

# JIT through the ages

## Evolution of just-in-time compilation from theoretical performance improvements to smartphone runtime and browser optimizations

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### Abstract

This paper is a study on just-in-time compilation and traces its evolution from being a theoretical performance optimization to a technology that provides concrete speed-ups for constrained applications and in dynamic programming languages. Also highlighted are the increase in sophistication of the techniques used to deal with the complexities that arise in these problem domains and the inherent trade-offs.

## 1 Introduction

The advances in software and information technology today put great demands on the hardware and system software of devices. Devices like smart phones have larger capabilities than an average computer in the y2k era [16][18]. However, this increase in capability has also lead to a mind-boggling spectrum of applications that these devices find. Further, with the tremendous increase in the number of developers, the quality of software being written is also varied.

In such a scenario, platform and system engineers are pushing the boundaries when it comes to increasing the performance of these systems. This process has lead them to revisit some of the dormant ideas in computer science and try to apply them from a newer perspective and in a different computing landscape. One such idea is just-in-time compilation. Just-in-time compilers translate byte codes during run time to the native hardware instruction set of the target machine [1]. Though this idea was first proposed in the early seventies, it has seen a renaissance with interpreted languages like Java and dynamic languages like JavaScript and Python being adopted for large scale applications. This paper studies this trend and discusses the evolution of this concept for modern day computing.

The rest of this paper is organized as follows. Section 2 gives a brief overview about just-in-time compilation and talks about the trade-offs involved, while Section 3 describes some of the earlier implementation of JIT compilation. Section 4 describes a generic JIT Compiler, mostly based on the Java run-time environment. Section 5 describes some of the basic infrastructure needed for a JIT compiler, namely in terms of data structures and also . Section 6 describes a couple of the embedded Java JIT, namely the Android Dalvik VM's JIT compiler and the HotpathVM and contrasts the two while explaining why we would require a just-in-time compiler for an embedded system. Section 7 describes a just-in-time compiler for Dynamic Languages like JavaScript and Python and what features make these distinctive and provide for such great performance increases.

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## 2 JIT compilation

Just-in-time compilation attempts to bridge the gap between the two approaches to program translation: compilation and interpretation. Generally, compiled programs run faster as they are translated to machine code or other such native code. However, they occupy a larger memory footprint as the binaries are larger. Further, they also take a longer to optimize the code. Interpreted code on the other hand takes up a smaller memory footprint as it is represented at a higher level and hence can carry more semantic information. Thus, it's more portable. However, interpreters need access to the runtime of the system and they need to gather much more information during the runtime to successfully execute the programs. This makes interpretation more expensive in terms of time to run and overall complexity of the application.

### 2.1 Overview

In the just-in-time compilation process, starting with the interpreter, some features of a static compiler are built into the system. Typically, a JIT compiler will isolate some sections of the code, at run-time, which

are accessed more often and then statically compile them, aggressively optimizing those sections in the process. The sections of code that are to be statically compiled can be identified in many ways, and this is briefly described in Section 3. These sections of code are commonly called *hot-paths*.

## 2.2 Hot-path detection

Hot-paths could be identified at various granularities. Most JIT compilers that are written for statically-typed languages like Java, working on servers and desktops, performed Method-based identification, where the hot-paths are identified at the granularity of each method. While this technique works well in simplifying the design of the JIT and provides incredible speed-ups, studies have shown that there's an additional overhead in terms of memory and power consumption [6]. This is because at this coarse granularity, there are different sections of the code which are compiled even though they are not hot sections. This includes exceptions and other such code. To avoid this, a more complex method of identifying hot-paths, known as trace-based just in time compilation has been proposed. Here hot-paths, which are also called traces, are selected based on various criteria. A trace-based JIT is explained in detail in Section 4.

## 2.3 A few considerations

The nature of a JIT system is such that there are bound to be many trade-offs. The most major consideration to take into account is the fact that having both a compiler and an interpreter at run-time could prove expensive. This was the reason this idea did not catch on in the early stages [4]. Further, constant switching between interpreted and compiled code could prove for choppy execution. Thus, a JIT compiler writer must take care to ensure smooth transitions between the two modes of execution. Different systems do this differently. A few JIT compilers manage this by having an additional data structure called the translation cache that provides for quick reference to the compiled code.

