocation and needs to be stored to a stack location after its definition and loaded from the stack before every use.

### **isRTConst**

This item is set to 1 if this variable is a runtime constant. This information can be used to specialize a method.

**unavailRegs**

This item contains a set of registers should not be assigned to this value because it somehow conflicts with the lifetime of this value. This set could include the scratch registers, if the value is live across a method call, or other physical registers which have been assigned to values and conflict with this value.

**useCount**

The `useCount` item contains the number of values that use this value as an input argument.

**uses**

The `uses` item contains a list of pointers to `valueInfo` structures that contain the values that use this value as an input argument. The length of this list is defined by the `useCount` item.

**paramCount**

The `paramCount` item contains the number of argument values to the operations described within this value.

**params**

The `params` item contains a list of pointers to `valueInfo` structures that contain the arguments to the operation described within this value. The length of this list is defined by the `paramCount` item.

**container**

The `container` item contains the `blockInfo` that holds this value. Thus, the `values` item of this `container` will also contain a pointer back to this `valueInfo`.

**aux**

The `aux` item contains any auxiliary information for a value that cannot be stored within the `params`. This information includes constants, field and method references, and argument numbers. This item is of variable length and depends upon the type tag that is defined by the `auxInfo` structure.

## *Auxiliary Information*

Every `valueInfo` and `blockInfo` structure contains an auxiliary item for holding any extra information. This information includes constants, field and method references, and argument numbers. This item is of variable length and depends upon the `tag`.

**NOTE:** Auxiliary information structs are shared amongst all of the methods in the JET file, much like the constants in the constant pool. When relocating pointers, make sure to relocate them once instead of numerous times which may happen if you relocate them on each encounter through the values arrays.

The basic form of all the auxInfo structures is the following:

```
auxInfo {
    u2      tag;
    u1      isResolved;
    u1[]    info;
}
```

The items in the auxInfo structure are as follows:

### tag

The tag item contains a number that represents the type of information stored within the auxInfo structure. This tag also gives information as to the length of the info array.

The following table describes the possible tags for an auxInfo structure. The length column tells the length of the info array that can be expected.

<b>Tag</b>	<b>Value</b>	<b>Length</b>
VAL_Void	0	4
VAL_Integer	1	8
VAL_Float	2	8
VAL_Long	3	16
VAL_Double	4	16
VAL_String	5	16
VAL_Fref	6	32
VAL_Mref	7	32
VAL_BlockVec	8	16
VAL_RuntimeProc	9	16
VAL_RefType	10	16
VAL_FrefOffset	11	32
VAL_JumpTable	12	32
BLOCK_ExcLabel	13	16
BLOCK_IntLabel	14	16

### isResolved

Since auxInfos are shared between different values, a space is left available in the auxInfo struct for determining whether this auxInfo has been resolved during the read-in process.

**info**

The `info` item contains the actual data for an `auxInfo` structure. This array is of variable length, and its size is determined by its `tag`. The different types of `info` are described in the next sections.

***VAL\_Void***

```
VAL_Void {
    u2 tag;
    u2 isResolved;
}
```

A `VAL_Void` `info` structure contains nothing other than the header of the `auxInfo` structure.

***VAL\_Integer, VAL\_Float***

```
VAL_Integer, VAL_Float {
    u2 tag;
    u2 isResolved;
    i4 val;
}
```

`VAL_Integer` and `VAL_Float` `info` structures have four bytes for the value of the number. `VAL_Float` values are encoded using the `Float.floatToIntBits()` method. Numbers are encoded in little-endian byte order.

***VAL\_Long, VAL\_Double***

```
VAL_Long, VAL_Double {
    u2 tag;
    u2 isResolved;
    i8 val;
}
```

`VAL_Long` and `VAL_Double` `info` structures have eight bytes for the value of the number. `VAL_Double` values are encoded using the `Double.doubleToLongBits()` method. Numbers are encoded in little-endian byte order.

***VAL\_String***

```
VAL_String {
    u2 tag;
    u2 isResolved;
    utf8* string;
}
```

`VAL_String` `info` structures contains a pointer to a null-terminated character array which is the utf-encoded version of a Java string



***VAL\_Fref, VAL\_Mref***

```

VAL_Fref, VAL_Mref {
    u2    tag;
    u2    isResolved;
    utf8* class;
    utf8* name;
    utf8* signature;
}

```

The items in a `VAL_Fref` or `VAL_Mref` info structure are as follows:

**class**

The `class` item contains a pointer into the `cpool` table for the name of the owner class that contains this field/method.

**name**

The `name` item contains the name of this field/method.

**signature**

The `signature` item contains the Java signature of this field/method.

***VAL\_BlockVec***

```

VAL_BlockVec {
    u2    tag;
    u2    isResolved;
    u2    blockCount;
    BlockInfo** blocks;
}

```

The items in a `VAL_BlockVec` structure are as follows:

**blockCount**

The `blockCount` item contains the number of blocks within this `BlockVec`.

**blocks**

The `blocks` item is an array of block numbers that make up this `BlockVec`. These block numbers are also the offset into the `blocks` table used to create the CFG.

**VAL\_RuntimeProc**

```

VAL_RuntimeProc {
    u2          tag;
    u2          isResolved;
    u2          type;
    auxInfo*    aux;
}

```

The items in a VAL\_RuntimeProc structure are as follows:

**type**

The `type` item contains the unique numerical identifier of a runtime procedure. The list of types can be found the table below with their aux types.

**aux**

The `aux` item contains any extra information needed by the RuntimeProc. This is a VAL\_Integer in the case of creating a new array, otherwise it is a VAL\_String that contains the name of a class.

