Reducing the Overhead of Dynamic Compilation

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Abstract

The execution model for mobile, dynamically-linked, object–oriented programs has evolved from fast interpretation to a mix of interpreted and dynamically compiled execution. The primary motivation for dynamic compilation is that compiled code executes significantly faster than interpreted code. However, dynamic compilation, which is performed while the application is running, introduces execution delay. In this paper we present two dynamic compilation techniques that enable high performance execution while reducing the effect of this compilation overhead. These techniques can be classified as: 1) decreasing the amount of compilation performed, and 2) overlapping compilation with execution.

We first present and evaluate *Lazy Compilation*, an approach used in most dynamic compilation systems in which individual methods are compiled on-demand upon their first invocation. This is in contrast to *Eager Compilation*, in which all methods in a class are compiled when a new class is loaded. In this work, we describe our experience with eager compilation, as well as the implementation and transition to lazy compilation. We empirically detail the effectiveness of this decision. Our experimental results using the SpecJVM Java benchmarks and the Jalapeño JVM show that, compared to eager compilation, lazy compilation results in 57% fewer methods being compiled and reductions in total time of 14% to 26%. Total time in this context is compilation plus execution time.

Next, we present profile-driven, background compilation, a technique that augments lazy compilation by using idle cycles in multiprocessor systems to overlap compilation with application execution. With this approach, compilation occurs on a thread separate from that of application threads so as to reduce intermittent, and possibly substantial, delay in execution. Profile information is used to prioritize methods as candidates for background compilation. Methods are compiled according to this priority scheme so that performance-critical methods are invoked using optimized code as soon as possible. Our results indicate that background compilation can achieve the performance of off-line compiled applications and masks almost all compilation overhead. We show significant reductions in total time of 14% to 71% over lazy compilation.

Introduction

The execution model for mobile, dynamically-linked, object–oriented programs has evolved from fast interpretation to a mix of interpreted and dynamically compiled execution [1, 2, 3]. The primary motivation for dynamic compilation is significantly faster execution time of compiled code over interpreted code. Many implementations of object–oriented languages (such as Java [4], Smalltalk [5], and Self [6]) use dynamic compilation to improve interpreted execution time. Dynamic compilation also offers the potential for further performance improvements over static compilation since runtime information can be exploited for optimization and specialization. Several dynamic, optimizing compiler systems have been built in industry and academia [7, 8, 9, 1, 10, 11, 12, 13].

Dynamic compilation is performed while the application is running and, therefore, introduces compilation overhead in the form of intermittent execution delay. The primary challenge in using dynamic compilation is to enable high performance execution with minimal compilation overhead. Unfortunately, a common practice thus far in the evaluation of dynamic compilers for Java has been to omit measurements of compilation overhead and to report only execution time [14, 15, 13, 3]. Hence, it is difficult for users to evaluate the tradeoff between compilation overhead and execution speedup.

We first evaluate *Lazy Compilation*, an approach in which individual methods are compiled on-demand upon their first invocation. This is in contrast to *Eager Compilation*, in which all methods in a class are compiled when a new class file is loaded. Most Just-In-Time (JIT) compilers for Java[1] perform lazy compilation [10, 11, 13, 3] but have not provided an empirical study to support this choice. In this work, we discuss the tradeoffs between eager and lazy compilation. We use the Jalapeño JVM as our implementation infrastructure, a dynamic compilation system that originally used the eager approach by default. We then detail our experiences with the implementation of lazy compilation in Jalapeño and quantify the performance effects (as well as the compiler implications) of both approaches on the SpecJVM benchmarks. To the best of our knowledge, this is the first study to provide such an evaluation. Our experimental results show that, compared to eager compilation, lazy compilation results in 57% fewer methods being compiled and reductions in *total time* (compilation plus execution time) of 14% to 26%.

We then present profile-driven background compilation, a technique that augments lazy compilation by using idle cycles in multiprocessor systems to overlap compilation with application execution. Profile information is used to prioritize methods as candidates for background compilation. Our background compilation technique is designed for use in symmetric multiprocessor (SMP) systems in which one or more idle processors might be available to perform dynamic compilation concurrently with application threads. We believe that such systems will become more prevalent in the future, especially with the availability of systems built using single-chip SMPs. Our results using Jalapeño show that background compilation can deliver significant reductions in total time (14% to 71%) beyond the benefits enabled by lazy compilation.

The infrastructure used to perform our measurements of compilation overhead is Jalapeño, a new JVM (Java Virtual Machine) built at the IBM T. J. Watson Research Center. Jalapeño [7] is a multiple–compiler, compile–only JVM (no interpreter is used). Therefore, it is important to consider compilation overhead in the overall performance of the applications executed. Prior to the work reported in this paper, the default compilation mode in Jalapeño was eager compilation. After the results reported in this paper were obtained, the default compilation mode for Jalapeño was changed to lazy compilation.

[1] The implementation results described in this paper are for Java, but the techniques are relevant to any dynamic compilation environment.

General Methodology

The infrastructure in which we evaluate our compilation approaches is Jalapeño, a Java virtual machine (JVM) being developed at the IBM T. J. Watson Research Center [16, 7]. We first describe this infrastructure and then we detail our general experimental methodology.

The Jalapeño Virtual Machine

Jalapeño is written in Java and designed to address the special requirements of SMP servers: performance and scalability. Extensive runtime services such as parallel allocation and garbage collection, thread management, dynamic compilation, synchronization, and exception handling are provided by Jalapeño.

Jalapeño uses a compile–only execution strategy, i.e., there is no interpretation of Java programs. Currently there are two fully–functional compilers in Jalapeño, a fast *baseline* compiler and the *optimizing* compiler. The baseline compiler provides a near-direct translation of Java class files thereby compiling very quickly and producing code with execution speeds similar to that of interpreted code. Jalapeño, using the baseline compiler, performs in much the same way as an interpreted system.

The second compiler is the optimizing compiler and builds upon extensive compiler technology to perform various levels of optimization [15]. The compilation time using the optimizing compiler is 50 times slower on average for the programs studied than the baseline, but produces code that executes 3–4 times faster. To warrant its use, compilation overhead must be recovered by the overall performance of the programs. All results were generated using a December, 1999 build of the Jalapeño infrastructure. We report results for both the baseline and optimizing compilers. The optimization levels we use in the latter include many simple transformations, inlining[2], scalar replacement, static single assignment optimizations, global value numbering, and null check elimination.

As shown in Figure I, a Jalapeño compiler can be invoked in three ways ([1], [2], and [3] in the figure). First, when an unresolved reference made by the executing code causes a new class to be loaded, the class loader invokes a compiler to compile the class initializer, if one exists. With eager compilation ([2]), the class loader then invokes a compiler to compile all methods in the class during class loading as denoted by the eager compilation arrow.

[2]The optimizing compiler performs both unguarded inlining of static and final methods and guarded inlining of non-final virtual methods.