# 3 Chronology

In the purest sense, one of the first ideas for a JIT compiler can be dated back to McCarthy's 1960 Lisp paper [17] where he talks about compiling the source to machine code. However, more concrete implementations surfaced about a decade later for various languages like FORTRAN, Smalltalk, Self, Erlang, O'Caml and even ML and the ubiquitous C [4].

Some of the early ideas for JIT compilation can be

summarized in terms of mixed-code and throw-away code compilation. Another interesting paradigm shift is to view JIT compilers in terms of simulators.

## 3.1 Mixed code and throw-away code compilation

Work by Dawson [9] and Dakin and Poole [8] are the earliest ideas that talk about just-in-time compilation as we know it. Published in 1973 in the same journal, both papers talk about how performance of interpreted code can be improved by compiling it down to machine code. In the mixed code approach in [8], Dakin and Poole propose that in order to achieve the right balance between the poor space utilization of the direct compilation and the slower running times of the interpreted mode, a common approach with data structure that keeps track of procedure calls in both cases must be used. Similarly, in [9], Dawson notes the three classes of instructions: very rarely used, occasionally used and often used and address how we would select which of these instructions should be compiled. He states that the cost of compilation is relatively lesser than that of storing the compiled code and thus, once the buffer reaches its limit, it can be flushed for the next compiled section of the code.

## 3.2 Simulation and binary translation

Early simulators were classified 4 generations. The first generation were plain interpreters, while the second generation dynamically translated the source instructions into target instructions one at a time. The third generation translated entire blocks of the source code dynamically while the fourth generation improved on the third by isolating a few key paths and translating them. The third generation of simulators are similar in idea to method based JITs while the fourth generation is similar to trace based JITs as discussed in section 4.3. The main considerations of both fourth generation simulators as well as Trace-based JITs include, profiling of execution, detection of hot-paths, code generation and optimization and an exit mechanism. These features are explained in detail for Trace-based JITs in the sections below

# 4 A Generic Trace-based JIT Compiler

This section aims to explain the working of a simple just-in-time compiler. For the purpose of this section and most of the rest of the paper, unless stated, we would be talking about a Java-based JIT compiler. The choice to work with a Java JIT is because Java is

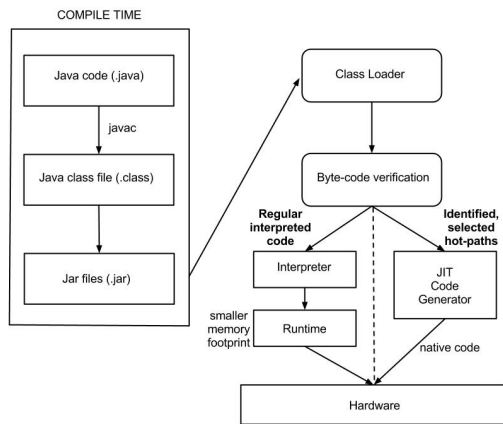


Figure 1: Generic Java-based JIT Compiler

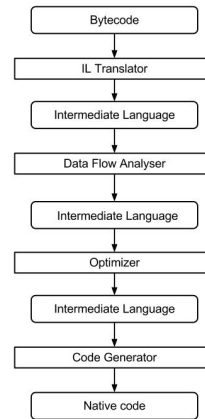


Figure 2: JIT Compiler Internals

one of the interpreted languages that benefit significantly by the use of a just-in-time compiler. Further, as java is one of the most widely-used languages that is being used today [20], studies in optimization of the Java runtime has greater relevance for speeding up most commonly available systems.

#### 4.1 Run-time environment with a JIT compiler

Figure 1 above provides a general schematic of a java-based just-in-time compiler. The major components include the java compilers and the class loader as well as the byte-code verifier in addition to the . The .java files are first compiled down to .class files and then they are bundled as jar files. This is all done at compile-time.

At run-time, the class loader first loads all these class files on to the Java virtual machine. Then the byte-code verifier then performs type checking to ensure that typing information is maintained constantly. In addition to these steps, depending on the exact implementation of the JIT, in some earlier stage, the potential hot-paths are detected and marked accordingly. Then, during runtime, the runtime keeps track of the number of times these potential hot-paths are run. When the count of execution of that particular hot-path hits a particular threshold, it is then statically compiled. JIT compilers differ in the manner in which the statically compiled binary is maintained as well. Most times, they are stored in a cache-like data structure that is designed keeping the system configurations in mind.

