Walkabout – A Retargetable Dynamic Binary Translation Framework

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***Abstract*— Dynamic compilation techniques have found a renaissance in recent years due to their use in high-performance implementations of the Java(TM) language. Techniques originally developed for use in virtual machines for such object-oriented languages as Smalltalk are now commonly used in Java virtual machines (JVM(TM)) and Java just-in-time compilers. These techniques have also been applied to binary translation in recent years, most commonly appearing in binary optimizers for a given platform that improve the performance of binary programs while they execute.**

The Walkabout project investigates and develops dynamic binary translation techniques that are based on properties of retargetability, ease of experimentation, separation of machine-dependent from machine-independent concerns, and good debugging support. Walkabout is a framework for experimenting with dynamic binary translation ideas, as well as techniques in related areas such as interpreters, instrumentation tools, and optimization.

In this paper, we present the design of the Walkabout framework and its initial implementation. Tools generated from this initial framework include disassemblers, machine code interpreters (emulators), and binary rewriting tools for the SPARC(R) and x86 architectures.

I. Introduction

Binary translation, the process of translating binary executables[1], makes it possible to run code compiled for a source (input) machine M_s on a target (output) machine M_t. Unlike an interpreter or emulator, a binary translator makes it possible to approach the speed of native code on machine M_t. Translated code may run more slowly than native code because low-level properties of machine M_s must often be modeled on machine M_t. For example, the Digital Freeport Express translator [Dig95] simulates the byte order of the SPARC(R) architecture, and the FX!32 translator [Tho96], [HH97] simulates the calling sequence of the source x86 machine, even though neither of these is native to the target Alpha architecture.

The Walkabout framework is a retargetable binary translation framework for experimenting with dynamic translation of binary code. The framework had its inspiration in the University of Queensland Binary Translator (UQBT) framework [CE00], [CERL02], [CERL01], which enabled static translations of binary codes. We took what we had learned in the areas of retargetability and separation of machine-dependent from machine-independent concerns, and applied these techniques to the new dynamic framework. Of course, the code transformations we could support were different due to differences between dynamic and static translation. For example, a static translator operates before the target program executes, and so, it can afford to use expensive optimizations. A dynamic translator, on the other hand, operates while the target program is executing, and the time it requires is unavailable to the target program.

A. Goals and Objectives

Binary translation requires machine-level analyses to transform source binary code onto target binary code, either by emulating features of the source machine or by identifying such features and transforming them into equivalent target machine features. In the Walkabout system, we make use of both types of transformations, and determine when it is safe to make use of native target features.

One question that must be answered early in the development of a binary translation system is what intermediate representation to use. In the UQBT system, we made use of two intermediate representations: a low-level one, RTL, and a high-level one, HRTL. RTL is a register transfer language that makes explicit every assignment to a register, while HRTL is a high-level register transfer language that resembles simple imperative languages, with explicit transfers of control instructions.

Many other binary translation systems have used machine code itself as the intermediate representation, mainly because these systems were binary code reoptimizers and were generating code for the same machine. Such systems include Dynamo [BDB00], Wiggins/Redstone [DGR99] and Mojo [CLCG00].

For Walkabout, we initially use machine code as the intermediate representation. We plan to use RTL as the next step. However, we want to experiment with how well machine code-level RTLs support translation into a target representation. RTLs are still machine-dependent as they expose such features as delayed branches and register windows.

The goals of the project are:

- to derive components of binary translators as much as possible from machine descriptions,

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[1] In this document, the terms *binary executable*, *executable*, and *binary* files are used as synonyms to refer to the binary image file generated by a compiler or assembler to run on a particular computer.

- to understand how to instrument interpreters in a retargetable way,
- to determine whether an RTL representation is best suited for dynamic machine translation, and how to best map M_s-RTLs to M_t-RTLs[2],
- to understand how debugging support needs to be integrated into a dynamic binary translation system, and
- to develop a framework for quick experimentation with dynamic binary-manipulation techniques.

We limit binary translation to user-level code and to multi-platform operating systems such as Solaris(TM) and Linux.

II. Previous Work

Dynamic binary translation techniques evolved from emulation and simulation techniques as a more efficient way of running programs on other machines by generating target native code on the fly. Many of the techniques used in dynamic binary translation systems were originally developed in language interpreters and virtual machines for languages such as APL, Forth, Smalltalk, Self, and now Java(TM). We review the literature in three main areas: existing examples of dynamic binary translators, binary rewriting tools, and virtual machines for object-oriented languages.

A. Other Dynamic Binary Translators

DAISY (Dynamically Architected Instruction Set from Yorktown), is a VLIW virtual machine that emulates existing machines in order to run applications, including low-level system programs, on the DAISY machine [EA96]. The machines it supports are the PowerPC, x86, and S/390. DAISY was developed at IBM T.J.Watson to aid in determining what features a new VLIW architecture should have in order to successfully run a variety of existing programs. The DAISY system provides simulations of how well a new architecture might perform if it were built.

HP's Aries is a PA-RISC to IA-64 dynamic translator for the HP-UX operating system, which is planned to be shipped with all IA-64 HP-UX systems [ZT00]. Aries combines a fast interpreter with a dynamic optimizing compiler (i.e., a just-in-time, or JIT, compiler). It operates by compiling frequently interpreted code sequences into native IA-64 code. Aries allows users to migrate their PA-RISC applications transparently, without user intervention. Runtime verification support was also built as part of this tool.

Transmeta's Crusoe architecture makes use of dynamic binary translation—which they term "code morphing"—to support running x86 applications on the Crusoe processor, a VLIW machine with instruction level parallelism [Kla00]. The code morphing software resides in a ROM and is effectively a layer that sits in between the BIOS and the VLIW processor. Crusoe has support at the hardware level for features that are hard or expensive to support at the software level. Precise exception handling is done by shadowing all registers holding x86 state information, and providing a commit and rollback operation to copy registers between the working and the shadow copies. Alias detection hardware guards against illegal moves of load instructions ahead of store instructions, when the store instruction overwrites the previously loaded data. Self-modifying code is supported by detecting when it happens, so that previously-translated code can be flagged as invalid. This is done by protecting pages with a translated bit.

Two academic systems have been described in the literature: UQDBT [UC00] and bintrans [Pro01]. Both systems show that retargetable dynamic binary translation is feasible. The former is based on the UQBT system and makes use of one intermediate representation for both code generation and machine-independent translation purposes. The latter makes no use of an intermediate representation and compiles all the code that is decoded on-the-fly, achieving better performance for the limited class of architectures on which it was tested.