Alternatively, with lazy compilation ([1]), the class loader simply initializes all methods of the newly loaded class to a *lazy compilation stub*. When a stub is executed, a compiler is invoked to compile the method as denoted by the arrow from the executing code to the compiler. The implementation of lazy compilation in Jalapeño is a contribution of this paper, and is discussed in the section entitled *Lazy Compilation*. The third compilation path ([3]) involves a background compilation thread as denoted by the *Optimizing Compilation Thread* (OCT) in Figure I, that uses off-line profile data to schedule pre-emptive optimizing compilations of performance-critical methods. The class loader notifies the OCT of class loading events, but the actions taken by the OCT are otherwise decoupled from the application's execution, i.e. they occur in the background. Background compilation is a contribution of this paper, and is discussed in the section of the same name; in this section, we also empirically compare background and lazy compilation.

Jalapeño is invoked using a boot image [16]. A subset of the runtime and compiler classes are fully optimized prior to Jalapeño startup and placed into the boot image; these class files are not dynamically loaded during execution. Including a class in the boot image, requires that the class file does not change between boot-image creation and Jalapeño startup. This is a reasonable assumption for Jalapeño core classes. This idea can be extended with mechanisms to detect if a class file has changed since it was statically compiled to enable arbitrary application classes to be pre-compiled. This topic is further described in [17]. Infrequently used, specialized, and supportive library and Jalapeño class files are excluded from the boot image to reduce the size of the JVM memory footprint and to take advantage of dynamic class file loading. When a Jalapeño compiler encounters an unresolved reference, i.e., an access to a field or method from an unloaded class file, it emits code that when executed invokes Jalapeño runtime services to dynamically load the class file. This process consists of loading, resolution, compilation, and initialization of the class. If, during execution, Jalapeño requires additional Jalapeño system or compiler classes not found in the boot image, then they are dynamically loaded: there is no differentiation in this context between Jalapeño classes and application classes once execution begins. To ensure that our results are repeatable in other infrastructures, we isolate the impact of our approaches to just the benchmark applications by placing all of the Jalapeño class files required for execution into the boot image.

Experimental Methodology

We present results gathered by repeatedly executing applications on a dedicated, 166MhzX4–processor PowerPC-based machine running AIX v4.3. The applications we examine are the single-threaded subset of the SpecJVM programs [18]. We report numbers using inputs of size 10 and size 100. According to Spec, input 100 is full execution of an example application and input 10 is execution that is 10% of the full execution. The size 10 input is designed to be used as a training input for size 100 input; execution behavior from the size 10 input is representative, yet not as extensive, as that of the size 100 input. Since size 10 and 100 better represent execution times of existing Java programs, we exclude the Spec size 1 input which defined to be 1% of full execution. Throughout this study we refer to size 10 as the small input and size 100 as the large.

Table I shows various characteristics of the benchmarks used in this study. Total size and static class count are given as well as dynamic counts, or the number of used classes, for the two inputs. In addition, compilation time (CT) and execution time (ET), in seconds, using the Jalapeño optimizing and the fast baseline compilers are shown for each input. The compilation time includes the time to compile only the class files that were used. Despite repeated execution, some noise occurs in the collected results. For example, the DB data shows that the compile time for the small input is 0.2 seconds slower than that for the large, even though both inputs compile the same classes. The variance is due to system side–effects, e.g., files system service interruptions.

Lazy Compilation

Dynamic class loading in Java loads class files as they are required by the execution on demand. Using Just-In-Time (JIT) compilation, each method is compiled upon initial invocation. We refer to this method-level approach as **Lazy Compilation**. Lazy compilation is used in most dynamic compilation systems [1, 11, 19, 3].

An alternative approach is *Eager Compilation*. Instead of compiling a single method at a time, an entire class file is compiled when it is first accessed. Prior to this study, the Jalapeño virtual machine only used eager compilation. In this section, we describe our experiences with, and the implementation of, lazy compilation in Jalapeño. As a result of this work, both eager and lazy compilation were made available in Jalapeño; lazy compilation has become the default. More importantly, with this study we empirically quantify the performance differences between eager and lazy compilation.

We implemented eager compilation in Jalapeño for its reduced complexity and potential benefits. First, eager compilation reduces the overhead caused by switching between execution and compilation. Switching may decrease application memory performance by polluting the cache during compiler operation. If all of the methods in a class file are used during execution, eager compilation results in compilation of the same methods and substantially less switching overhead. Second, eager compilation can also potentially improve execution performance since it simplifies interprocedural analysis and optimization by ensuring that all methods of a class are analyzed before any of them are compiled.

However, eager compilation increases the time required by class file loading since the entire class file is compiled before execution continues. This delay is experienced the first time each class is referenced. In some cases, it may take seconds to compile a class if high optimization levels are used, affecting a user's perception of the application performance. In addition, for some applications, many methods may be compiled and optimized but never invoked, leading to unnecessary compilation time and code bloat. It is unclear whether lazy or eager compilation results in the best overall performance. This study empirically determines the answer. To our knowledge, no such study has yet been performed.

Implementation of Lazy Compilation

As part of loading a class file in Jalapeño, entries for each method declared by the class are created in the class' virtual function table and/or a static method table. These entries are the code addresses that should be jumped to when one of the methods is invoked. In eager compilation, these addresses are simply the first instruction of the machine code produced by compiling each method. To implement lazy compilation, we instead initialize all virtual function table and static method table entries for the class to refer to a single, globally shared stub[3]. When invoked, the stub will identify the method the caller is actually trying to invoke, initiate compilation of the

[3]Note that using a single globally shared stub complicates the implementation of the "method test" used by the optimizing compiler to perform guarded inlinings of non-final virtual methods. This test relies on the invariant that pointer equality of target instructions implies that the source-level target methods are equal. Therefore, when the method test is being used for guarded inlining, the virtual function tables are initialized with unique trampolines that jump to the globally shared stub.

target method as necessary[4], update the table through which the stub was invoked to refer to the real compiled method, and finally, resume execution by invoking the target method. Our implementation of lazy compilation is somewhat similar to the backpatching done by the Jalapeño baseline compiler to implement dynamic linking [20] and shares some of the same low-level implementation mechanisms (notably, special compilation of "dynamic bridge" methods to ensure that both volatile and non-volatile registers are saved by the callee). After the stub method execution completes, all future invocations of the same class and method pair will jump directly to the actual, compiled method.

Lazy Compilation Results

To gather our results using this lazy approach, we time the compilation using internal Jalapeño performance timers. Whenever a compiler is invoked, the timer is started; the timer is stopped once compilation completes. To measure the execution time of the program, we use the time reported by a wrapper program called SpecApplication.class distributed with the Spec JVM98 programs [18]. Programs are executed repeatedly in succession, and timings of the execution are made separately.

To analyze the effectiveness of lazy compilation we first compare the total number of methods compiled with and without lazy compilation. Figure II depicts the percent reduction in the number of methods compiled using the large input. The numbers are very similar for the small input since the total number of methods used is similar in both inputs. Above each bar is the number of methods compiled lazily, shown to the left of the slash, and eagerly, shown to the right of slash. On average, lazy compilation compiles 57% fewer methods than eager compilation.