The following table contains all of the possible RuntimeProcs as well as their associated values and the types of their aux fields:

<b>type</b>	<b>value</b>	<b>aux type</b>
SYNC_ENTER	1	VAL_Void
SYNC_EXIT	2	VAL_Void
NEW	3	VAL_String
FCMPL	4	VAL_Void
FCMPG	5	VAL_Void
DCMPL	6	VAL_Void
DCMPG	7	VAL_Void
NEWARRAY	8	VAL_Integer
ANEWARRAY	9	VAL_String
MULTIANEWARRAY	10	VAL_Void
INSTANCEOF	11	VAL_String
CAST_CK	12	VAL_Void
IDIV	13	VAL_Void
IREM	14	VAL_Void
LDIV	15	VAL_Void
LREM	16	VAL_Void
FREM	17	VAL_Void
DREM	18	VAL_Void
THROW	19	VAL_Void
INIT_CK	20	VAL_String
D2I	21	VAL_Void

D2L	22	VAL_Void
AASTORE	23	VAL_Void
SYNC_EXIT_RET	24	VAL_Void

### ***VAL\_RefType***

```
VAL_RefType {
    u2    tag;
    u2    isResolved;
    utf8* name;
}
```

The items in a `VAL_RefType` info structure are as follows:

#### **name**

The `name` item contains the name of the class that this value is referencing.

### ***VAL\_FrefOffset***

```
VAL_FrefOffset {
    u2    tag;
    u2    isResolved;
    u2    offset;
    utf8* class;
    utf8* name;
    utf8* signature;
}
```

The items in a `VAL_FrefOffset` info structure are as follows:

#### **offset**

The `offset` item contains the byte offset of this field reference from the beginning of the object it references in memory.

#### **class**

The `class` item contains the name of the owner class which this field.

#### **name**

The `name` item contains the name of this field.

#### **signature**

The `signature` item contains the Java signature of this field.

***VAL\_JumpTable***

```

VAL_JumpTable {
    u2      tag;
    u2      isResolved;
    u2      type;
    u2      baseIndex;
    u2      tableOffset;
    i4      min;
    i4      max;
    u4      nonDefaultEntries;
    blockInfo* block;
}

```

The items in a VAL\_JumpTable structure are as follows:

**type**

This is the type of the Jump Table. The `type` item contains a value of 0 for a LOOKUPSWITCH type and a value of 1 for a TABLESWITCH type.

**baseIndex**

Index of the instruction that gets the base pointer

**tableOffset**

Offset of the emitted table from the baseIndex instruction

**min**

The minimum value for a label in the jump table

**max**

The maximum value for a label in the jump table

**nonDefaultEntries**

The number of non-default labels in the jump table.

**block**

This item is a pointer to the block that holds the switch statement responsible for this Jump Table.

***BLOCK\_ExcLabel***

```

BLOCK_ExcLabel {
    u2      tag;
    u2      isResolved;
    u2      excCount;
    excLabel* exceptions;
}

```

```
excLabel {
    utf8*      excName;
    blockInfo* handler;
}
```

The items in a `BLOCK_ExcLabel` info structure are as follows:

### **excCount**

The item contains the number of exceptions that can be raised within this block.

### **exceptions**

The item contains a table of `excLabels` that hold the information on which exceptions can be thrown in a block and the blocks that contain the handler information.

The items in an `excLabel` structure are the following:

### **excName**

This item contains a pointer to the class name for an exception thrown by this block. If a faulting instruction returns to this block with an exception of `excName` type, it jumps to the `handler` block. If the handler catches all exception, `excName` will contain the empty string.

### **handler**

This item contains a pointer to the `blockInfo` that holds the handler code for a caught exception of `excName` type.

## ***BLOCK\_IntLabel***

```
BLOCK_IntLabel {
    u2      tag;
    u2      isResolved;
    u2      labelCount;
    intLabel* labels;
}
intLabel {
    i4      label;
    blockInfo* destination;
}
```

The items in a `BLOCK_IntLabel` structure are as follows:

### **labelCount**

This item contains the number of labels that can be used to transfer control in this block.

**labels**

The item contains a table of `intLabel` labels that are the branch determining values. Each successor has an `intLabel`, but the number of labels associated with a successor may be greater than one. The size of this table is determined by the `labelCount` item.

The items in an `intLabel` structure are as follows:

**label**

This item contains the integer that is the label for a switch statement. The successor to branch to for this label is described in the `destination` item.

**destination**

This item contains the block in the `successors` array that should be the destination block of a switch statement if the result of the switch is the value in `label`.

## *Bit Vector*

Each block in the CFG also contains helpful information about the liveness of the variables as execution proceeds through the block. This liveness information is calculated in a final phase of the Swift compiler and passed along into the binary output. The representation chosen to represent these sets is bit vectors. Each value in the set is represented by the integer from the values' `index` field.

```
bitvec {
    u8 length;
    u8* set;
}
```

The items in a `bitvec` structure are the following:

**length**

This item contains the maximum magnitude of integers represented in this set. It is also the number of values in the method containing this set.

**set**

This item contains a list of quadwords that form the bit vector representation of this set.

## *Exception Information*

Each block that can throw an exception must contain a list of `excLabels`. These labels contain the type of the exception, by class name, and a pointer to the block that holds handler for that particular exception. This information is gathered from the exception table in the classfile and passed down with the IR.

```
excLabel {
    utf8*      excName;
    blockInfo* handler;
}
```

The items in an `excLabel` structure are the following:

### **excName**

This item contains a pointer to the class name for an exception thrown by this block. If a faulting instruction returns to this block with an exception of `excName` type, it jumps to the `handler` block. If the handler catches all exception, `excName` will contain the empty string.

### **handler**

This item contains a pointer to the `blockInfo` that holds the handler code for a caught exception of `excName` type.

## *UTF8-String constants*

An UTF8-String contains a list of one-byte utf-encoded Unicode characters followed by a null-terminating character. One can consider the `utf8` type to be the same as an `u1` or a `char`.