B. Other Binary Rewriting Tools

Areas related to dynamic binary translation include emulation and simulation, where work has been done since the 1960s. Recent emulators and simulators include the Sun Microsystems tools Shade [CK93] and Wabi [HMR96], [FN96], as well as the Stanford research simulators SimOS [RHWG95] and Embra [WR96].

In the last few years, several dynamic reoptimizers have been developed as research projects. Their goal is to transparently reoptimize binaries at runtime to improve their performance. None of these systems has been used commercially since there are still a number of open research questions in how to implement these systems. For example, it is hard to achieve consistently good performance while correctly executing all programs. The systems include: HP Labs' Dynamo [BDB00], a reoptimizer of PA-RISC code; Compaq's Wiggins/Redstone [DGR99], a reoptimizer for Alpha code; and Microsoft Research's Mojo [CLCG00], a reoptimizer of (x86,Windows) binaries.

Both Dynamo and Mojo count branching instructions while interpreting code to detect frequently executed code and generate native code for it, applying a variety of optimizations. Wiggins/Redstone samples CPU events for frequently executed instructions in the target program using hardware event counters and the Digital Continuous Profiling Infrastructure (DCPI [ABD+97]). This allows the tool to determine a seed instruction out of which a trace of frequently executed code is determined.

All systems show mixed results: some SPEC benchmark programs perform faster, while others perform slower. For programs where performance is degradated, no study has been reported in the literature that aids in understanding what features affected these programs; some of the programs that worked well under Dynamo did not work well under Wiggins/Redstone, for

[2] RTLs for a given machine M are denoted M-RTLs.

example. In addition, common problems involving changes in a program's phase behaviour have not been studied.

C. Virtual Machines for Object-Oriented Languages

In recent years, there has been a renaissance of dynamic compilation techniques, mainly due to the popularity of the Java programming language and the drive to build high-performance Java virtual machines (JVM(TM)[3]) that run Java code faster.

JVMs such as Sun Microsystems Java HotSpot(TM) virtual machine [HBG+97], [GM00], [PVC01], Intel's JUDO [CLS00] and the Open Runtime Platform [CLS02], and IBM's Jalapeño [AAB+00] use dynamic compilation techniques to produce good quality native code. These techniques have been derived over time from virtual machine technology used to implement object-oriented languages such as Smalltalk [GR83], [DS84] and Self [US87], [Hol94]. Self was the inspiration for the original Java HotSpot virtual machine.

The architecture of optimizing virtual machines is based on the premise that most programs spend 90% of the time in 10% of the code—therefore, the VM only optimizes that 10% of the code and interprets or generates naive code for the rest, where little time is spent.

III. Architecture of Walkabout

The Walkabout framework was designed with retargetability in mind. We were interested in supporting binaries for different input and output machines, so we designed the framework to be retargetable for both input and output machines. In our notation, we refer to the input machine as the *source machine* (M_s), and the output machine as the *target machine* (M_t). The framework was designed so that users could instantiate new translators out of the framework for their source and target machines of choice to run on a *host machine*. A host machine belongs to the same family of machines as the target machine, for example, we may generate code for a SPARC V8 machine and run it on a SPARC V9 machine. Unless the host and the target machines are the same, some target machine-specific optimizations may not be in place.

The architecture of the Walkabout framework borrows from the architecture of most existing dynamic compilation systems. Figure 1 illustrates the architecture of the Walkabout framework. The source binary program for machine M_s is loaded into virtual memory and initially interpreted until a hot path is found. A hot path is a frequently executed path in a program. Code for the target machine M_t is generated for that hot path and placed into a translated instruction cache (called the fragment cache or F$). During code generation, simple optimizations are applied to obtain better code locality. Once the generated code is executed, control transfers to the dispatcher, which decides whether to interpret more code or transfer control to code in the fragment cache. If interpreted, the process

[3]The terms "Java virtual machine" and "JVM" mean a virtual machine for the Java(TM) platform.

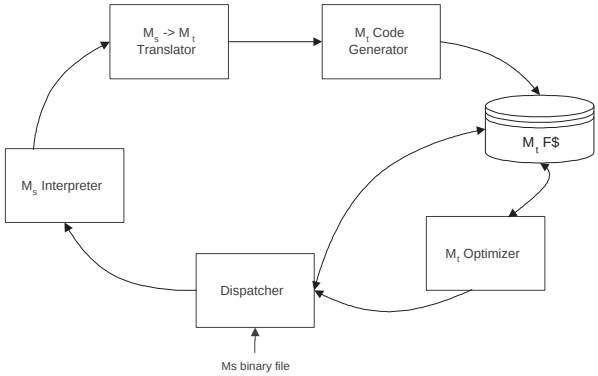

Fig. 1. The Architecture of the Walkabout Framework

repeats. Reoptimization of translated code occurs when a piece of translated code in the fragment cache is executed "too often", i.e., when a threshold is met.

Retargetability is supported in the Walkabout framework through the use of specifications: machine descriptions and specifications of the hot path selection methods. The machine descriptions specify the syntax and semantics of machine instructions, and allow the automatic generation of machine-code interpreters (emulators) and instruction encoders.

The 2001 implementation of the Walkabout framework does not implement the complete framework. The system was built in stages, starting from the interpreters, over a period of 9 months. Next we describe different tools that can be built from this initial implementation.

IV. The Disassembler

The Walkabout framework uses specifications of the syntax of machine instruction sets to automatically generate machine disassemblers. We reused the specifications we used in the UQBT project [CE00], which were SLED descriptions supported by the New Jersey Machine Code (NJMC) toolkit [RF97].

SLED specifications allow users to specify the mapping between the binary and the assembly representation of a machine instruction set, as well as the machine's registers and names for those registers. The NJMC toolkit processes the machine SLED specifications, and generate abstractions suitable for either decoding or encoding machine instructions. The decoding abstraction provides for a *matching* statement whose syntax resembles that of a C language `switch` statement, and whose semantics is equivalent to matching the series of bits that make up an instruction and returning the values of the variable fields of an instruction.

The disassembler generator combines the decoding abstraction from the NJMC toolkit with pretty printing facilities and a loader front end to generate the machine disassembler. Disassemblers for the SPARC Solaris and x86 Linux environments were generated by this tool.

V. The Interpreter

Interpreters in the Walkabout framework are automatically generated from specifications of syntax and semantics of machine instruction sets. Specifications include NJMC toolkit's SLED descriptions [RF97] and the UQBT's SSL descriptions [CS98].