To understand the impact of lazy compilation in terms of reduction in compilation overhead, we measured compilation time in Jalapeño with and without lazy compilation. Figure III shows the percent reduction in compilation time due to lazy compilation in relationship to eager compilation for both the optimizing compiler, shown in the left graph, and baseline compiler, shown in the right graph, for the large input. The data shows that lazy compilation substantially reduces compilation time for either compiler. On average, for the optimizing compiler,

[4] Because we lazily update virtual function tables on a per-class basis, it is possible that the target method has already been compiled but that some virtual function tables have not yet been updated to remove the stub method.

29% of the compilation overhead is eliminated. Using the baseline compiler, on average 50% is eliminated. Since methods require varying amounts of time for optimization (depending upon method size and complexity), the relationship between the reduction in number of methods compiled and compilation time is not proportional.

Table II provides the raw execution and compilation times with and without lazy compilation using the optimizing compiler for both inputs. The data in this table includes compilation times used in Figure III as well as execution times. Data for the baseline compiler is not shown because compilation overhead is a very small percentage of total execution time, and thus the 50% reduction in compilation time only results in a 1% reduction in total time. Columns 2 through 6 are for the small input and 7 through 11 are for the large. The sixth and eleventh columns, labeled "Ideal" contain the execution time alone for batch–compiled applications. *Batch Compilation* is off–line compilation of applications in their entirety. We include this number as a reference to a lower–bound on the execution time of programs given the current implementation of the Jalapeño optimizing compiler. Batch compilation is not restricted by the semantics of dynamic class file loading; information about the entire program can be exploited at compile time. In particular all methods are available for inlining and all offsets are known at compile time.

Columns 2 and 3, and 7 and 8, are the respective execution and compile times for eager compilation. Columns 4 and 5, and 9 and 10, show the same for the lazy approach. In addition to reducing compilation overhead, the data shows that lazy compilation also significantly reduces execution time when compared to eager compilation. This reduction in execution time was caused by the direct and indirect costs of dynamic linking. In the following section, we provide background on dynamic linking and explain the unexpected improvement in optimized execution time enabled by lazy compilation.

The Impact of Dynamic Linking

Generating the compiled code sequences for certain Java bytecodes, e.g. `invokevirtual` or `putfield`, requires that certain key constants, such as the offset of a method in the virtual function table or the offset of a field in an object, be available at compile time. However, due to dynamic class loading, these constants may be unknown at compile time: this occurs when the method being compiled refers to a method or field of a class that has not yet been loaded. When this happens, the compiler is forced to emit code that when executed, performs any necessary class loading thus making the needed offsets available, and then performs the desired method invocation or field access. Furthermore, if a call site is dynamically linked because the callee method belongs to an unloaded class, optimizations such as inlining cannot be performed. In some cases, this indirect cost of missed optimization opportunities can be quite substantial.

Dynamic linking can also directly impact program performance. A well-known approach for dynamic linking [21, 22] is to introduce a level of indirection by using lookup tables to maintain offset information. This table-based approach is used by the Jalapeño optimizing compiler. When it compiles a dynamically linked site, the optimizing compiler emits a code sequence that, when executed, loads the missing offset from a table maintained by the Jalapeño class loader.[5] The loaded offset is checked for validity; if it is valid it can be used to index into the virtual function table or object to complete the desired operation. If the offset is invalid, then a runtime system routine is invoked to perform the required class loading updating the offset table in the process, and execution resumes at the beginning of the dynamically linked site by re-loading the offset value from the table. The original compiled code is never modified. This scheme is very simple and, perhaps more importantly, avoids the need for self-modifying code that entails complex and expensive synchronization sequences on SMPs with relaxed memory models such as the PowerPC machine used in our experiments. The tradeoff of simplicity is the cost of validity checking: subsequent executions of dynamically linked sites incur a four-instruction overhead. [6]

If dynamically linked sites are expected to be very frequently executed, then this per-execution overhead may be unacceptable. Therefore, an alternative approach based on backpatching, or self-modifying code, can be used [20]. In this scheme, the compiler emits a code sequence that when executed invokes a runtime system routine that performs any necessary class loading, overwrites the dynamically linked sites with the machine code the compiler would have originally emitted if the offsets had been available, and resumes execution with the first instruction of the backpatched, or overwritten, code. With backpatching, there is an extremely high cost (aggravated by the synchronization and memory barriers required on the PowerPC) the first time each dynamically linked site is executed, but the second and all subsequent executions of the site incur no overhead.

The Jalapeño optimizing compiler used in this paper uses the table-based approach. This design decision was

[5] All entries in the table are initialized to 0, since in Jalapeño all valid offsets will be non-zero

[6] The four additional instructions executed are two dependent loads, a compare, and a branch.

mainly driven by the need to support type-accurate garbage collection (GC). As in other systems that support type-accurate GC, compilers must produce mapping information at each *GC-safe point* detailing which registers and stack-frame offsets contain pointers. By definition, all program points at which an allocation may occur, either directly or indirectly, must be GC-safe points, since the allocation may trigger a GC. Because allocation will occur during class loading, all dynamically linked sites must also be GC-safe points. If the optimizing compiler used backpatching, it would actually need to generate two GC-maps for each dynamically linked site: one that described the initial code sequence and one that described the backpatched code. Although the two maps would contain very similar information, both are needed since the GC-safe point in the initial and backpatched code sequences are at different offsets in the machine code array. In practice, it turned out to be burdensome to modify the optimizing compiler's GC-map generation module to produce multiple maps for a single intermediate language instruction, so the issue was avoided by using the table-based approach which only requires one GC-map for a dynamically linked site.

Since class files are not changed once loaded, we are able to increase the probability that an accessed class will be resolved at the time the referring method is compiled with the delayed compilation of the lazy approach. Table III shows the number of times dynamically linked sites are executed with eager and lazy compilation. On average, code compiled lazily executes through dynamically linked sites 92% fewer times than eager compilation for the small input and 99% fewer times for the large input. Although the reduction in direct dynamic linking overhead can be quite substantial, e.g. roughly 25 million executed instructions on `compress` with the large input, the missed inlining opportunities are even more important. For example, more than 99% of the executed dynamically linked sites in the eager version of `compress` are calls to very small methods that are inlined in the lazy version. Thus, the bulk of the 25 second reduction in `compress` execution time as shown in Table II is due to the direct and indirect benefits of inlining, and not only to the elimination of the direct dynamic linking overhead. Similar inlining benefits also occur in `mpegaudio`.

The effect of lazy compilation on total time is summarized in Figure IV. The graph shows the relative effect by lazy compilation both on execution time as well as compilation time using the optimizing compiler. The left graph is for the small input and the right graph is for the large input. The top, dark-colored portion of each bar represents compilation time, the bottom light-colored portion represents execution time. A pair of bi-colored bars is given for each benchmark. The first bar of the pair results from using the eager approach; the second bar from lazy compilation. Lazy compilation reduces both compilation and execution time significantly when compared to eager compilation. On average, lazy compilation reduces total time by 26% for the small input and 14% for the large. Execution time alone is reduced by 13% and 11% on average for each input, respectively, since lazy compilation greatly reduces both indirect and direct costs of dynamic linking.