## Appendix B: JET Opcodes

IN_ARG	1	PHI	31
Input argument to subroutine		Abstract value representing a node whose value differs depending on the instruction path executed to reach this node.	
SELECT	2	IF	32
Abstract value representing the result of a memory operation.		Abstract value representing flow control.	
COPY	3	REAL_RETURN	33
NOP	4	SWITCH	34
PIN	5	tableswitch or lookupswitch	
Used as a fake input to operations that need to be pinned within a certain region of the CFG.		NULL_CK	35
SPILL	6	Null check.	
Store to stack location (used for spilling)		LENGTH	37
RESTORE	7	Array length.	
Load from stack location (used for spilling)		GET_FIELD_ADDR	45
ADD	8	Get object field address	
SUB	9	INVOKE_VIRTUAL	46
MUL	10	INVOKE_SPECIAL	47
DIV	11	INVOKE_INTERFACE	48
		INVOKE_STATIC	49
		INVOKE_DIRECT	50
AND	16	INSTANCEOF	51
OR	17	Object type verification.	
XOR	18	RT_CALL	59
NEG	19	Generic call to a runtime routine	
Arithmetic negation		EXCOBJ	61
NOT	26	Object for exception handler	
Logical not		PUT_MT	62
		Store method table of object.	



PUT_SIZE	63	ALPHA_BLBC	84
Store size of object.		Branch if register low bit is clear	
ALPHA_LITERAL	64	ALPHA_CMPEQ	85
Immediate constant (0...255)		Compare signed equal	
Value stored in auxiliary field.		ALPHA_CMPLE	86
ALPHA_IZERO	65	ALPHA_CMPLT	87
Integer register r31		Compare signed less than	
ALPHA_FZERO	66	ALPHA_CMPULT	88
Floating-point register f31		Compare unsigned less than	
ALPHA_LDA	67	ALPHA_CMPULE	89
Load 16-bit constant.		ALPHA_CMOVEQ	90
ALPHA_LDAH	68	ALPHA_CMOVGE	91
Load 16-bit constant high. (Use		ALPHA_CMOVGT	92
in combination with LDA to load		ALPHA_CMOVLE	93
32-bit constant.)		ALPHA_CMOVLT	94
ALPHA_SRA	69	ALPHA_CMOVNE	95
Shift right arithmetic		Conditional move if register not	
ALPHA_SLL	70	equal to zero	
Shift left logical		ALPHA_ZAPNOT	96
ALPHA_SRL	71	Zero out Ra bytes not specified	
Shift right logical		in Rb	
ALPHA_S4SUB	72	ALPHA_SEXTB	97
Scaled by 4 subtract		Sign extend byte	
ALPHA_S4ADD	73	ALPHA_SEXTW	98
Scaled by 4 add		Sign extend word	
ALPHA_S8SUB	74	ALPHA_EXTQH	99
Scaled by 8 subtract		Extract quadword high	
ALPHA_S8ADD	75	ALPHA_EXTBL	100
Scaled by 4 add		Extract byte low	
ALPHA_BITCOMP	76	ALPHA_EXTWL	101
Bit-wise negation		Extract word low	
ALPHA_BEQ	77	ALPHA_INSBL	102
Branch if register equal to zero		Insert byte low	
ALPHA_BGE	78	ALPHA_INSWL	103
ALPHA_BGT	79	Insert byte low	
ALPHA_BLE	80	ALPHA_MSKBL	104
ALPHA_BLT	81	Mask byte low	
ALPHA_BNE	82	ALPHA_MSKWL	105
ALPHA_BLBS	83	Mask word low	
Branch if register low bit is set		ALPHA_SEXTL	106
		Sign extend longword.	

ALPHA_STB	107	ALPHA_CVT_STORE	126
Store byte		Store to stack for conversion	
ALPHA_STW	108	ALPHA_CVT_LOAD	127
Store word		Load from stack for conversion	
ALPHA_STL	109	ALPHA_CVT_STS	128
Store longword		Store to stack for conversion	
ALPHA_STQ	110	ALPHA_CVT_LDL	129
Store quadword		Load from stack for conversion	
ALPHA_STS	111	ALPHA_LOAD_MT	130
Store longword floating		Load method table pointer	
ALPHA_STT	112	ALPHA_LOAD_VTABLE	131
Store quadword floating		Load proc pointer from vtable	
ALPHA_STQ_U	113	ALPHA_LOAD_ITABLE	132
Store unaligned quadword		Load proc pointer from itable	
ALPHA_LDBU	114	ALPHA_LOAD_IID_LOW	133
Load unaligned byte		Load low bits of interface method id	
ALPHA_LDWU	115	ALPHA_LOAD_IID_HIGH	134
Load unaligned word		Load high bits of interface method id	
ALPHA_LDL	116	ALPHA_GLOBAL_HIGH	135
Load longword		Operation for getting the high 16 bit displacement in preparation for accessing global data	
ALPHA_LDQ	117	ALPHA_GLOBAL_LOW4	136
Load quadword		ALPHA_GLOBAL_LOW8	137
ALPHA_LDS	118	Operation for loading a global constant. Takes as input the corresponding GLOBAL_HIGH value.	
ALPHA_LDT	119	ALPHA_PUT_STATIC4	138
ALPHA_LDQ_U	120	ALPHA_PUT_STATIC8	139
Load unaligned quadword		ALPHA_GET_STATIC4	140
ALPHA_ITOFT	121	ALPHA_GET_STATIC8	141
Convert integer to floating		Operations for loading/storing global variables. Takes as input the corresponding GLOBAL_HIGH value, and have an FREF as its auxiliary field.	
ALPHA_CVTQS	122		
Convert quadword integer to longword floating			
ALPHA_CVTQT	123		
Convert quadword integer to quadword floating			
ALPHA_CVTTSSU	124		
Convert quadword float to longword floating			
ALPHA_CVTSTS	125		
Convert longword float to quadword floating			