#### 4.2 Inside a JIT compiler

Figure 2 depicts the internals for a general just-in-time compiler block that is seen as a black-box in

Figure 1. As we can see from the figure, the code is aggressively optimized and checked multiple times to ensure that there is no loss in the semantics with respect to the original interpreted code. Starting with the byte code, it is first translated to a carefully chosen intermediate language. The intermediate representation must have the properties that allow it to be translated to a tree-like structure that allows for better optimizations [2][12][14]. Then data and/or control flow analysis is performed on this IR to ensure that there is consistency between the compiled version and the original code. The most common representation that is used is the static single assignment form [7]. The SSA form is most amenable to optimizations like constant propagation, code motion and elimination of partial redundancies. After all optimizations are performed this is then translated out of the SSA form and back to the original intermediate representation. This is then fed into a code generator to produce native machine language code.

The data structures, optimizations and maintenance of the hot-paths depends on each individual implementation of the JIT and how closely the system is integrated. We will discuss this in slightly more detail for a few systems in the later sections. However, the general schematic of most of the JIT compilers follows the template as described above.

#### 4.3 Trace selection and compilation

The optimizations that can be done on a JIT are greatly dependent on the granularity of the hot-path detection. The finer the granularity of the hot-path, greater the optimizations can be done. However this increases the cost of transitioning between the compiled and interpreted modes of execution and neces-

sitates the two units to be integrated more tightly.

Two of the most common hot-path detection is done at the trace and method based granularity. In method based JITs, as the name suggests, the potential hot-paths are marked at the beginning of each method implementation. However, what is most prevalent and effective is the Trace-based JIT compiler, which compiles certain sections of the code that are most likely to be called often. These could include certain obvious choices like targets of backward branches [14]. The trace is ended when it forms a cycle in the buffer, executes another backward branch, calls a native method or throws an exception [15]. These potential traces are profiled with some additional meta-data keeping track of their execution count.

At each stage when the potential trace head is reached, the counter is incremented. When this count reaches a predefined threshold value, the trace is then compiled as described in the previous section. This compiled trace is then stored in a translation cache like structure. Most modern JIT systems enable chaining of multiple traces for greater flexibility. This allows the execution to transfer a little less between the JIT and interpreter.

The above section described the generic JIT compiler that is seen in most systems today. For the rest of this paper, we will talk about what special corner case optimizations are handled for systems like smartphones and fast web-browsers.

## 5 JIT on Smartphones and Tablets

Handheld devices today are changing the entire computing landscape. This phenomenon has made computing accessible to almost any one. The innovations that can take credit making this possible include the hardware manufacturers and the open source developers. The hardware manufacturers can be credited for the System on Chip (SoC) design that make it possible to have multiple components on a single piece of silicon that functions beautifully as a single unit. The open source developers drive the phenomenon for developing various applications for these devices. These provide information and services to the user on-the-go, making life more connected. Many open-source developers have applications for these devices that are available for free or for a small nominal amount. These include applications for productivity, news and information, entertainment and games.

While these developers work on frameworks on the runtime that are provided by Software development

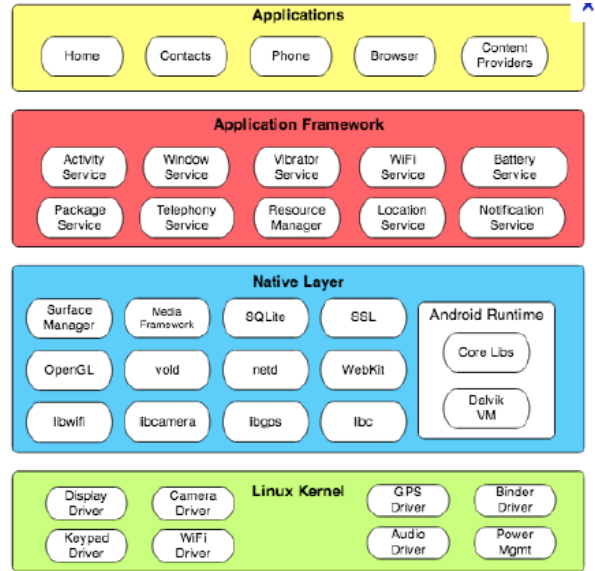


Figure 3: The Android Application Framework

kits (SDKs), the engineers themselves have implemented tremendous amounts of optimizations both at the hardware level as well as at the operating systems. In particular, the optimizations at the operating system level are very complex and worth looking into. The three major players in this industry include Apple’s iOS that runs the iPhones, iPads family and Google’s Android that runs various devices that are manufactured in accordance to the open-handset alliance and the Windows 8 touchscreen OS by Microsoft. In this paper we will talk about the Android operating system in particular and how they use the JIT compilation techniques to improve performance.