Background Compilation

In this section, we describe background compilation, a technique that reduces compilation overhead by overlapping compilation with computation. With lazy compilation, each method is compiled upon initial invocation. However, the execution characteristics of the method may not warrant its, possibly expensive, optimization. In addition, this on–demand compilation in an interactive environment may lead to inefficiency. In environments characterized by user interaction, the CPU often remains idle waiting for user input. Furthermore, the future availability of systems built using single-chip SMPs makes it even more likely that idle CPU cycles will intermittently be available. The goal of background compilation is to extend lazy compilation to further mask compilation overhead by using idle cycles to perform optimization.

Implementation of Background Compilation

Background compilation consists of two parts. The first occurs during application execution: when a method is first invoked, it is lazily compiled using a fast, non–optimizing compiler or the method is interpreted. This allows the method to begin executing as soon as possible. However, since this type of compilation can result in poor execution performance, methods which are vital to overall application performance should be optimized as soon as possible.

This is achieved with the second part of the background compilation by using an *Optimizing Compiler Thread* (OCT). At startup we initiate a system thread that is used solely for optimizing methods. The OCT is presented with a list of methods that are predicted to be the most important methods to optimize. The OCT processes one method at a time, checking whether or not the class in which it is defined has been loaded. If it has, then the method is optimized. Once compiled, the code returned from the optimizing compiler is used to replace the baseline compiled code or the lazy compilation stub if the method has not yet been baseline compiled. Future invocations of this method will then use the optimized version. If existing stack frames reference previously compiled code, then this code will be used until the referenced invocation returns.

To predict which methods should be optimized by the OCT, we use profiles of the execution time spent in a method. To generate these profiles for our experimental results, we execute the application off–line and accumulate measurements of the amount of time spent in a method, each time it is executed. We gather this timing data for executions using two inputs. The small input (as described in the Experimental Methodology section) is commonly referred to as the training set. The profile information from the large input, or testing set, is used for the same-input results presented in this paper. That is, we use the profile from the large input to guide priority setting of methods when the large input is executed. These results establish an upper limit on the potential benefit from our techniques, since we have perfect information about the priorities of methods. For cross-input results, we use the profile from the training set to establish priorities of methods when the testing set is used for execution. These results, show how well the small input predicts the time spent in methods when executing the large input and how performance will be impacted when are profiles are imperfect. If the small input is not representative of the large, then there may be a substantial discrepancy between the performance of same-input and cross-input results

At JVM startup, the profiled list of methods and the time spent in each is read into memory and processed. Each method is assigned a global priority ranking with respect to all other methods executed by the application. We then record the global priorities with the methods in each class. As each class is loaded, any methods of the class that have been prioritized are inserted into the priority queue of the OCT for eventual optimization. If the priority queue becomes empty, the OCT sleeps until class loading causes new methods to be added.

This model extends to a dynamic, mobile environment in which class files may be uploaded into the Jalapeño server from different sources. At each source, profiles are generated and methods within each class are prioritized prior to transfer, as described above. Often, execution of an application accesses library files that are not transfered as part of the application but are dynamically loaded from the machine on which the program is executed. Information about high priority methods in these classes, are sent to the destination with the application in the form of annotations. Annotation is a mechanism for including additional information in a class file. For background compilation, each application method contains an annotation consisting of its priority as well as the name and priority of any library, or other non-transfered methods. When a class is loaded by a Jalapeño server, the annotated priority for important methods guides insertion into the global priority queue of the OCT. Bytecode annotations of method priorities are inserted into the bytecode as method attributes using a bytecode re-writing tool. A detailed study of using annotations to reduce dynamic optimization time can be found in [23].

We currently use a single OCT that synchronously compiles prioritized methods. When uncompiled methods are invoked, they are compiled using the baseline compiler. We may be able to gain additional performance benefits through the use of multiple OCTs once the Jalapeño optimizing compiler is made re-entrant. In this case, the baseline compiler will still be used to compile newly-invoked methods so that optimization decisions are made solely by the OCT system. We estimate that having multiple OCTs will provide additional performance benefits in certain cases. For example, currently the OCT uses one processor separate from the one used by the application thread. If there are additional processors or idle cycles, more compilation can be performed using multiple OCTs. The system should be adaptive however, so that the application is not starved for resources. That is, when the application is in need of processing cycles, the OCT activity should be reduced so as to maintain acceptable application performance while continuing to compile high-priority methods, even if it must scale back to a single thread. This implementation and the associated analysis to achieve a beneficial performance balance is part of future work.

Background Compilation Results

In this section, *total time* refers to the combination of compilation, execution, and all other overheads. The total time associated with background compilation includes:

- Baseline, or fast, compilation time of executed methods
- Execution time from methods with baseline-compiled code

- Execution time from methods invoked following code replacement by the optimizing background thread, and
- Thread management overhead

The examples in Figure V illustrate the components that must be measured as part of total time for a different scenarios involving a method, Method1. In the first scenario, Method1 is invoked, baseline compiled, and executed. Following its initial execution the OCT encounters Method1 in its list and optimizes it. By the time it is able to replace Method1's baseline compiled code, Method1 has executed a second time. For the third invocation, however, the OCT has replaced the baseline compiled code and Method1 executes using optimized code. Total time for this scenario includes baseline compilation time of Method1 and execution time for two Method1 invocations using baseline compiled code and one using optimized code.

In the second scenario, the OCT encounters, optimizes, and replaces Method1 before it is first invoked. This implies that the class containing Method1 has been loaded prior to OCT optimization of Method1. The OCT replaces a stub that is in place for Method1 with the optimized code. When this occurs the use of background compilation can also reduce the memory footprint of the Jalapeño VM and the executing program since baseline code is not kept in memory. All executions of Method1 use the optimized code. Total time for this scenario includes only the execution time for three invocations of Method1 using optimized code.

To measure the effectiveness of background compilation, we provide results for the total time required for execution and compilation using this approach. Figures VI and VII compare total time with background compilation to total time for the eager, lazy, and ideal configurations results from Table II (for the small and large input, respectively). Four bars (with absolute total time in seconds above each bar) represent the total time required for each approach for a given benchmark. The first bar shows results from eager and the second bar from the lazy approach. The third bar is the total time using background compilation and the fourth bar is "ideal" execution time alone. Ideal execution time results from a batch-compiled application (complete information about the application enables more effective optimization and removes all dynamic linking, and there is no compilation cost).

The summary figures show that background compilation eliminates the effect of almost all of the compilation overhead that remains when using the lazy approach. On average, background compilation provides an additional 71% average reduction in total time over lazy compilation for the small input (14% for the large). On average there are 151 fewer methods optimized by the OCT over lazy compilation. In comparison with eager compilation, background compilation reduces the total time (execution plus compilation) by 79% and 26% for the small and large input, respectively. The percentage of total time due to compilation is 79% and 20%; hence background compilation reduces total time by more than just the compilation overhead. This occurs since background compilation extends lazy compilation and thereby enables additional optimization and avoids the dynamic linking effects (as discussed in the Lazy Compilation section). That is, when the OCT optimizes each method, most required symbols are resolved.