ALPHA_FLOAD1	142	ALPHA_LOAD_STKARRAY	159
ALPHA_FLOAD2	143	Load pointer to temp array on	
ALPHA_FLOAD4	144	stack	
ALPHA_FLOAD8	145		
Simple field load		ALPHA_BOUNDS_TRUE	162
		Raise bounds if input is true	
ALPHA_FSTORE1	146		
ALPHA_FSTORE2	147	ALPHA_TRAPB	163
ALPHA_FSTORE4	148	Trap instruction for catching	
ALPHA_FSTORE8	149	exceptions	
Simple field store			
		ALPHA_JMP	164
ALPHA_FLOAD_BASE	150	Indirect jump	
Load from roundup(offset, 4)			
ALPHA_FSTORE_BASE	151	ALPHA_BRNEXT	165
Store to roundup(offset, 4)		Branch to next instruction: note	
ALPHA_FIELD_SLL	152	that this instruction is not really a	
Shift left for sign-extension		control instruction. It is just used	
ALPHA_FIELD_EXTBL	153	to capture the address of the next	
ALPHA_FIELD_EXTWL	154	instruction.	
Extract field bits into right place			
ALPHA_FIELD_INSBL	155	ALPHA_LD_JT	166
ALPHA_FIELD_INSWL	156	Load entry from jump table	
Insert field bits into right place			
ALPHA_FIELD_MSKBL	157		
ALPHA_FIELD_MSKWL	158		
Mask out all except field bits			

## Appendix C: JET Calling Standard<sup>2</sup>

### Register Usage Conventions

#### Integer Registers

Register	Description
\$0	Function value register. In a standard call that returns a non-floating-point function result in a register, the result must be returned in this register. In a standard call, this register can be modified by the called procedure without being saved and restored.
\$1 - \$8	Conventional scratch registers. In a standard call, these registers can be modified by the called procedure without being saved and restored.
\$9 - \$14	Conventional saved registers. If a standard-conforming procedure modifies one of these registers, it must save and restore it.
\$15	Stack frame base (FP) register. For procedures with a run-time variable amount of stack, this register is used to point at the base of the stack frame (fixed part of the stack). For all other procedures, this register has no special significance. If a standard-conforming procedure modifies this register, it must save and restore it.
\$16 - \$21	Argument registers. In a standard call, up to six non-floating-point items of the argument list are passed in these registers. In a standard call, these registers can be modified by the called procedure without being saved and restored. Additional arguments must be passed through the stack.
\$22 - \$25	Conventional scratch registers. In a standard call, these registers can be modified by the called procedure without being saved and restored.
\$26	Return address (RA) register. In a standard call, the return address must be passed and returned in this register.
\$27	Procedure value (PV) register. In a standard call, the procedure value of the procedure being called is passed in this register. In a standard call, this register can be modified by the called procedure without being saved and restored.
\$28	Volatile scratch register. The contents of this register are always unpredictable after any external transfer of control to or from a procedure. This unpredictable nature applies to both standard and nonstandard calls. This register can be used by the operating system for external call fixing, auto loading, and exit sequences.
\$29	Global pointer (GP) register. For a standard-conforming procedure, this register must contain the calling procedure's global offset table (GOT) segment pointer value at the time of a call and must contain the calling procedure's GOT segment pointer value or the called procedure's GOT segment pointer value upon return. This register must be treated as scratch by the calling procedure.

---

<sup>2</sup> JET calling standard is the same as the Alpha calling standard

- \$30 Stack pointer (SP) register. This register contains a pointer to the top of the current operating stack. Aspects of its usage and alignment are defined by the hardware architecture.
- \$31 ReadAsZero/Sink register. This register is defined to be binary zero as a source operand or sink (no effect) as a result operand.

### **Floating-Point Registers**

Register	Description
\$f0	Floating-point function value register. In a standard call that returns a floating-point result in a register, this register is used to return the real part of the result. In a standard call, this register can be modified by the called procedure without being saved and restored.
\$f1	Floating-point function value register. In a standard call that returns a complex floating-point result in registers, this register is used to return the imaginary part of the result. In a standard call, this register can be modified by the called procedure without being saved and restored.
\$f2 - \$f9	Conventional saved registers. If a standard-conforming procedure modifies one of these registers, it must save and restore it.
\$f10 - \$f15	Conventional scratch registers. In a standard call, these registers can be modified by the called procedure without being saved and restored.
\$f16 - \$f21	Argument registers. In a standard call, up to six floating-point arguments can be passed by value in these registers. In a standard call, these registers can be modified by the called procedure without being saved and restored. Additional arguments must be passed through the stack.
\$f22 - \$f30	Conventional scratch registers. In a standard call, these registers can be modified by the called procedure without being saved and restored.
\$f31	ReadAsZero/Sink register. This register is defined to be binary zero as a source operand or sink (no effect) as a result operand.

## Appendix D: Register Allocation

The register allocation algorithms used in this research are adapted from classic compiler register allocation algorithms and may be found in Morgan's *Building An Optimizing Compiler*. The two major algorithms that accomplish local register allocation are the FAT algorithm by Hendron and the One-Pass Allocation algorithm. Below is the pseudo-code that describes how these algorithms work:

```

struct LALLOC {
    startTime = 0
    endTime = 0
    numRegister = 0
}

procedure local_allocate(METHOD *m) {
    info = new LALLOC

    for each block b in m {
        build_local_conflict_graph(info, b)

        while set of values in livestart_set is not null {
            t = a value from livestart_set
            remove t from livestart_set

            try_allocate_with_global(info, b, t)
        }

        one_pass_allocate(info, b)
    }
}

```

A generic local allocation algorithm would typically begin by classifying each value in the method and determine the various liveness sets. This calculation was done in Turbo and is not necessary in Afterburner. This algorithm allocates registers for values one block at a time. The first step is to build a local conflict graph that contains liveness ranges for each value node in the block. The live start set is the set of values that are live or in use at the beginning of the block. The values in the live set are global variables. Local allocation attempts to allocate local variables in the same register as these global variables if the liveness ranges of the local variables do not conflict with the liveness ranges of these global variables. Finally, a linear one-pass allocation algorithm is called on the block to allocate the remaining local variables.