While SLED describes the instruction syntax, SSL describes the instruction semantics. SSL specifications allow users to specify the mapping between assembly instructions and their equivalent register transfers, to name new registers and declare overlaps, to define superoperators in the form of macros for commonly set condition codes, and to specify the fetch-execute cycle for the machine.

The combined SLED and SSL specifications provide complete information to generate a user-level interpreter. The user-level restriction is imposed by the SSL descriptions, which describe semantics for user-level instructions only, as per the goals of the UQBT project [CERL01]. User-level code does not include kernel or system-level code.

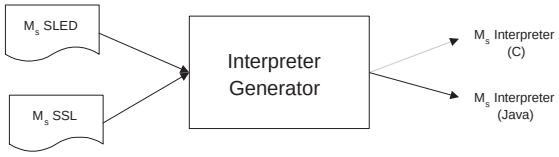

Fig. 2. The Interpreter Generator Genemu

The conceptual view of the interpreter generator is illustrated in Figure 2. The interpreter generator takes as input a SLED and an SSL description for a given machine and generates source code for an interpreter for that machine in either the C or Java(TM) language. The generated code can then be compiled, resulting in an interpreter.

The interpreter generator creates interpreters using either the C or Java language because we were interested in comparing the performance of interpreters implemented in these languages on a relatively fair basis. However, the Java-based interpreters are not as object-oriented as we would like due to implementation issues, which we discuss in the following section.

A. Implementation

The `genemu` tool is the implementation of the interpreter generator in the Walkabout framework. The process used by `genemu` to generate the C or Java language interpreters is illustrated in Figure 3. SLED and SSL files for a machine are parsed by `genemu` and checked for consistency. A matching file (i.e., a `.m` file) is generated, consisting of the core decoder for machine instructions, as well as the associated C language code to implement the semantics of each instruction in predefined interpreter data structures that capture the state of the machine being interpreted. The NJMC toolkit transforms the matching file into C language code. An optional postprocessing phase transforms the C source file into a Java language source file, primarily by making transformations on the syntax.

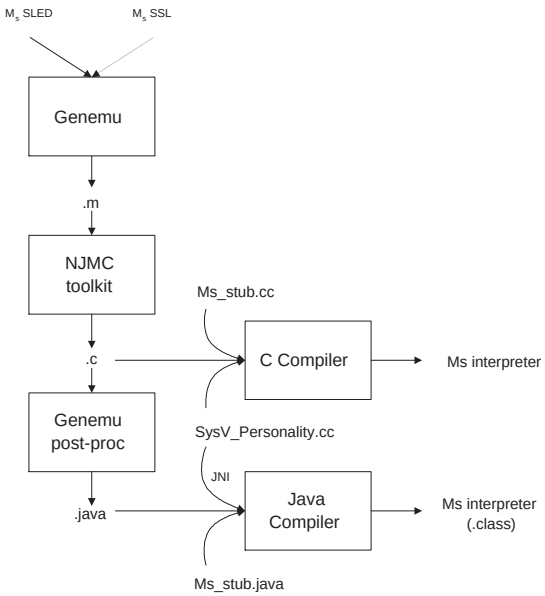

Fig. 3. The `genemu` Interpreter Generation Process

The generated C or Java language decoders are then compiled with three pieces of information: file loading and system calls for the operating system of interest (`SysV_Personality`), and machine stubs (`Ms stub`). `genemu`'s implementation of OS support is for ELF binaries for two SystemV operating systems: Solaris and Linux. System call support for both these OSs is part of `genemu`. Machine stubs are written to initialize the state of the machine being interpreted, that is, the interpreter's internal data structures, at program startup time.

B. Performance Results

Using `genemu` and the SPARC and x86 architecture's SLED and SSL descriptions, we generated interpreters for the SPARC and x86 architectures running the Solaris and Linux operating environments respectively. In this section, we report on our experimental results with interpreters for the SPARC architecture.

Table I shows results for the running of the C-language interpreter for the SPARC architecture on a lightly loaded 450 MHz UltraSPARC(R) machine with 4GB of memory. Results are for runs of SPECInt 95 programs, which were compiled for a SPARC V8 machine. For each program, the size of the program in bytes is listed, as well as the interpretation time and the native time in seconds needed to run the programs. The native time reported is the average of three runs and the interpretation time is the result of one run. The slowdown of the interpreter compared to native code is also shown: this is, on average, approximately 200x.

The Java language interpreters are considerably slower than their C counterparts. This is partly due to the difficulty of dynamically compiling a program that implements an interpreter. Much of the execution time is spent in a dispatching loop that

Program	Size	Interpreted	Native	Slow-down
go	364,412	57,388	412	139
m88ksim	198,264	47,068	180	261
li	83,168	32,210	181	178
ijpeg	175,268	38,294	187	205
perl	298,296	22,972	137	168
vortex	665,088	40,180	203	198
sieve(3K)	24,452	3,287	15	219
fibo(35)	24,668	184	1.3	141
Mean	229,202	30,198	375.74	189

TABLE I
PERFORMANCE RESULTS FOR AN AUTOMATICALLY-GENERATED C LANGUAGE INTERPRETER FOR THE SPARC ARCHITECTURE

switches on each instruction, and no significant amount of time is spent in any one path of the `switch` statement. In practice, we observed a 5x slowdown of the Java language version of the interpreter for the SPARC architecture on small benchmarks when compared against the unoptimized C version of the same interpreter, and a 15.5x slowdown when compared against an optimized (O4) version of the C interpreter. The results point at a 1000x-3000x slowdown for programs executed by the Java-based interpreter when compared against native code. These results were obtained using the Java SDK 1.3 on a SPARC machine.

VI. INTERPRETER INSTRUMENTATION

Some optimizing virtual machines rely on an instrumented interpreter that determines hot paths in the program being interpreted. Native code is then generated for such hot paths.

In the Walkabout framework, we were interested in experimenting with different ways to determine hot paths within an interpreter. This is more challenging in a dynamic translator because binary programs do not include such high-level information as procedure boundaries or loop information. In addition, binary programs are typically less structured and regular than the byte code programs executed by virtual machines, so it can be harder to find natural instrumentation points.

We designed a simple language called INSTR, for instrumentation language, to allow us to instrument the interpreters automatically generated by the `genemu` tool. INSTR allows us to easily create different instrumented interpreters that make use of different instrumentation rules. Figure 4 illustrates how INSTR is used.

The instrumented interpreter generator, `genemu'`, parses SLED and SSL machine descriptions, as well as the INSTR instrumentation description, and generates a C interpreter for that machine that can instrument selected instructions in the way specified in the INSTR specification file.