Most importantly, however, are the similarities between background and "ideal" execution time. Total time using the background approach is within 21% and 8% (on average for the small and large inputs, respectively) of the ideal execution time. Our background compilation approach therefore, correctly identifies performance-critical methods and achieves highly optimized execution times while masking almost all compilation overhead.

Related Work

Our work reduces the compilation overhead associated with dynamic compilation. Much research has gone into dynamic compilation systems for both object–oriented [15, 1, 6] and non–object–oriented [8, 9, 12] languages. Our approach is applicable to other dynamic compilation systems, and can be used to reduce their compilation overhead.

Lazy compilation, as mentioned previously, is used in most Just-In-Time compilers [1, 11, 19, 13, 3] to reduce the overhead of dynamic compilation. However, a quantitative comparison of the associated tradeoffs between lazy and eager compilation, to our knowledge, has not yet been presented. In addition, we provide a detailed description of the implementation and the interesting effects on optimization due to lazy compilation in the Jalapeño VM.

Most closely related to our background compilation work is that by Hölzle and Ungar [24]. They describe an adaptive compilation system for the Self language that uses a fast, non–optimizing compiler and a slow, optimizing compiler like those used in Jalapeño. The fast compiler is used for all method invocations to improve program responsiveness. Program "hotspots" are then recompiled and optimized as discovered. Hotspots are methods invoked more times than an arbitrary threshold. When hotspots are discovered, execution is interrupted and the method, with possibly an entire call chain, is recompiled and replaced with optimized versions. In comparison, background compilation uses off–line profile information to determine which methods to optimize and never causes stalls in execution due to optimization. In addition, background compilation can potentially eliminate all compilation overhead for some methods since method stubs for lazy compilation of loaded, but as yet unexecuted, methods can be replaced with the optimized code prior to initial invocation of the methods. That is, for methods for which optimization is vital to overall application performance, no threshold of invocation count or execution time has to be reached for optimization to be initiated. This is an advantage over all dynamic, adaptive, compilation environments. Another advantage is that our techniques introduce no runtime overhead due to dynamic measurement. Lastly, we perform optimization on a separate thread of execution and exploit idle processors; the combination of which, to our knowledge, has not been examined and published prior.

In other work, Arnold, et. al. [25] uses profiles to guide static compilation. The goal of this project was to determine the performance potential of dynamic, adaptive compilation based on selective optimization in a feedback-based system. In comparison, we incorporate similar, off-line profiles but use them to drive on-line compilation using background compilation.

Another project that attempts to improve program responsiveness in the presence of dynamic loading and compilation is continuous compilation [2]. Continuous compilation overlaps interpretation with Just–In–Time (JIT) compilation. A method, when first invoked, is interpreted. At the same time, it is compiled on a separate thread so that it can be executed on future invocations. They extend this to Smart JIT compilation: on a *single* thread, interpret *or* JIT compile a method upon first invocation. The choice between the two is made using profile or dynamic information. Our background compilation approach uses a separate thread and processor to selectively background compile only methods predicted as important for application performance. Only a single processor is used in this prior work and only a single thread in Smart JIT compilation. Our infrastructure uses a compile–only approach, so interpretation in our project is replaced by fast compilation. Interpretation and JIT compilation overlap is also used in the Symantec Visual Cafe JIT compiler, a Win32 JIT production compiler delivered with some 1.1.x versions of Sun Microsystems Inc. Java Development Kits [26].

Another form of background compilation is described in the HotSpot compiler specification [1] from Sun Microsystems. A separate thread is used for compilation which is interrupted once a a threshold of time has been spent compiling a single method. Another thread then interprets the method to reduce the effect of the compilation overhead for the method. This system differs from Jalapeño in that no profile information is used and the documentation does not provide measurement of the impact of background compilation as a separate process.

Lastly, we previously proposed prefetching class files on separate threads to overlap the overhead associated with network transfer in [27] with execution. Network latency increases the delay during class file loading much like compilation overhead does. In this prior work, we show that by premature access and transfer of a class file by a separate, background thread during application execution, we are able to mask the transfer delay and reduce the time the application stalls for class loading of non-local class files. As in background compilation, we generate profiles off–line but use them to determine the order in which class files are first accessed. Background compilation differs in that we attempt to overlap compilation with execution; hence these techniques are complementary and can be used in coordination to reduce both transfer and compilation overhead.

Future Directions

As part of future work, we will extend our background compilation approach to further reduce the effect of compilation overhead. We plan to annotate class files so that when non–local class files are loaded by Jalapeño, a profile list can be constructed, eliminating the need for the OCT to read in a list from the local file system. In addition, we plan to extend our single OCT approach to multiple OCTs. That is, we will include the option of using multiple available processors for background optimization. Currently, Jalapeño's optimizing compiler is not re-entrant; only one thread can use the optimizing compiler at a time. Once this changes, our background optimization will be used to exploit multiple idle processors. Lastly, as code quality of baseline, or fast, compilers improves, the discrepancy between baseline execution time and optimized execution may decrease. However, compilation overhead will remain. We may be able to use background compilation to mask compile time by the baseline compiler if it becomes a more substantial proportion of total time. To do this we can prefetch and background compile methods that we predict will be used next.

One limitation imposed on background compilation by the current Jalapeño implementation is lack of a mechanism for setting thread priorities. Currently a thread is executed on its own processor and the application thread runs on a separate processor. With the current infrastructure, using a single processor, we are unable to *only* compile when the primary thread(s) of execution is idle since each thread is given an equal length time-slice and is not interrupted. The application thread and the OCT must contend equivalently for resources restricting potential for improvement on a single processor. We believe that for interactive programs, execution on a single processor can benefit from background compilation since optimization can be performed when the application suspends waiting for user input. Thread priorities are also required to provide a realistic evaluation of background compilation with multi-threaded applications. It is for this reason that we only evaluate the effect of background compilation on single-threaded benchmarks in this study, hence, the Spec benchmark `mtrt` is not included. Once thread priorities are implemented as part of future work, we will empirically evaluate the tradeoffs required for background compilation of multi-threaded applications as well.

Also as part of future work, we plan to compare lazy and background compilation with adaptive optimization. In such systems, measurements of application execution behavior, e.g., method invocation counts or statistical sampling, are taken to determine when to optimize a method. The adaptive optimization functionality was recently added to the Jalapeño virtual machine [28], building on the lazy compilation and background compilation ideas presented in this paper. As shown in this paper, lazy compilation is effective in reducing the number of dynamically linked call sites. Adaptive optimization can go one step further than lazy compilation and use dynamic context information to generate better-quality specialized code for the call sites that are not dynamically linked.

Adaptive optimization also includes background compilation i.e., compilation of selected methods in the background, concurrent with application execution. On-line profile information is used to guide selection of methods for optimized compilation in adaptive optimization. We believe that background compilation driven by off-line profiling (as described in this paper) can be used as an additional improvement to adaptive optimization. Off-line profile information can trigger background compilation of critical methods earlier than on-line profiling. For example, the use of off-line profile information can completely eliminate compilation delays for any performance-critical method that is compiled and optimized in the background before its first invocation. Current adaptive compilation environments require that methods are initially baseline-compiled or interpreted a number of times before they are dynamically optimized [25, 29, 24, 2]. We plan to study the relationship between background compilation and adaptive optimization as part of future work.