Typically local allocation would also have to reduce the register pressure before the algorithm begins, but since Turbo maintains that the maximum register pressure is not larger than the number of register available, a register spilling and pressure reducing step is unnecessary. While this property states that the maximum register pressure is no greater than the number of registers available, this does not imply register spilling is

entirely avoidable. One-pass allocation will still encounter situations where it is too difficult or impossible to allocate all the variables and spill code will have to be emitted.

```

procedure build_local_conflict_graph (LALLOC *info, BLOCK *b) {
    timeCount = 0
    live_set = liveout_set
    endTime[] = int[number of values in method]
    startTime[] = int[number of values in method]
    pressure = 0

    for each value v in the method that contains this block {
        endTime[v] = timeCount
    }

    for each value v in block b in reverse order {
        timeCount++
        startTime[v] = timeCount
        remove v from live_set

        timeCount++
        for each input p to value v {
            if p is not in live_set {
                endTime[p] = timeCount
                insert p into live_set
            }
        }
        cnt = number of elements in live_set
        if (cnt > pressure) {
            pressure = cnt
        }
    }
    timeCount++
    for each value v in live_set {
        startTime[v] = timeCount;
    }

    info->startTime = startTime
    info->endTime = endTime
    info->numRegister = pressure
}

```

Build\_local\_conflict\_graph is responsible for figuring out the range over which each variable is live within a particular block. This is accomplished by determining the first and last times a variable is used. This range is the liveness range of the variable. This calculation begins by initializing all end times for each variable to zero. The algorithm then steps through each value in the block in reverse execution order. Time is measured as relative displacement from the end of the block. Each instruction contributes 2 units of time, one unit for write and one for read. The live set starts out as the set of values that are live at the end of the block. As the algorithm marches through the values, values are inserted into the set of live values if they are read and are not already in the live set. If values are written to then the values are removed from the live set. Start time is set to be the first time that the value is written, and end time is the last time that the value is read.

Some values are live at the beginning of the block and have start time set equal to the beginning of the block.

```

procedure try_allocate_with_global (LALLOC *info, BLOCK *b, VALUE *g) {
  /* this is the FAT algorithm */
  beginTime = info->endTime[g]
  finishTime = 0
  for each value v in block b in reverse order {
    if v has the same type and color as g {
      finishTime = info->startTime[v]
    }
  }

  for each value v in block b in reverse order {
    if v has the same type as g and v has not been colored {
      /* if liveness of g and v do not overlap */
      if (info->endTime[v] >= finishTime and
          info->startTime[v] < beginTime) {
        v->location = g->location
        finishTime = info->startTime[v]
      }
    }
  }
}

```

Local variables can be allocated with global variables if their liveness ranges do not overlap. This algorithm is called once for every global variable. During its execution, it calculates the liveness range for the register used by the global variable by concatenating liveness ranges of all variables that share the same register. Next, it assigns local variables to the same register as the global variable if the liveness ranges of the local variable do not overlap the liveness range of the register.

```

procedure one_pass_allocate (LALLOC *info, BLOCK *b) {
  /* Initialize the free register sets */
  free_regs = set of available registers

  /* Initialize the global register sets */
  for each value v in livestart and livethru sets for block b {
    insert v->location into global_regs
  }

  /* delete liveEnd from freereg set and copy into live set */
  live_set = new set
  for each value v in liveend set {
    remove v->location from free_regs
    insert v into live_set
  }

  free_regs = free_regs - global_regs

  f_set = new set
  for each value v in block b in reverse execution order {
    remove v from live_set
  }
}

```



```

if (v requires a location and
    v->location is not on stack and
    v->location is not in global_regs) {
    insert v->location into free_regs
}

for each parameter p of value v {
    if (p requires a location and
        p is not in live_set) {
        insert p into live_set

        if (p->location is symbolic and
            p->location is not on stack) {
            f_set = free_regs - v->unavailRegs
            if f_set is empty {
                set p->spill SPILL_OUT flag
                p->location.type = STACK_TMP
                p->location = new stack_tmp slot
            } else {
                s = a register from f_set
                remove s from free_regs
                p->location = s
            }
        }
    }
} /* end for each parameter */
} /* end for each value */
}

```

One-pass allocation is a linear algorithm that allocates all the remaining local variables. The algorithm determines the set of free registers by subtracting the registers occupied by global variables from the set of available registers. The algorithm then iterates over each value in the current block in reverse execution order. Each time a read occurs, the value is inserted into the live set; each time a write occurs the value is removed from the live set. When a value is removed from the live set, its registers are put back into the free register set. When a value is added to the live set, a register is chosen from the intersection of the set of free registers and the set of registers that are available to that variable. This is because some variables can only be assigned to certain registers, while other variables are less restrictive. Once one-pass allocation completes, all variables should have been allocated.

## Appendix E: Constant Propagation

The constant propagation algorithm employed is an adaptation of the classic compiler constant propagation algorithm by Wegman and Zadeck. These algorithms may be found in Morgan's *Building An Optimizing Compiler*. The following is pseudo code and detailed descriptions of the algorithm:

```

procedure constant_propagation (METHOD *m, JSP_TYPE *jsp_type) {
    rtconsts = set of arguments that are constants for jsp_type

    worklist = new FIFO queue
    blocklist = new FIFO queue

    /* initializations */
    add entry block of m to blocklist
    for each value v in m {
        set v->state.status = TOP
        if v is a phi node {
            v->state.count = 1;
        } else {
            v->state.count = v->paramCount + 1;
        }
    }
    for each argument value v in rtconsts {
        v->state.value = actual value of corresponding argument
    }

    while (worklist is not empty or blocklist is not empty) {
        while blocklist is not empty {
            b = remove next block from blocklist
            if b is marked reachable {
                skip
            }
            mark b as reachable
            for each value v in b {
                if (--v->state.count <= 0) {
                    /* all inputs are initialized */
                    add v to worklist
                }
            }
            if b is not a conditional block {
                add each successor block of b to block list
            }
        }
        while worklist is not empty {
            v = remove next value from worklist
            oldstatus = v->state.status
            if (oldstatus == BOT) {
                skip
            }
        }

        eval_state(v)
    }
}