### 5.1 Android Application Framework and Dalvik

From Figure 3, we see that the Android operating system runs on the Linux kernel. While the kernel itself and its many features are abstracted away from the user, the individual applications are sandboxed on top of the Dalvik virtual machine. This VM was developed by Google instead of the regular Java VM. There were many reasons for this, the foremost being that Dalvik is more sensitive to the constraints that are imposed on embedded devices like smartphones, like lower frequency, smaller RAM sizes as well as battery power [10]. This, along with some core libraries that are abstracted from the kernel drivers, constitutes the main runtime of Android. The applications themselves, written in Java, are run on top of a framework which further abstract some features and provide for appropriate package managers for

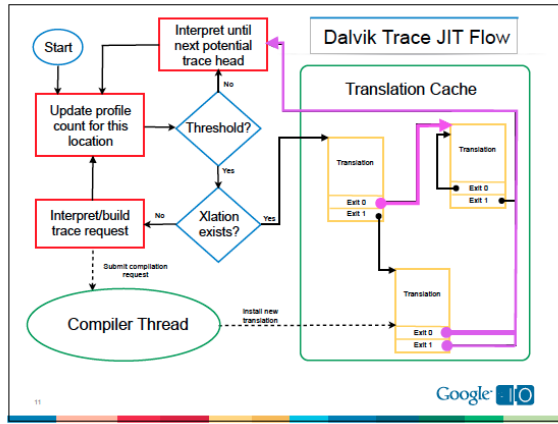


Figure 4: The Dalvik Trace JIT Flow

each of the service. In this manner, the kernel and the lower layers are abstracted from the developer and the user, providing for both ease of use and development

The Dalvik VM is a very lightweight implementation as each of the different services that are run on an Android powered device are all run on an individual instance of the Dalvik VM. More so, the initial system server process, which includes the activity manager, libc and other such components, is also bundled and run on an instance of Dalvik. The component that provides for the magic of forking out an instance of Dalvik upon request is called the Zygote and its a very crucial to the Android system itself.

Thus, it is clear that any optimizations made to Dalvik will help speed up the overall runtime. Further, many of the applications that are commonly run tablets and smartphones are games. Most games are extremely compute intensive (not exclusively games but other applications as well), running the same sections of code repeatedly. Thus it is natural to see an implementation of the JIT compiler in Dalvik. The next subsection discusses the Dalvik JIT in slight detail.

## 5.2 Dalvik JIT

The Dalvik JIT is very similar to the generic JIT that was explained in Section 4. As the applications are written in Java and run on top on a virtual machine that replaces the JavaVM, the schematic is very similar to Figure 1. The only significant change is during compile time, instead of storing each of the class files into a separate jar file, there is a tool called the dx tool which compiles multiple class file into a single dex file. The dex file format provides for about 5% improvement in storage as compared to the Jar file over uncompressed data. This is significant in terms

of the memory savings.

The JIT itself is a generic Trace-based JIT whose flow is depicted in Figure 4. The potential trace heads are identified in the front-end of the compiler at the parsing stage after the conversion to bytecode. The opcodes of the dex byte code instructions are checked. The front-end analyses each method from a high level and marks out sections which may not be optimized and does other such maintenance of the source code. When the traces are compiled, similar to generic trace-based JIT in Section 4, they are stored in the translation cache. This cache is maintained during the run-time as and when the traces are compiled. There is provision to chain multiple traces, which decreases the bouncing between the compiler and interpreter. The translation cache is designed in such a way that it integrates the compiler and interpreter tightly, acting as a buffer between the two.

The trace is aggressively optimized before it is compiled. This is done by converting it into the SSA notation. Some of the optimizations included are dead store elimination, variable folding and inlining of getters and setters. On the whole, the Dalvik JIT by design itself is highly efficient and is optimized to be lightweight and take up very less overhead on a constrained system.

