

# Examining the Connection Between Hardware Architecture and Virtual Machine Design

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## Abstract

Virtual machines for programming language interpretation have become popular despite the long-standing truth that machine code is faster than interpreted code. By viewing interpreters as virtual machines, we can exploit the similarity between virtual machines and the underlying hardware architectures on which they run to take advantage of optimizations implicit in hardware and improve the performance of virtual machines.

## 1. Introduction

Interpreters have played a central role in the study of programming languages for as long as programming languages have been studied. Explicit in McCarthy’s definition of LISP [6] is the notion of an evaluator, a program designed to run (evaluate) other programs. For many years, interpreters have been used to study the design and semantics of programming languages. Until recently, however, languages like FORTRAN, COBOL, and later C remained popular for programming, because of how fast programs compiled to machine code from these languages were.

Java, which appeared in 1995, was one of the first interpreted languages to use a so-called *virtual machine*, and has proved popular. Java programs are compiled down to Java bytecode, which is machine code for the Java Virtual Machine. Since Java, bytecode interpreters have become commonplace, and indeed, even in the original academic circles where interpreters were conceived and made popular, researchers have connected the old notions of interpretation as evaluation with the modern idea of interpreter as virtual machine [1]. With the advent of the virtual machine language runtime has come an opportunity to rectify the main flaw of interpretation alluded to above: the speed gap between interpretation of high-level code and execution of machine code. One of the major ways that this has been done is through exploitation of properties of the underlying hardware architectures on which these interpreters run.

We divide this paper into three main parts. In the first part, we discuss two papers related to improving hardware branch prediction accuracy for virtual machines, and in the second part, we discuss three papers related to exploiting memory models and caching. Lastly, we conclude by discussing the possibility of turning the tables and applying techniques developed in virtual machine design to the design of new hardware architectures.

## 2. Branch Prediction

Programming language design has always been a tricky area of research. More importantly the design of the runtime plays an important role in enabling interesting language features while maintaining acceptable performance. When we consider the implementation of modern language runtimes, implementing a quick interpreter has

mostly been the first choice. The main reason for this is the ease of implementation and the ease of extensibility. Unfortunately, interpreters come with a large performance overhead. Classical big-step style interpreters which traverse through the AST of a program suffer from this. An improvement over this design are the bytecode based interpreters where the bytecodes are fetched, decoded and then executed in a loop. The classical way of implementing this is using switch statement matching the opcode with various possible cases and executing the corresponding opcode handler.

The major drawback of this approach is the bytecode fetching and branching overhead. Other alternatives to the switch-case approach like direct threading, indirect threading also suffer from the similar branch mis-prediction overhead. There branches that are taken depend on the flow of execution or the stream of bytecodes of the program being executed. It does not follow any pattern which is very much the foundation of branch prediction strategies implemented in the hardware. It is important to note here that the branches that we are describing are the ones in the interpreter loop and should not be confused with the branches in the program being interpreted. The problem with branch mis-prediction is even more exaggerated in the case of Dynamic Scripting Languages (DSLs) where the opcode handlers for a dynamic instruction have to first determine the types of the opcodes and then perform operations based on the observed types. This is generally implemented using a *if-else* chain or a *switch-case* construct adding to the number of branches mis-predicted during execution.

### 2.1 Dynamo and DynamoRIO

Dynamo is an pseudo interpreter which interprets machine code and specializes the hot traces that are executed at runtime. It follows the same philosophy as a JIT compiler but at a much lower level. Sullivan et. al presented DynamoRIO, based on IA-32 version of Dynamo, as a solution to reduce the interpretation overhead. Using Dynamo or DynamoRIO naively as a binary optimizer for any interpreter does not yield any speedup. This is because DynamoRIO relies on its trace collection heuristic to optimize a binary and as mentioned above the trace of execution of any interpreter depends on the program being interpreted which is unpredictable at runtime. To solve this problem DynamoRIO infrastructure provides APIs to language runtime developers to instrument their interpreters with hooks to a special tracing framework. The hooks provide signals to the underlying framework when to start and stop the trace collection. The idea here is to make sure that the trace that is collected matches the program that is being interpreted rather than the interpreter that is interpreting it. This gives lot more information to the tracing infrastructure to work on and optimize.

## 2.2 Context Threading

## 2.3 Instruction replication and Superinstructions

# 3. Memory models and Caching

## 3.1 Garbage Collection

## 3.2 Instruction caches

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