```

```

        if v->state.status != oldstatus {
            if v is a conditional branch {
                if v->state.status = CONST {
                    determine which branch's successor
                    block will be executed and add
                    that block to blocklist
                } else { /* status = BOT */
                    add all successor blocks to
                    blocklist
                }
            } /* end if v is conditional branch */
            for each value u that uses v {
                if (u->state.count <= 0) {
                    add u to worklist
                }
            }
        } /* end if new status != old status */
    }
}

/* update m to use new constants and remove excess code */
update(m)
}

```

The main concept in this constant propagation algorithm is that each value node can be in any of 3 status states, TOP, CONST, or BOT. Status states can only transition from TOP towards BOT. Specifically, once a status reaches BOT it can never transition to CONST or TOP. TOP indicates a node is un-initialized or not yet executed. CONST indicates a node is assumed to have constant value. BOT signifies a node has variable value and cannot be transformed into a constant. The constant propagation algorithm uses a block FIFO queue and a value FIFO queue. The algorithm begins with only entry block in the block queue. The algorithm continues until both the block and the value queues are empty. If a block being examined is not a conditional block, its successor blocks are placed on the block queue. Blocks that are conditional must wait until its corresponding branch instruction has been examined before the algorithm can determine which successor block to add. Values whose inputs have all been examined at least once are potential candidates for evaluation and are added to the value queue. When a value is examined, its state is evaluated. If the value's new state differs from its old state, then users of this value need to be updated and are added to the value queue. If the value that was evaluated is a conditional branch then its appropriate target blocks need to be added to the block queue. Once all reachable blocks and values are examined and no further updates are necessary, the algorithm completes.

```

procedure eval_state(VALUE *v) {
    switch (v) {
    case v is input argument:
        if v is an argument marked as constant by the jsp_type {
            v->state.status = CONST
            v->state.value = argument value
        }
        else {
            v->state.statis = BOT
        }
    }
}

```

```

case v is a constant:
    v->state.status = CONST
case v is a phi node:
    if (all inputs to v whose state.status != TOP have the same
        state.value) {
        v->state.status = CONST
        v->state.value = state.value of v's inputs
    } else {
        v->state.status = BOT
    }
}
case v is a node that can be propagated:
    if any param of v has state.status = BOT {
        v->state.status = BOT
    } else if any param of v has state.status = TOP {
        v->state.status = TOP
    } else {
        v->state.status = CONST
        v->state.value = value of operation given constant
                        params
    }
default:
    v->state.status = BOT
}

```

This algorithm determines the state for a given value node. A node's state is determined by examining the inputs to that value. There are roughly three categories of nodes, constant, phi, and normal. If a node is a constant node or an input argument that is classified as a constant by the specialization category, its state is set to CONST and its value set accordingly. A phi node is a value node with multiple inputs. The output value of a phi node equals the value of one of its inputs. The selection of which input differs depending on the flow of execution taken to reach the phi node. This is used typically when a variable is set to different values in different branches. A phi node can be marked as a constant if all of the input nodes that are initialized have the same value. This approach is known as optimistic because it assumes that phi nodes will usually be constants and corrects the assumption once the algorithm determines that the phi node is actually not a constant. This optimistic approach allows more values to potentially become constants. Normal (non-phi and non-constant) nodes are marked as BOT if any of that node's inputs are BOT. Nodes are marked as TOP if any of that node's inputs are TOP. If all inputs to a node are CONST, then that node can be evaluated and marked as a constant. Certain nodes have operations that cannot be transformed into a constant and are marked as BOT.

```

procedure update(METHOD *m) {
    const_set = set of values in m whose state.status = CONST
    needed_set = set of values in const_set that are used by values
                whose state.status = BOT
    remove_set = (const_set - needed_set) + set of values in m whose
                state.status = TOP

    delete from m all values in remove_set
    modify all values in needed_set so that the node is an
        appropriate constant
}

```

```
    remove from m all blocks that are not marked as reachable  
}
```

The update phase of the constant propagation algorithm makes use of all the information gained during constant propagation. Nodes that are not initialized are not executed and can be removed from the JET IR. Blocks that are not reached are also not executed and can also be removed from the JET IR. Constant nodes need to remain only if the constant node is used as input to a non-constant node. All other constant nodes can be removed. Constant nodes that are used by non-constant nodes need to be modified into a JET IR constant. The output of the process is a specialized and reduced JET IR that will be passed to the generator. The generator will use the specialized JET IR to generate specialized code.

## Appendix F: Sample Generation and Specialization

### Java Source

```

public static int Test(int a, int b) {
    int r = a+b;
    int x = 5;
    int y = 9;
    int z = 234;

    if (a > b) {
        r += a;
        r *= y;
        r %= x;
    }
    else {
        r %= x;
        r += a;
        r /= x;
        r += z;
    }
    return r;
}

```

### Non-Specialized Generation

```

0x20021b40 Test [exp 1.60, cum 3.08]
0x20021b40 lda    sp, -16(sp)
0x20021b44 stq    ra, 0(sp)
0x20021b48 bis    a0, a0, t1
0x20021b4c addl   a0, a1, a0           ; r = a+b
0x20021b50 lda    t2, 5(zero)         ; x = 5
0x20021b54 cmple  t1, a1, v0
0x20021b58 bne    v0, 0x20021b60
0x20021b5c br     zero, 0x20021b7c
0x20021b60 bis    t2, t2, a1           ; else {
0x20021b64 bsr    ra, 0x203f5cd4       ;     r %= x;
0x20021b68 addl   v0, t1, a0           ;     r += a
0x20021b6c bis    t2, t2, a1
0x20021b70 bsr    ra, 0x203f5d4c       ;     r /= x
0x20021b74 addl   v0, 0xea, v0        ;     r += z
0x20021b78 br     zero, 0x20021b8c     ; } if (a > b) {
0x20021b7c addl   a0, t1, v0           ;     r += a
0x20021b80 s8addl v0, v0, a0           ;     r *= y
0x20021b84 bis    t2, t2, a1
0x20021b88 bsr    ra, 0x203f5cd4       ;     r %= x
0x20021b8c ldq    ra, 0(sp)
0x20021b90 lda    sp, 16(sp)
0x20021b94 ret    zero, (ra), 1