The INSTR language allows the Walkabout framework to be used to construct other kinds of instrumentation tools that insert

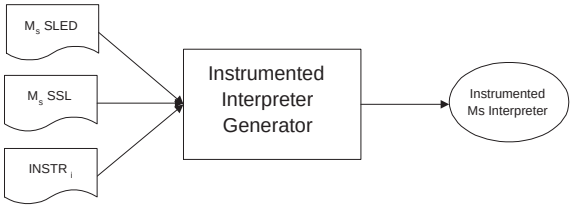

Fig. 4. The Instrumented Interpreter Generator

code during interpretation in order to understand the behaviour of running programs. These tools can do basic block counting and profiling. They can also record dynamic memory accesses, branches taken or not, and instruction traces. The data they collect can be used to drive related tools such as pipeline and memory system simulators. The following sections describe the language and gives examples of its usage.

A. The INSTR Language

The INSTR language was designed to work in conjunction with an interpreter, therefore, it relied on simple abstractions available in interpreters. An interpreter interprets code one instruction at a time. It also knows about the fetch-execute cycle of the machine being interpreted. Consequently, INSTR's abstractions are centered around individual instructions and the fact that the interpreter has a fetch-execute cycle to decode instructions for the given machine. Further, the interpreters of interest were those automatically generated by the Walkabout framework using the `genemu` tool; therefore, the language required a way to relate to the instruction names that are used in the SLED and SSL specifications from which the interpreters are generated.

Other instrumentation languages used in tools like ATOM [ES95] and Vulcan [SEV01] make available high-level abstractions of the program to developers; the aims of these languages are different than one that needs to be integrated with an automatically generated interpreter, and therefore could not be reused for our purposes.

INSTR allows developers to instrument an instruction at three different points in time:

- before the instruction is fetched,
- before the instruction's semantics are executed, or
- after the instruction's semantics are executed.

Instrumenting in the fetch-execute cycle allows for instrumentation of repetitive actions on all instructions that get fetched, for example, to observe and record each instruction's opcode or to count the number of instructions executed. Instrumenting before or after an instruction's semantics means that such actions are only executed on that particular instruction instead of on each instruction being fetched.

An instrumentation file consists of three main sections:

1) Definition,
2) Fetch-execute cycle, and
3) Support code.

The definition section specifies which instructions are to be instrumented and their corresponding instrumentation code. The fetch-execute cycle section specifies what, if any, commands need to be executed at each iteration of the cycle. The support code section contains support functions used in the instrumentation code; this code is expressed in the C/C++ language. Figure 5 provides the EBNF for the language.

In the INSTR language, both `%action` and `%c_code` denote valid C/C++ language code; the difference between them is that `%action` can make use of predefined keywords to refer to fields of an instruction. The keywords and their meaning are:

1) `"SSL_INST_SEMANTICS"`: this keyword denotes the standard semantics of an instruction, as described in the SSL specification file.
2) `"PARAM(" %STRING ")"`: the `"PARAM"` keyword stands for parameter and it is the way to refer to the *value* of a named parameter (i.e., operand) of an instruction. For example, when instrumenting the `BA label` instruction, `PARAM(label)` refers to the value of the branch's label.
3) `"SSL(%" %STRING ")"`: the `"SSL"` keyword denotes one of the SSL-named register locations. For example, `SSL(%pc)` is the location holding the value of the emulated PC register.

B. Examples

The INSTR language allows the Walkabout framework to be used to construct instrumentation tools that insert code during interpretation in order to understand the behaviour of running programs. These tools can do basic block counting and profiling. They can also record dynamic memory accesses, branches taken or not, and instruction traces. The data they collect can be used to drive related tools such as pipeline and memory system simulators.

1) Basic Block Counting: If we want to count the number of basic blocks executed in a program, we need to increment a counter each time an instruction that causes an end-of-basic block condition is reached.

Using INSTR, we can group all the SPARC architecture branching instructions in a table called `branch` and then give semantics to that group of instructions as the instrumentation for such instructions. In the example code, all branching instructions of the kind `branch` will now increment a counter called `BB_count` in the instrumented interpreter and will also maintain their original semantics (as specified in the SSL representation of those instructions).

```
DEFINITION

branch [ "BA", "BN", "BNE", "BE", "BG",
         "BLE", "BGE", "BL", "BGU", "BLEU",
         "BCC", "BCS", "BPOS", "BNEG",
         "BVC", "BVS", "BNEA", "BEA",
         "BGA", "BLEA", "BGEA", "BLA",
         "BGUA", "BLEUA", "BCCA", "BCSA",
         "BPOSA", "BNEGA", "BVCA", "BVSA",
         "RET", "RETL", "CALL", "JMPL" ]

branch label {
   BB_count++;
   SSL_INST_SEMANTICS
}
```

2) Load Monitor: A load monitor could be specified in the following way. All load instructions of interest are grouped in a `load` table. All load instructions take two operands, the effective address of the load (`eaddr`) and the register where the value is to be loaded to (`reg`). Whenever a load instruction is decoded, if the `monitor_mode` flag is set, the C function `monitor_eaddr` will be called before the semantics of the load instruction is executed by the interpreter. The `monitor_eaddr` function monitors the runtime value of the effective address of the load instruction (referred to as `PARAM(eaddr)`) and records the memory reference of the load instruction (`SSL(%pc)`; i.e., the PC value). The `monitor_eaddr` function would be defined in the support section of the specification file.

```
DEFINITION

load [ "LD", "LDA", "LDD", "LDUH", "LDUHA",
       "LDUB", "LDUBA", "LDSH", "LDSHA",
       "LDSB", "LDSBA", "LDF", "LDDF",
       "LDSTUB" ]

load eaddr, reg {
  if (monitor_mode) {
    monitor_eaddr (SSL(%pc), PARAM(eaddr));
  }
  SSL_INST_SEMANTICS
}
```

3) Edge Counting: In order to instrument all branches of an x86 architecture, we can define a table `jump32s` with the names of all such branches. If we want to count the number of occurrences of edges taken in the program, we can extend the behaviour of the branches by incrementing a counter before the instruction's semantics is executed by the interpreter, as follows

```
DEFINITION

jump32s [ "JVA", "JVNBE", "JVAE", "JVNB",
          "JVB", "JVNAE", "JVBE", "JVNA",
          "JVC", "JVCXZ", "JVE", "JVZ",
          "JVG", "JVNLE", "JVGE", "JVNL",
          "JVL", "JVNGE", "JVLE", "JVNG",
          "JVNC", "JVNE", "JVNZ", "JVNO",
          "JVNP", "JVPO", "JVNS", "JVO",
          "JVP", "JVPE", "JVS", "JMPJVOD" ]

jump32s label
{
  increment_counter(SSL(%pc), PARAM(label));
  SSL_INST_SEMANTICS
}
```

where the function `increment_counter` is defined in the support code section of the specification file. In the above example, all branches take one operand, the target address of the

```
specification:          parts+
parts:                  definition | support_code
definition:             "DEFINITION" instrm+
instrm:                 table | semantics
table:                  %STRING "[" SLED_names "]"
semantics:              (%STRING parameter_list instrument_code)+
                        ["FETCHEXECUTE" instrument_code]

parameter_list:         %STRING ("," %STRING)*
instrument_code:        "{" (%action)* "}"
support_code:           "IMPLEMENTATION_ROUTINES" %c_code
```

Fig. 5. EBNF for the INSTR Language

branch instruction, referred to as `label` in the example.