Finally, there is an important issue that needs to be addressed by all dynamic compilation schemes viz., reclaiming space used by code that is no longer required. The Jalapeño virtual machine is an ideal infrastructure for exploring this possibility in future work, since the compiled code for each method is allocated as a separate object in the Jalapeño heap. The key extensions that would be required are to add information to the GC maps on which stack/register locations contain code addresses, and provide support for identifying the code object that contains a given code address. Code addresses are like interior pointers which will need to be supported anyway as more aggressive optimizations are added to the Jalapeño optimizing compiler.

Conclusion

In this work, we focus on reducing the effect of compilation overhead imposed by dynamic compilation. We first quantitatively compare the tradeoffs between eager, or class–level, and lazy, or method–level, compilation. Lazy compilation reduces the number of methods compiled, thereby reducing compilation overhead. We also introduce and evaluate background compilation using an SMP, an approach that optimizes important methods on a background thread to mask compilation overhead due to optimization.

The infrastructure we use to examine the impact of our compilation strategies is the Jalapeño Virtual Machine, a compile–only execution environment being developed at IBM T. J. Watson Research Center. Currently in Jalapeño, two compilers are used, the fast baseline compiler that produces code with execution speeds of interpreted versions, and the optimizing compiler, a slow but highly optimizing compiler that produces code with execution speeds two to eight times faster than the code produced by the baseline compiler. Our goal was to design and implement optimizations that enable compilation times of the baseline compiler and execution speeds of optimized code.

We first empirically quantify the effect of lazy compilation on both compilation time and execution time. We show that lazy compilation requires 57% fewer methods be compiled on average than eager compilation for each input of the benchmarks studied. In terms of compilation time, this equates to approximately 30% reduction on average for either input, since the number of methods used between inputs is relatively the same. In addition to reducing compilation overhead, lazy compilation also improves execution time by greatly reducing the number of dynamically linked sites, thus avoiding both the direct costs of dynamic linking and the indirect costs of missed optimization opportunities. Lazy compilation reduces optimized execution time 13% and 10% on average for the small and large input, respectively. In terms of total time, lazy compilation enables a 26% and 14% reduction over eager compilation using the optimizing compiler. Jalapeño, as a result of this work, uses lazy compilation by default.

We also present a compilation approach that extends lazy compilation. Background compilation masks the overhead incurred by compilation by overlapping it with useful work. With this optimization, we use the Jalapeño optimizing compiler on a background thread to compile only those methods we predict as important for optimization. On the primary thread(s) of execution, the Jalapeño baseline compiler is used so that methods can begin executing much earlier than if they are optimized. The background thread then replaces the baseline compiled method with an optimized version so that future invocations of the method call the optimized version. Our results show that background compilation achieves execution times of optimized code with compilation overhead of baseline compilation. On average, background compilation effectively reduces total time by 79% and 26% for the small and large input, respectively. When compared to lazy compilation, the background optimization reduces total time of 71% for the small input and 14% for the large. We also show that background compilation achieves the runtime performance of applications that are batch compiled, i.e. off–line optimization of the entire application at once.

The Java programming language provides an architecture–independent intermediate representation that is and will continue to be exploited by the distributed execution of Internet–computing applications. In order for the execution of these applications to be practical, execution speeds must be fast and overheads associated with execution, i.e., optimization, must not create performance bottlenecks. Dynamic compilation enables state-of-the-art optimizations to improve the execution speeds of Java programs, but also introduces compilation overhead due to optimization. Compilation approaches like the ones presented here are important since they enable optimization while reducing the effect of compilation overhead.

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Figures

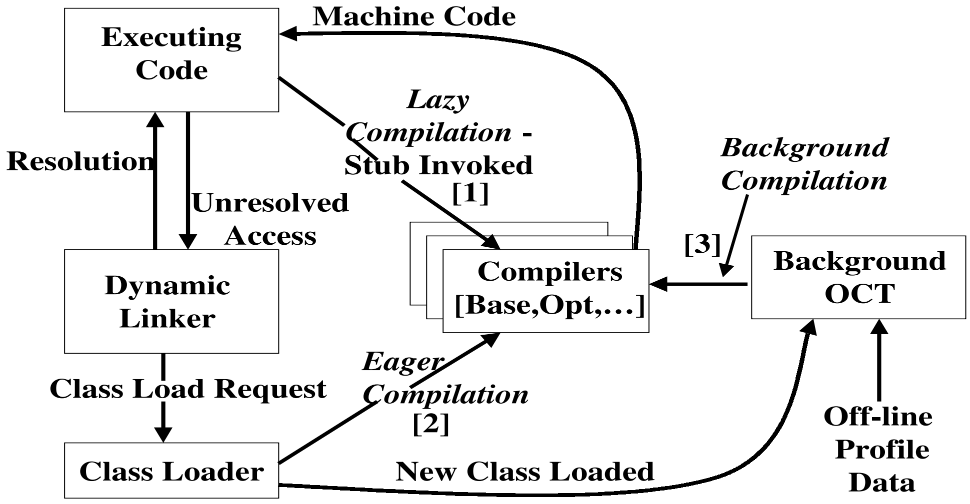


Figure I: Compilation Scenarios in the Jalapeño JVM. The compiler is invoked in three ways indicated by [1] - lazy compilation, [2] - eager compilation, and [3] - background compilation.

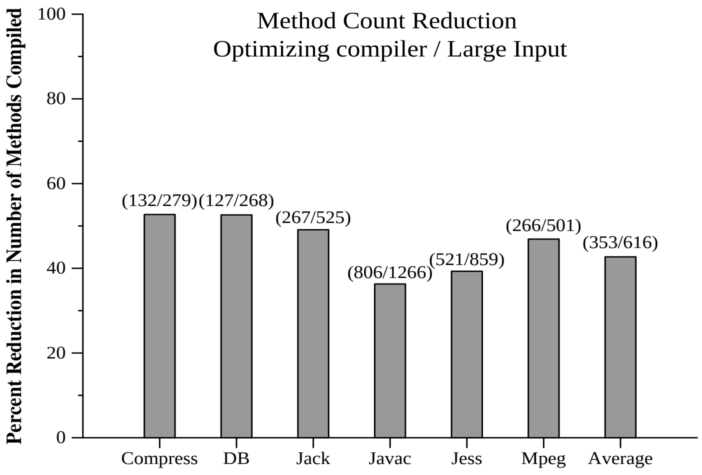
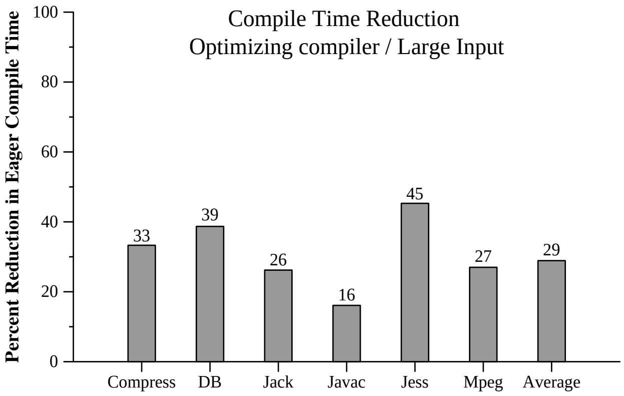


Figure II: Percent reduction in the number of methods required for eager compilation using lazy compilation. Above the bars, we include the the number of methods compiled over the total number of methods. We only include data for the large input since the number of used methods is similar across inputs for the Spec JVM98 benchmarks. In addition these numbers are typical regardless of which compiler,optimizing or baseline, is used.