```

Specialization

```

Test(a=76, b=77) {
    int r = a+b = 76+77 = 153;
    int x = 5;
    int z = 234;

    if ((a > b) = false) {
    }
    else {
        r %= x;
        r += 76;
        r /= x;
        r += 234;
    }
    return r;
}

```

```

0x20021b50 Test [exp 0.87, cum 3.04]
0x20021b50 lda    sp, -16(sp)
0x20021b54 stq    ra, 0(sp)
0x20021b58 lda    a0, 153(zero)           ; r = 153
0x20021b5c lda    a1, 5(zero)            ; x = 5
0x20021b60 bsr    ra, 0x203f5cd4         ; r %= x
0x20021b64 addl   v0, 0x4c, a0          ; r += 76
0x20021b68 lda    a1, 5(zero)
0x20021b6c bsr    ra, 0x203f5d4c         ; r /= x
0x20021b70 addl   v0, 0xea, v0          ; r += 234
0x20021b74 ldq    ra, 0(sp)
0x20021b78 lda    sp, 16(sp)
0x20021b7c ret    zero, (ra), 1

```

```

Test(a=77, b=76) {
    int r = a+b = 77+76 = 153;
    int x = 5;

    if ((a > b) = true) {
        r = 230; /* r += 77; */
        r = 2070; /* r *= 9; */
        r %= x;
    }
    return r;
}

```

```

0x20022e80 Test [exp 0.58, cum 3.07]
0x20022e80 lda    sp, -16(sp)
0x20022e84 stq    ra, 0(sp)
0x20022e88 lda    a0, 2070(zero)         ; r = 2070
0x20022e8c lda    a1, 5(zero)            ; x = 5
0x20022e90 bsr    ra, 0x203f5cd4         ; r %= x
0x20022e94 ldq    ra, 0(sp)
0x20022e98 lda    sp, 16(sp)
0x20022e9c ret    zero, (ra), 1

```

## Appendix G: Performance Data

### Classfile Size Comparison

File	Java (KB)	JET (KB)	JET / Java
cmark3.0/AboutDialog.class	1231	23155	18.81
cmark3.0/BenchmarkAtom.class	331	695	2.10
cmark3.0/BenchmarkMonitor.class	174	250	1.44
cmark3.0/BenchmarkUnit.class	1322	52677	39.85
cmark3.0/CaffeineMarkApp.class	506	7425	14.67
cmark3.0/CaffeineMarkApplet.class	914	22373	24.48
cmark3.0/CaffeineMarkBenchmark.class	3382	208553	61.67
cmark3.0/CaffeineMarkEmbeddedApp.class	1049	43554	41.52
cmark3.0/CaffeineMarkEmbeddedBenchmark.class	2858	156695	54.83
cmark3.0/CaffeineMarkFrame.class	6406	413572	64.56
cmark3.0/DialogAtom.class	1641	61985	37.77
cmark3.0/FloatAtom.class	1184	60434	51.04
cmark3.0/GraphicsAtom.class	2179	118903	54.57
cmark3.0/ImageAtom.class	2811	101285	36.03
cmark3.0/LogicAtom.class	1261	19639	15.57
cmark3.0/LoopAtom.class	940	26685	28.39
cmark3.0/MethodAtom.class	934	26775	28.67
cmark3.0/SieveAtom.class	817	24620	30.13
cmark3.0/StopWatch.class	638	19942	31.26
cmark3.0/StringAtom.class	1121	27819	24.82
cmark3.0/TestDialog.class	1159	31483	27.16
cmark3.0/TestWindow.class	467	7234	15.49
<b>Average</b>			<b>32.04</b>

### Caffeine Mark Performance Ratios

Overall Ratios	Java	JIT	Java on JET	JET w/o SP	JET w/ SP
<b>Java</b>	1	3.085985	1.046884	5.514781	5.517856
<b>JIT</b>	0.324046	1	0.339238	1.787041	1.788037
<b>Java on JET</b>	0.955216	2.947782	1	5.267806	5.270743
<b>JETw/o SP</b>	0.181331	0.559584	0.189832	1	1.000558
<b>JET w/ SP</b>	0.18123	0.559272	0.189727	0.999443	1



### Caffeine Mark Performance Data

These benchmarks were run on a 4 SMP EV-56 Alpha machine.

	Sieve	Loop	Logic	String	Float	Method	Overall
Java	1854	4662	11368	3182	3107	1105	3199
Java	1854	4662	11357	3202	2943	1110	3176
Java	1854	4660	11369	3198	3102	1109	3203
Java	1854	4661	11361	3196	3063	1110	3196
Java	1854	4662	11334	3222	2813	1121	3159
<b>Average</b>	<b>1854</b>	<b>4661.4</b>	<b>11357.8</b>	<b>3200</b>	<b>3005.6</b>	<b>1111</b>	<b>3186.6</b>

	Sieve	Loop	Logic	String	Float	Method	Overall
JIT	5146	10170	33745	10730	5306	8894	9815
JIT	5146	10166	33733	10542	5307	8915	9789
JIT	5147	10164	33904	10815	5307	8917	9839
JIT	5143	10160	33938	10972	5304	8908	9860
JIT	5148	10166	33980	10957	5307	8920	9866
<b>Average</b>	<b>5146</b>	<b>10165.2</b>	<b>33860</b>	<b>10803.2</b>	<b>5306.2</b>	<b>8910.8</b>	<b>9833.8</b>