For illustration purposes, we show the support code section for this specification, in which the function `increment_counter` is implemented.

```
IMPLEMENTATION_ROUTINES

#include <map>
#include <iostream>

map<pair<unsigned,unsigned>,int> edge_cnt;

void increment_counter(int addr1,int addr2){
  pair<unsigned,unsigned> edge =
      pair<unsigned,unsigned>(addr1, addr2);
  map<pair<unsigned,unsigned>,int>::iterator i;
  if ((i=edge_cnt.find(edge))==edge_cnt.end())
    edge_cnt[edge] = 1;
  else
    i->second++;
}
```

The `increment_counter` routine makes use of the `edge_cnt` map of edges to execution counts, in order to record occurrences of branch taken edges during execution time. When a count on a taken edge is to be incremented, the routine gets an iterator to traverse the map of pairs (i.e., the edges) and increment the counter for that edge.

At runtime, the instrumented emulator will increase the count on each edge taken during the execution of the input program. A support print routine can then display the number of occurrences of each edge.

VII. The PathFinder

The PathFinder is a simple virtual machine that can be used to experiment with dynamic code optimization. The PathFinder is the core of the 2001 implementation of the Walkabout framework. Figure 6 illustrates the PathFinder's architecture.

The PathFinder is a dynamic binary rewriting tool for SPARC V8 machine code that generates SPARC V9 code for hot paths, performs simple optimizations during code generation, and places the generated code in a fragment cache. SPARC V9 is the most recent SPARC architecture, it has a number of changes designed to improve the performance of programs as well as

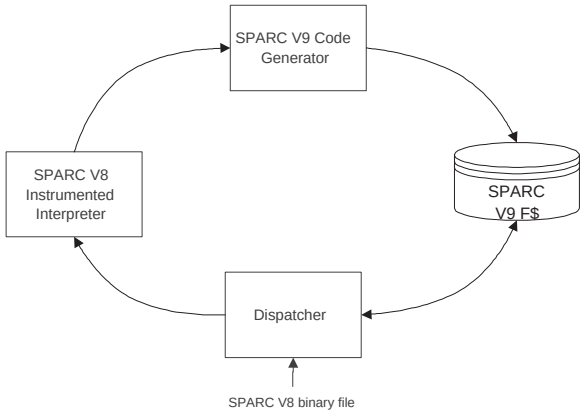

Fig. 6. PathFinder: The Implementation of the 2001 Walkabout Framework

supporting 64-bit address spaces. The 64-bit operations simplify many integer code sequences involving, e.g., shifts and multiplies. The prefetching instructions can help some programs too. As other long-lived ISAs, there are a lot of programs compiled for older versions of the ISA that could benefit from recompilation or reoptimization, hence our choice of source and host platforms.

In the PathFinder, the instrumented SPARC V8 interpreter is automatically generated by the `genemu'` tool based on the SLED and SSL specifications for the SPARC instruction set, and several different INSTR specification files. In its present form, the PathFinder tool for the SPARC architecture resembles the dynamic optimizing systems Dynamo [BDB00], Wiggins/Redstone [DGR99] and Mojo [CLCG00], which were written for the PA-RISC, Alpha and x86 platforms, respectively. Part of the objective for the PathFinder was to be able to contrast techniques used in other systems in the context of a retargetable framework. However, the PathFinder does not currently implement a reoptimizer, and so cannot be fully compared experimentally with those systems. Conceptually, all these translators work in similar ways: i.e., they generate target code for hot pieces of source machine code based on some criteria for determining what paths are frequently executed, and perform varying levels of optimization.

The PathFinder's code generator implements code layout optimizations as well as several simple optimizations, which we explain in turn. No intermediate representation is used by the PathFinder; the code generator transforms SPARC V8 assembly instructions directly onto V9 instructions.

The PathFinder's memory system is simple. We reserve a fixed-sized fragment cache: once that cache is full, it is flushed; no attempt is made to decide what fragments to keep.

A. Optimizations

The PathFinder implements several machine-independent optimizations such as code layout, branch inversion, branch linking and inline caching. These optimizations can be performed regardless of the source machine in use, however, knowledge of which instructions are branches is needed (these can be simply grouped in SLED under a new name for each access to them).

1) Code Layout: Code layout is a simple optimization that is achieved by placing frequently executed basic blocks contiguously in memory, to achieve better code locality as well as to reduce the number of branches needed.

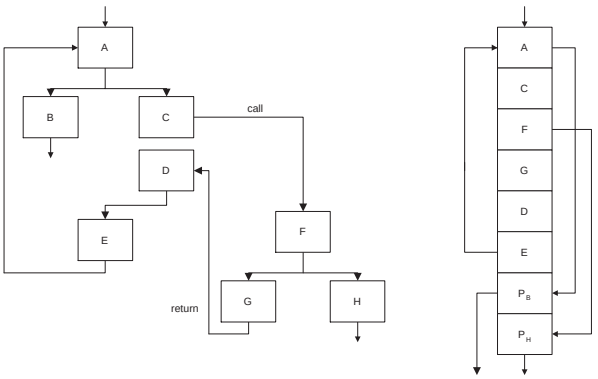

Fig. 7. Code Layout Example

Figure 7 shows an example of code layout. To the left of the diagram is a control flow graph for a program. The program executes a loop quite a large number of times by following the path ACFGDEA. Note that the loop includes the call to a routine and its return from that routine. The right side of the diagram illustrates how the code is placed in the fragment cache, therefore improving code locality. In the diagram, ACFGDE are placed sequentially in memory. Nodes P_B and P_H are the *exit portals* of this fragment. An exit portal is an exit basic block for a fragment of code. It contains code that allows the program to go back to the interpreter or to another fragment of code.