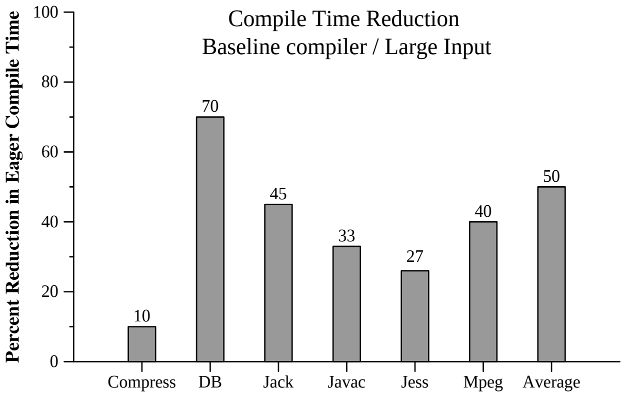


Figure III: Reduction in compilation time due to lazy compilation. The percent reduction is shown above each bar explicitly. The left graph shows the reduction in compilation time over eager compilation for the optimizing compiler and the right graph shows the reduction for the baseline compiler. Since the results are similar for the small and large inputs, we only report data for the large input here.

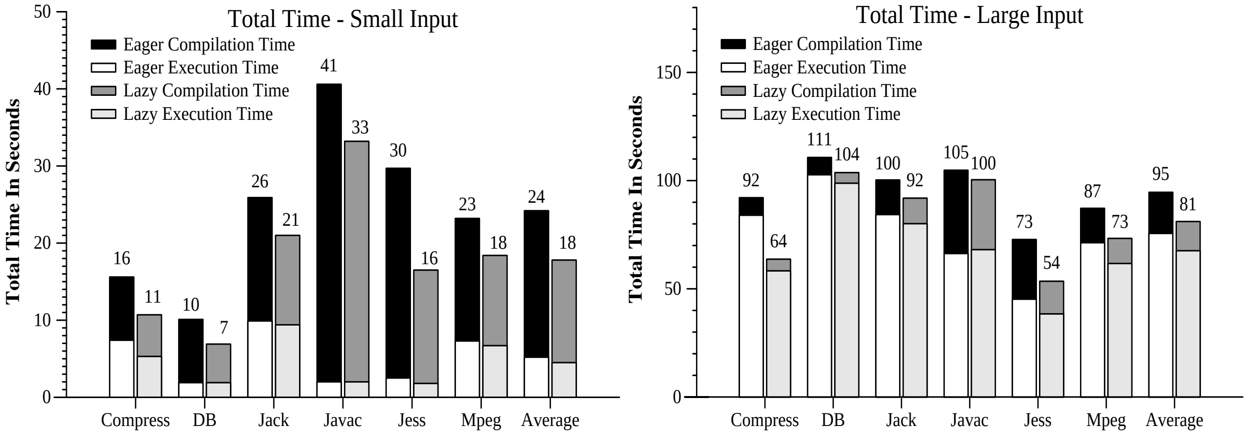


Figure IV: Overall impact of lazy compilation application performance. The left bar results from using eager compilation, the right bar lazy. The top, dark colored, portion of each bar is compilation time, the bottom, light-colored execution. The number above each bar is the total time in seconds required for both execution and compilation time. Lazy compilation reduces both execution time as well as compilation time.

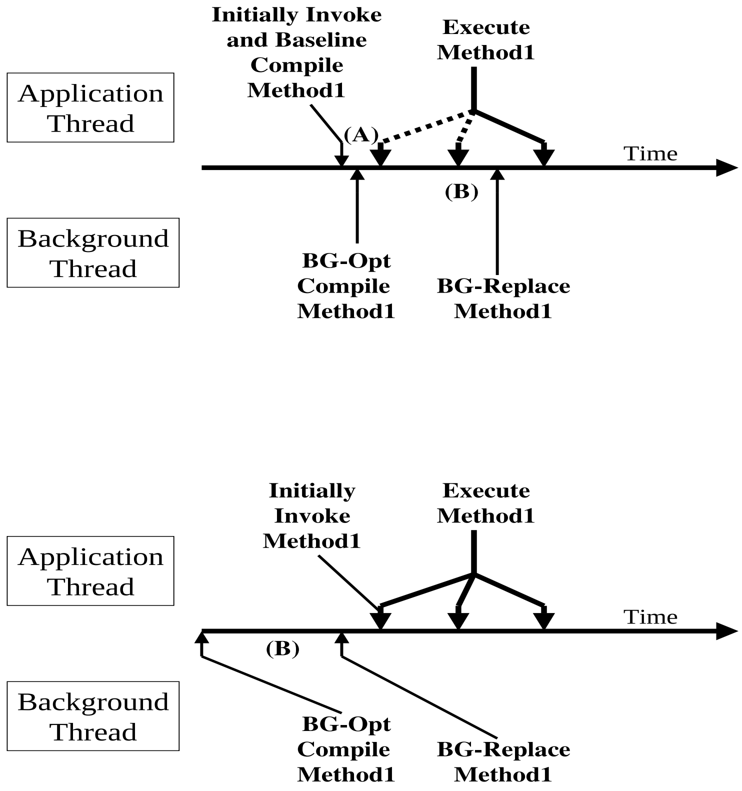


Figure V: Example scenarios of background compilation. In the top figure, when Method one is first invoked, it is baseline-compiled while execution is suspended. Baseline compilation time is represented by "(A)". Execution of Method1 proceeds using baseline-compiled code (dotted arrow). Next, the optimizing compilation thread (OCT) optimizes Method1 in the background; this compilation time is shown by "(B)". Meanwhile, Method1 is invoked and executed a second time with the baseline-compiled code before the OCT is able to replace the baseline-compiled code with the optimized version. Once replaced (represented by a solid line), Method1 executes using the optimized version of the code. In the second scenario, the OCT is able to compile and replace Method1 before any invocations of Method1 occur; therefore, all executions use the optimized code.