	Sieve	Loop	Logic	String	Float	Method	Overall
Java on JET classfiles	2434	4663	11372	3236	2950	1081	3317
Java on JET classfiles	2434	4663	11361	3256	3097	1084	3348
Java on JET classfiles	2434	4461	11396	3260	2964	1084	3326
Java on JET classfiles	2434	4661	11364	3265	3099	1076	3346
Java on JET classfiles	2434	4662	11349	3237	3102	1081	3343
<b>Average</b>	<b>2434</b>	<b>4622</b>	<b>11368.4</b>	<b>3250.8</b>	<b>3042.4</b>	<b>1081.2</b>	<b>3336</b>

	Sieve	Loop	Logic	String	Float	Method	Overall
JET without Specialization	6211	26835	140178	10525	10836	11146	17597
JET without Specialization	6229	26821	140145	10524	10751	11142	17579
JET without Specialization	6233	26830	140189	10516	10796	11146	17594
JET without Specialization	6220	26814	140100	10209	10824	11138	17503
JET without Specialization	6229	26810	140109	10589	10741	11146	17594
<b>Average</b>	<b>6224.4</b>	<b>26822</b>	<b>140144.2</b>	<b>10472.6</b>	<b>10789.6</b>	<b>11143.6</b>	<b>17573.4</b>

	Sieve	Loop	Logic	String	Float	Method	Overall
JET with Specialization	6238	26826	140192	10511	10738	11142	17578
JET with Specialization	6238	26817	140205	10577	10707	11150	17589
JET with Specialization	6228	26826	140170	10497	10821	11146	17592
JET with Specialization	6238	26833	140153	10490	10746	11146	17575
JET with Specialization	6235	26820	140184	10522	10746	11146	17582
<b>Average</b>	<b>6235.4</b>	<b>26824.4</b>	<b>140180.8</b>	<b>10519.4</b>	<b>10751.6</b>	<b>11146</b>	<b>17583.2</b>

## References

1. Arnold, Ken and James Gosling. *The Java Programming Language*. 2<sup>nd</sup> ed. Reading, Massachusetts: Addison-Wesley, 1998.
2. Cooper, Keith D., Mary W. Hall, and Ken Kennedy. "Procedure Cloning." *Proceedings of 1992 IEEE International Conference on Computer Languages* (1992): 96-105.
3. Consel, C., L. Hornof, R. Marlet, G. Muller, S. Thibault, E.-N. Volanschi, J. Lawall, and J. Noyé. "Tempo: Specializing Systems Applications and Beyond." *ACM Computing Surveys, Symposium on Partial Evaluation* (1998).
4. Fitzgerald, Robert, Todd B. Knoblock, Erik Ruf, Bjarne Steensgaard, and David Tarditi. *Marmot: An Optimizing Compiler for Java*. Technical Report MSR-TR-99-33, Microsoft Research, June 1999.
5. Gosling, James, Bill Joy, and Guy Steele. *The Java Language Specification*. Reading, Massachusetts: Addison-Wesley, 1996.
6. Grant, Brian, Markus Mock, Matthai Philipose, Craig Chambers, and Susan Eggers. "DyC: An Expressive Annotation-Directed Run-Time Specializations in C." To appear in *Theoretical Computer Science*.
7. Hendron, L.J., G. R. Gao, E. Altman, and C. Mukerji. *Register Allocation Using Cyclic Interval Graphs: A New Approach to an Old Problem*. (Technical Report.) McGill University, 1993.
8. Keppel, David, Susan J. Eggers, and Robert R. Henry. "A Case for Runtime Code Generation." Technical Report 91-11-04. University of Washington, 1991.

9. Lindholm, Tim and Frank Yelling. *The Java Virtual Machine Specification*. Reading, Massachusetts: Addison-Wesley, 1997.
10. Morgan, Robert. *Building an Optimizing Compiler*. Boston: Digital Press, 1998.
11. Muller, Gilles, Bárbara Moura, Fabrice Bellard, and Charles Consel. "Harissa: A Flexible and Efficient Java Environment Mixing Bytecode and Compiled Code." *Proceedings of the Third Conference on Object-Oriented Technologies and Systems* (1997).
12. Poletto, Massimiliano, Wilson C. Hsieh, Dawson R. Engler, and M. Frans Kaashoek. "C and tcc: A Language and Compiler for Dynamic Code Generation." *ACM Trans. Prog. Lang. Sys.* 21(2): 324-369 (1999).
13. Proebsting, Todd, Gregg Townsend, Patrick Bridges, John H. Hartman, Tim Newsham, and Scott A. Watterson. "Toba: Java For Applications: A Way Ahead of Time (WAT) Compiler." *Proceedings of the Third Conference on Object-Oriented Technologies and Systems* (1997).
14. Shaylor, Nik. *JCC – A Java to C Converter*. 8 May 1997  
<<http://www.geocities.com/CapeCanaveral/Hangar/4040/jcc.html>>.
15. Stoltz, Eric, Michael Wolfe, and Michael A. Gerlek. "Demand-Driven Constant Propagation." Technical Report 93-023. Oregon Graduate Institute of Science and Technology, 1994.
16. Sun Microsystems. *Java 2 SDK Documentation*.  
<<http://java.sun.com/products/jdk/1.2/docs>>
17. Sun Microsystems. *Java HotSpot Performance Engine*.  
<<http://www.javasoft.com/products/hotspot/index.html>>.

18. Tower Technologies. *A High Performance Deployment Solution for Java Server Applications (Native Java Compiler and Runtime Environment)*.  
<<http://www.towerj.com>>.
19. Wegman, M. N., and F. K. Zadeck. "Constant Propagation with Conditional Branches." *Conference Proceedings of Principals of Programming Languages XII*, 1985. 291-299.