2) Branch Inversion: During code layout, it is necessary to invert certain branch instructions to keep basic blocks contiguous in memory. Branch targets that are not part of the trace jump to exit portals in that fragment.

Inverting some delayed control transfer instructions in the SPARC and other architectures is not as straightforward as replacing the branch by its inverse branch, as these instructions may not be antonyms based on the delay slot semantics. In the following code, the annulling branch instruction `bne,a` at address `0xfe08d10` must be inverted as the most common behaviour in that program is to branch on not equals. This annulling branch executes the delay slot instruction only if the branch is taken, otherwise it annuls it.

```
Trace:
0xfe08d0c:      cmp  %o0, 0
0xfe08d10:      bne,a   0xfe08d2c
0xfe08d14:      ld  [ %i3 + 0xc ], %i3
...
```

Inverting the branch requires a non-annulling branch on equal, i.e., `be`, and a `nop` in the delay slot of that branch, so that the fall through case executes the code that was previously located at addresses `0xfe08d14` and `0xfe08d2c`; now located starting at `<code_cache+628>`. The resulting code fragment looks as follows

```
...
<code_cache+616>:    cmp  %o0, 0
<code_cache+620>:    be  <code_cache+696>
<code_cache+624>:    nop
<code_cache+628>:    ld  [ %i3 + 0xc ], %i3
...
```

3) Branch Linking: Branch linking relates to the removal of unconditional branches when the target of the branch is moved to be located immediately following the branch instruction in the fragment cache. These branches typically include the branch always (`ba`) and branch never (`bn`) instructions, as well as their annulled counterparts. The following code serves as example, where the branch to address `0x50034` is removed in the fragment cache, and the code at source address `0x74ae0` is placed after the delay slot instruction.

```
0x4fe68:        ba  0x50034
0x4fe6c:        add  %i5, 4, %i5
...
0x50034:        ba  0x74ae0
0x50038:        add  %l0, 4, %l0
0x5003c:        ba  0x7e510
0x50040:        ld  [ %l0 + %i0 ], %g2
```

The SPARC call instruction is a special case of an unconditional branch, one that affects the state of register `%o7` when the program counter is written to that register (in order to preserve the return address). In this case, the semantics of the assignment to `%o7` is preserved, while the instruction is modified, as per the following example, which includes one call instruction.

```
0x49f98:        ld  [ %i0 + 0x11c ], %o1
0x49f9c:        call  0x60f24
0x49fa0:        mov  %l4, %o0
...
```

The fragment generated for the above trace computes the return address of the source program (`0x49f9c`), and stores it

in register %o7, as per standard call semantics, leading to the following code

```
<code_cache+3432>:     ld  [ %i0 + 0x11c ], %o1
<code_cache+3436>:     sethi  %hi(0x49c00), %o7
<code_cache+3440>:     add  %o7, 0x39c, %o7
<code_cache+3444>:     mov  %l4, %o0
...
```

Figure 9 shows a sample SPARC assembly code for a program on the left-hand side and its corresponding code fragment. The left-hand side shows in bold face the instructions that belong to a trace in this program. The branch at 0xfe1c970 transfers control to 0xfe1c9cc, the branch at 0xfe1c9e8 transfers control to 0xfe1cad4, and the branch at 0xfe1cad8 jumps back to the start of the trace at 0xfe1c960. In the example, code layout, branch inversion and branch linking has been applied to the code. The right-hand side shows in bold face the branch at 0x200b3ca0, which has been inverted, and the last branch at 0x200b3ccc which jumps to the start of the fragment. The pieces of code at 0x200b3cd4, 0x200b3d00, etc, are all exit portals.

4) Inline Caching: Inline caching is a technique originally developed for Smalltalk virtual machines to cache "in line" a lookup result for a message send call, hence removing the overhead of the system's lookup routine [DS84]. The inlined routine adds, in its prologue, guard code to determine that the receiver type is the expected one.

Inline caching is used in the PathFinder to predict the target address of indirect transfers of control. The technique is simple: given a trace of the targets for such transfers of control at a given point in a program, the most frequent target becomes the predicted one.

For example, an indirect jump on the contents of register %g1 at offset 0xf4

```
jmp %g1 + 0xf4
```

can be transformed into an unconditional branch to the predicted location (labelled predicted in the below code). Lets say that the target address for this jump is predicted to be that stored in predicted_val, then, the code at the predicted location ensures that jumps reaching this code are the right ones, i.e., it compares the predicted value against the expected value. This code transformation avoids the indirect transfer of control for the most common destination address of the branch

```
predicted: add %g1, 0xf4, scratch1
           set predicted_val scratch2
           cmp scratch1, scratch2
           bne exit_scratch1
           ...
```

In a similar way, indirect calls and returns with no corresponding call instructions in the fragment, are treated as indirect jumps. In the SPARC architecture, return instructions are indirect transfers of control on the contents of register %i7, which holds the address of the instruction that invoked the procedure. The following code shows a trace that has a return instruction but no corresponding call instruction in the trace itself. Once the return is executed, execution continues at address 0x4fb50.

```
0x4fc40:        sll  %i0, 2, %g2
0x4fc44:        mov  1, %o3
0x4fc48:        ld  [ %g2 + %o5 ], %g2
0x4fc4c:        ld  [ %o1 + %o5 ], %g3
0x4fc50:        cmp  %g3, %g2
0x4fc54:        be  0x4fc64
0x4fc58:        cmp  %o3, 0
0x4fc5c:        ret      ! jmpl %i7+8, %g0
0x4fc60:        restore  %g0, 0, %o0

0x4fb50:        cmp  %o0, 0
0x4fb54:        bne,a   0x4fb78
0x4fb58:        clr  %o0
...
```

The following code fragment shows how the one return instruction at address 0x4fc5c in the trace, is replaced by 5 instructions in the fragment cache, starting at address <code_cache+3932>. This is because a guard has been placed to check that the correct jump targets reach the address <code_cache+3956>, as this address is now contiguous to the rest of the trace code.

```
<code_cache+3904>: sll  %i0, 2, %g2
<code_cache+3908>: mov  1, %o3
<code_cache+3912>: ld   [ %g2 + %o5 ], %g2
<code_cache+3916>: ld   [ %o1 + %o5 ], %g3
<code_cache+3920>: cmp  %g3, %g2
<code_cache+3924>: be   <code_cache+4192>
<code_cache+3928>: cmp  %o3, 0
<code_cache+3932>: add  %i7, 8, %g5
<code_cache+3936>: sethi  %hi(0x4f800), %g6
<code_cache+3940>: add  %g6, 0x350, %g6
<code_cache+3944>: sub  %g5, %g6, %g6
<code_cache+3948>: brnz,pn %g6, <code_cache+4140>
<code_cache+3952>: restore  %g0, 0, %o0

<code_cache+3956>: cmp  %o0, 0
<code_cache+3960>: bne,a  <code_cache+4088>
<code_cache+3964>: clr  %o0
...
```

5) Fragment Linking: Fragment linking is the process of joining one fragment to another, so as to avoid going through the dispatcher; i.e., it reduces context switching. Fragment linking can be done during code generation of a fragment or as a reoptimization which patches an existing portal to a new fragment.