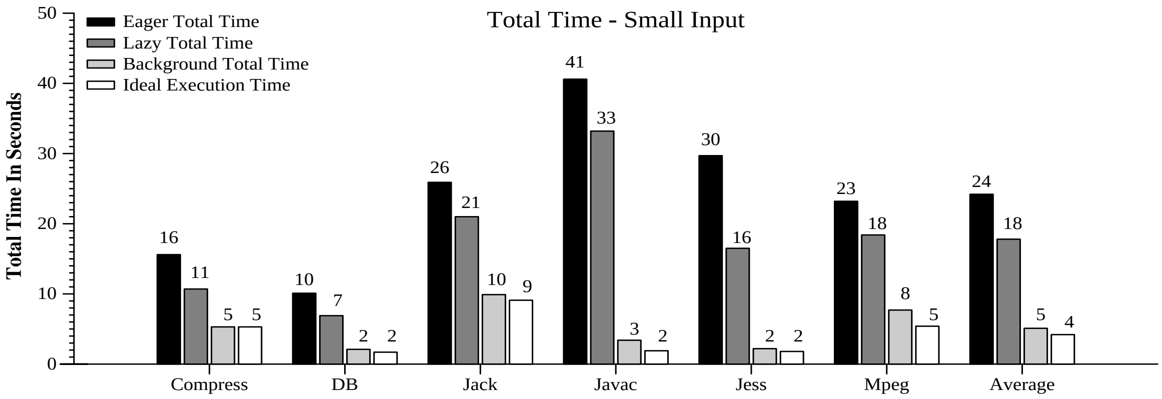


Figure VI: Summary of total time (in seconds) for all approaches including background compilation for the small input. Total time includes both compilation and execution time. Four bars are given for each input. The first three bars show total time using eager compilation, lazy compilation, and background compilation, respectively. The fourth bar shows "ideal" execution time alone (from execution of off-line compiled benchmarks). Absolute total time in seconds appears above each bar.

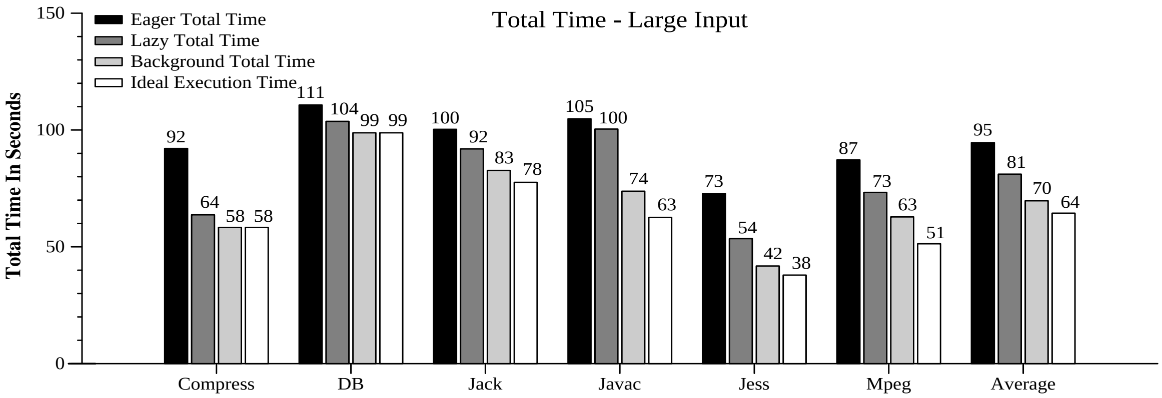


Figure VII: Summary of total time (in seconds) for all approaches including background compilation for the large input. Total time includes both compilation and execution time. Four bars are given for each input. The first three bars show total time using eager compilation, lazy compilation, and background compilation, respectively. The fourth bar shows "ideal" execution time alone (from execution of off-line compiled benchmarks). Absolute total time in seconds appears above each bar.

Tables

Benchmark	Total Size in KB	Total Count Classes	Used Class Count small	Used Class Count large	Optimized Time (Secs) (Used Classes) small ET	small CT	large ET	large CT	Baseline–Compiled Time (Secs) (Used Classes) small ET	small CT	large ET	large CT
Compress	17	12	11	12	7.4	8.2	84.0	8.1	47.0	0.1	525.1	0.1
DB	9	3	3	3	1.9	8.2	102.7	8.0	2.9	0.3	162.6	0.3
Jack	129	57	46	46	9.9	16.0	84.3	16.0	10.9	0.4	93.2	0.4
Javac	548	176	132	139	2.0	38.6	66.3	38.5	3.0	0.6	103.5	0.6
Jess	387	151	133	134	2.5	27.2	45.2	27.6	6.4	0.3	109.8	0.3
Mpeg	117	55	42	37	7.3	15.9	71.3	15.9	47.6	0.4	452.1	0.4
Average	201	78	61	62	5.2	19.0	75.6	19.0	19.6	0.4	241.1	0.4

Table I: Benchmark characteristics. The first column of data provides benchmark sizes in kilobytes. The second column is the total number of classes in each application. The third and fourth columns show the number of class files accessed during execution of each input. The middle four columns contain the execution (ET) and compile (CT) times when the Jalapeño optimizing compiler is used. The last four columns are the execution and compile times when the Jalapeño baseline compiler is used. Times for both input sizes are given. The small input is the SpecJVM 10% input and the large is the 100% input.

Benchmark	Small (in seconds)					Large (in seconds)				
	Eager		Lazy		Ideal	Eager		Lazy		Ideal
	ET	CT	ET	CT	ET	ET	CT	ET	CT	ET
Compress	7.4	8.2	5.3	5.4	5.3	84.0	8.1	58.3	5.4	58.3
DB	1.9	8.2	1.9	5.0	1.7	102.7	8.0	98.8	4.9	98.8
Jack	9.9	16.0	9.4	11.6	9.1	84.3	16.0	80.1	11.8	77.6
Javac	2.0	38.6	2.0	31.2	1.9	66.3	38.5	68.1	32.3	62.6
Jess	2.5	27.2	1.8	14.7	1.8	45.2	27.6	38.4	15.1	37.9
Mpeg	7.3	15.9	6.7	11.7	5.4	71.3	15.9	61.7	11.6	51.3
Average	5.2	19.0	4.5	13.3	4.2	75.6	19.0	67.6	13.5	64.4

Table II: Raw data: Execution (ET) and compile (CT) times in seconds with and without lazy compilation using the optimizing compiler. The sixth and eleventh columns contains the benchmark execution time when the application is batch compiled off-line. Batch compilation (Ideal) eliminates dynamic linking code from the compiled application and enables more effective inlining. Columns 2 through 6 are execution and compile times for the small input and columns 7 through 11 are for the large input. For each input, times for both the eager and lazy approaches are given.

Benchmark	Small			Large		
	x 100,000		Percent	x 100,000		Percent
	Eager	Lazy	Reduced	Eager	Lazy	Reduced
Compress	492	3	99	6202	3	100
DB	12	3	75	455	4	99
Jack	32	28	13	71	51	28
Javac	27	17	37	480	33	93
Jess	64	7	89	790	8	99
Mpeg	133	5	96	1547	6	100
Average	127	11	92	1591	18	99

Table III: Dynamic execution count of dynamically linked sites. Columns 2–4 are for the small input and 5–7 are for the large. Columns 2 and 5 give the counts in 100,000's of executed sites that were dynamically linked using the optimizing compiler. Columns 3 and 6 are the counts when lazy compilation is used and Columns 4 and 7 show the percent reduction.

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