## 5.3 Similar work

Gal et al. proposed an embedded Java JIT compiler for resource constrained devices [14]. Similar to Dalvik Trace JIT, this JIT compiler also optimized the traces in the SSA form. The HotpathJIT proposed to merge the trees when they were overlapping in terms of the traces that they compiled. Further they supported optimization of invariant code motion as well. The HotpathVM was a more complex system that was proposed rather than the Dalvik JIT which is a production quality compiler.

The above section concludes our discussion on the JIT compilers in smartphone/tablet or other handheld devices. We talked about how they helped to optimize the runtime and improve the speed and memory demands on them.

## 6 JIT on the internet

With the increase in the data that is available on the internet, there is a need to greatly increase the efficiency and speed at which webpages and servers are processed and requested. Most server-side scripting languages and front-end design languages are dynamic which by nature makes them on the slower side. This had lead to engineers coming up with

innovative solutions to improve performance, while maintaining the ease of use for developers. For instance, Facebook has come up with its source translator that compiles PHP down to C++. Called the HipHop, this translator uses g++ to run the compiled C++ code [11].

In such a landscape, it is natural that the developers look towards JIT compilers to increase performance as some of the functions that are implemented while querying webpages or rendering them are highly regular. Some of the most interesting implementations of JITs in terms of working with webpages and servers include the TraceMonkey for JavaScript in the Firefox and the JIT in the PyPy implementation of the Python interpreter. These topics will be covered very briefly in the following sections.

## 6.1 JavaScript JITs and TraceMonkey for Firefox

Based on the paper on Trace-based JIT Type Specialization for Dynamic Languages by Gal et al. [13], there have been many implementations of JIT compilers for JavaScript, the most popular of which is the TraceMonkey JIT that is found in the Firefox web browsers of versions 3.5 onwards.

This paper proposed an inexpensive and efficient method for performing type specialization by means of generating trace trees. The interesting name of TraceMonkey was proposed because the flow of execution jumps across the tree depending on the program counter in the interpreter. The trace selection and optimization is similar to the JIT compiler discussed in Section 4. The major difference that this has compared to the other implementations is additional information has to be incorporated in the Trace trees, namely the type information. This was implemented in the SpiderMonkey JavaScript VM in the Firefox browser and the authors observed an approximate speed up of 10x overall.

## 6.2 Some other developments on JavaScript JITs

Many different implementations of JavaScript JITs are available currently, the most popular of them being the dynamic optimization system called Dynamo [5]. Some other examples of JavaScript engines that have the interpreters generate native code include Apple's SquirrelFish [3] and Google's V8 JavaScript engine.

## 6.3 PyPy

Server-side scripting is a big bottleneck when it comes to data analysis of the billions of data files that are present. For instance, most Facebook's data is estimated at 100 peta bytes stored in a single Hadoop store. Accessing this data must be done quickly and efficiently without disturbing the configuration of the system overall. Most scripting languages, like Python are dynamic, which while making them very easy to use, make them highly inefficient.

Thus there have been many implementations that attempt to optimize Python and other such languages for speed-up. One such implementation is PyPy which is an alternative implementation of Python 2.7.2 that is fast and memory efficient [19]. The JIT compiler in PyPy is not built-in as a separate module but is instead generated by a JIT compiler generator. The authors exploit the fact that their interpreter is written in a high-level language to include this module. They believe that this will prevent their JIT compiler from going out of sync with their interpreter at any stage. Overall, the achieved an average speed-up of around 5.5 times over the regular implementation of Python. As this is ongoing work, it will be extremely interesting to see the speed-ups that they will be able to get after including additional optimizations to their interpreter.

This concludes our Section on how JIT compilation helps to improve performance of systems that are used to power the internet as we know it, both at the front-end rendering as well as the server-side scripting.

## 7 Conclusion

This paper was intended to be an introduction into some of the recent work in just-in-time compilation and how this is implemented some of the technology that affects our everyday lives. With greater need for faster and more reliable computing, just-in-time compilation along with many other enduring ideas for optimization, has seen a renaissance nearly three decades after it was first thought about. It will be interesting to see how just-in-time compilation will adapt further, with some of the more challenging problems that are going to rise in computing

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