During code generation, when generating a fragment where one of its exits leads to an address that is the start of another fragment, instead of creating an exit portal, a direct jump to the second fragment can be generated instead.

When performing reoptimization of code, fragment code that shows a frequently-executed behaviour can generate new hot traces (note that these are traces of code in the fragment cache). In these traces, exit portals can be patched so that the flow of control does not need to go through the dispatcher any longer.

```
...
0xfe1c960:  sll  %i2, 4, %i2
0xfe1c964:  bl  0xfe1ca20
0xfe1c968:  srl  %i5, 1, %i5
0xfe1c96c:  subcc  %i3, %i5, %i3
0xfe1c970:  bl  0xfe1c9cc
0xfe1c974:  srl  %i5, 1, %i5
0xfe1c978:  subcc  %i3, %i5, %i3
0xfe1c97c:  bl  0xfe1c9a8
0xfe1c980:  srl  %i5, 1, %i5
...
0xfe1c9cc:  addcc  %i3, %i5, %i3
0xfe1c9d0:  bl  0xfe1c9fc
0xfe1c9d4:  srl  %i5, 1, %i5
0xfe1c9d8:  subcc  %i3, %i5, %i3
0xfe1c9dc:  bl  0xfe1c9f0
0xfe1c9e0:  srl  %i5, 1, %i5
0xfe1c9e4:  subcc  %i3, %i5, %i3
0xfe1c9e8:  ba  0xfe1cad4
0xfe1c9ec:  add  %i2, 7, %i2
0xfe1c9f0:  addcc  %i3, %i5, %i3
0xfe1c9f4:  ba  0xfe1cad4
0xfe1c9f8:  add  %i2, 5, %i2
...
0xfe1cad4:  deccc  %i4
0xfe1cad8:  bge  0xfe1c96a
0xfe1cadc:  tst  %i3
0xfe1cae0:  bl,a   0xfe1cae8
0xfe1cae4:  add  %i3, %i1, %i3
0xfe1cae8:  tst  %l1
...
```

```
0x200b3c90:  sll   %i2, 4, %i2
0x200b3c94:  bl     0x200b3d84
0x200b3c98:  srl   %i5, 1, %i5
0x200b3c9c:  subcc %i3, %i5, %i3
0x200b3ca0:  bge   0x200b3d58
0x200b3ca4:  srl   %i5, 1, %i5
0x200b3ca8:  addcc %i3, %i5, %i3
0x200b3cac:  bl     0x200b3d2c
0x200b3cb0:  srl   %i5, 1, %i5
0x200b3cb4:  subcc %i3, %i5, %i3
0x200b3cb8:  bl     0x200b3d00
0x200b3cbc:  srl   %i5, 1, %i5
0x200b3cc0:  subcc %i3, %i5, %i3
0x200b3cc4:  add   %i2, 7, %i2
0x200b3cc8:  deccc %i4
0x200b3ccc:  bge   0x200b3c90
0x200b3cd0:  tst   %i3
0x200b3cd4:  !exit to 0xfe1cae0
...
0x200b3d00:  !exit to 0xfe1c9f0
...
0x200b3d2c:  !exit to 0xfe1c9fc
...
0x200b3d58:  !exit to 0xfe1c978
...
0x200b3d84:  !exit to 0xfe1ca20
...
```

Fig. 8. Code Layout Example: Sample Trace (in bold face) and Generated Code for the Trace

B. Experimental Results

We present experimental results for the PathFinder tool for the SPARC architecture using an INSTR specification for Dynamo's Next Executing Tail (NET) method for selecting instruction traces [DB00].

The NET method maintains counts only for executed targets of backward taken branches. Once the counter of any such target exceeds a threshold, the next executing path is predicted by collecting that information on the next iteration of the loop in a trace buffer, where its first element is named the trace-head. The end-of-trace conditions used by NET are:

1) the target of the backwards branch is to the trace-head,
2) the current instruction is a backward taken branch (i.e., a new start-of-trace), or
3) the history buffer has reached a size limit.

The PathFinder was tested against SPEC95 benchmarks. At present, no reoptimization of code is performed by the PathFinder; these results can be improved upon. We report on experimental results using a 1 MB cache size and the following optimizations: code layout, branch inversion, branch linking and fragment linking. Table II shows the results. For each program, its static size in bytes is given, as well as its user execution time running on first the SPARC emulator (no dynamic optimization), then the PathFinder virtual machine. For comparison, the execution time running on the native SPARC machine is also given. Results were obtained on a lightly loaded UltraSPARC II machine at 450 MHz per CPU and 4 GB of main memory.

Program	Static Size	Interpreter Time	PathFinder Time	Native Time
compress	85,572	n/a	74	76
go	364,412	57,388	3,717	412
m88ksim	198,264	47,068	709	180
li	83,168	32,210	1,821	181
ijpeg	175,268	38,294	1,816	187
perl	298,296	22,972	338	137
vortex	665,088	40,180	35,905	203
sieve(3K)	24,452	3,287	8.3	14.6

TABLE II

EXPERIMENTAL RESULTS USING THE INTERPRETER AND THE PATHFINDER, WITHOUT PERFORMING OPTIMIZATION OF THE CODE

In the results of Table II we include interpretation, PathFinder and native times for comparison purposes. Each of these times were obtained independently, by running the binary

using the relevant tool or standalone. Virtual machines (VMs) provide a variety of performance results based on the use of the VM. For example, in resource-constraint environments, an interpreter-based VM is acceptable; execution time is traded for resource availability. In server-based environments, a VM that approximates the times obtained by native compilers is desirable, as resources are available. The results reported in Table II place the current execution results of the PathFinder in between those results of an interpreter and those of natively-compiled code. Once a reoptimizer stage is built into the PathFinder, results should better approximate those of native code, within limits, as discussed below.

The results show that programs which have a tight loop that performs the buik of the program's work are good candidates to benefit from the current implementation. This is the case of the `compress` and `sieve` programs. Other benchmarks show slowdowns when compared against native execution runs. These results are due to two reasons: the fact that our system is not yet tuned for performance; simple optimizations such as constant propagation, inline caching, and better fragment linking are missing; and the behavior of some programs.

Benchmarks `go`, `ijpeg` and `vortex` behave badly; these benchmarks are the ones in which the Dynamo system bails out as the system cannot accurately predict which paths to compile. PathFinder does not implement a bail out option. In the case of `vortex`, the execution time in PathFinder approaches that of running the same program in interpretation mode.

In essence, two classes of programs showed bad behaviour using this trace selection method: large `switch` statement-based programs and recursive programs.

Programs where the core of the execution time is spent jumping between different arms of a `switch` statement do not normally exhibit good behaviour in VMs unless particular arms of the `switch` statement can be compiled. Using the NET method, PathFinder determines hot traces by executing the next iteration of the loop after identifying a hot instruction. However, for these programs, the trace that is collected is often poor: it does not reflect the path executed most often in the future.

Recursive programs do not have a back branch that can be easily detectable as an end-of-trace condition, hence, no trace is found to be hot in a method like NET. Some existing virtual machines, such as the Self VM, inline recursive methods to optimize recursive programs. Inlining was done once the count on a method entry became hot; in fact, the Self version of highly recursive programs such as Fibonacci and Takeuchi runs much faster than the native C version of the same program [Hol94]. Note that inlining procedures in machine code programs is not as straightforward as inlining methods in VM-based languages such as Self and Java. This is because the boundaries of a procedure in a binary program are not well defined.

Table III shows the results of running a highly recursive program, Fibonacci, using two different trace selection methods in the PathFinder: NET and a variation which we call "recursive". The recursive method keeps track of the stack levels formed in the trace, and adds a new end-of-trace condition to the NET method: stop building a trace after 5 levels of stack are in the trace (i.e., 5 levels of call or returns). In this way, calls to the procedure Fibonacci are replaced by the setting up of the `%o7` register. The stack frames themselves cannot be removed as the code may exit back to the interpreter or be re-entered into from the interpreter.

Program	Static Size	Scheme	PathFinder Time	Native Time
fibo (35)	24,668	NET	189s	1.3s
fibo (35)	24,668	Recursive	20s	1.3s

TABLE III
EXPERIMENTAL RESULTS FOR PROBLEMATIC PROGRAMS USING THE PATHFINDER CONFIGURED WITH NET TRACE SELECTION METHOD

The results in Table III show that the version of the PathFinder using the NET approach behaves just as slowly as the interpreter on its own; i.e., 189s vs 184s (see Table I). The results also show a considerable improvement in execution time when using procedure inlining.

VIII. EXPERIENCE

The Walkabout framework was designed and partially implemented over a period of 9 months by 2 researchers and 3 interns. This work was done at the same time as the final experiments in the static binary translation framework UQBT [CERL02] were done. The total effort was 3.5 researcher-months and 11 intern-months.

Our experiences with the implementation and results of the Walkabout framework are positive. These results were achieved thanks to a design that supported retargetability as well as a separation of machine dependence concerns. Retargetability was achieved through the use of specifications for both machine instruction sets and instrumentation.

The implementation of the Walkabout framework was staged. First, disassemblers were generated, then machine code interpreters (emulators), followed by instrumented emulators that determine hot paths in a program, followed by the creation of a binary-code rewriting tool called PathFinder. Many of the components of these tools were generated automatically. A Java language debugger was also written, it was basically a Swing interface to the disassembler, the machine code interpreter (emulator), and the PathFinder tool for a given machine.

The machine code emulator generator was a big win. We were able to reuse existing syntactic and semantic descriptions for the SPARC and x86 instruction sets and generate, automatically, emulators for these machines. These emulators were able to run existing programs including the SPEC95 benchmark suite. The emulator generator was able to generate two different versions of each emulator: one in the C language and another in the Java language. This allowed us to compare how well those

languages worked for this purpose. The use of the emulator generator allowed us to quickly experiment with multiple machines and to generate correct emulators, as extensive testing in the past had ensured that the specifications were correct.

The development of a new specification language for instrumenting machine code emulators, INSTR, was also a big win. The emulator generator was constructed in such a way that it allowed easy integration of instrumentation support code at different points in a program. The instrumentation language itself was simple and made it easy to specify new profiling schemes. It could also be used for other kinds of instrumentation: e.g., traditional EEL-like instrumentation of binaries. It was not restricted to use in a dynamic interpreter/reoptimizer.

Once we could specify and generate instrumented machine code emulators, the next step was to decide how to determine a program's hot paths. It proved straightforward to specify this criteria. Code generation for these hot paths on the SPARC architecture was done by reusing the syntactic instruction specifications for the SPARC architecture. The hot path analysis code was only concerned with deciding what types of transformations to apply to the source machine code, which simplified development time.

The current implementation of the Walkabout framework is incomplete. The PathFinder tool does not reoptimize code, which is needed to improve the performance of running applications. And the translator to M_t instructions is missing.

Since PathFinder does no optimizations at this time and, being mostly automatically generated, is not tuned, we did not expect it would consistently improve the performance of programs. This is confirmed by the performance results we obtained. The runtime of most programs is somewhere between native code and interpreted code. Some programs require close to native time, others run 10 or more times slower than native code, and others run close to interpretation time (200x slower in the Walkabout generated interpreters). Optimizations and fine tuning the code generated by PathFinder would improve these results.

We implemented a graphical debugger for Walkabout in the Java language that relied upon several components which were automatically generated from the Walkabout framework. This includes the Java version of the disassembler, the C version of the interpreter, and the C version of the PathFinder's hot trace generator. This debugger proved to be a help in debugging the system.

IX. Conclusions

This report describes the design of the Walkabout framework, a dynamic binary translation framework designed to simplify experiments with binary manipulation ideas and based on the use of specifications to simplify retargetability.

The 2001 implementation of the Walkabout framework provides mechanisms to automatically generate machine code interpreters (emulators) and disassemblers in both the C and Java languages. It also supports the automatic creation of instrumented interpreters in the C language by the use of a new specification language called INSTR. Finally, Walkabout includes a general-purpose binary rewriting tool called PathFinder that can be used to implement, for example, binary code reoptimizers. The Walkabout framework can generate tools for the SPARC and x86 platforms.

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The Walkabout distribution is available online under an open source license. Please refer to the Walkabout home site for more information about this project and for links to the distribution:
`http://research.sun.com/walkabout`

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