Go with the flow: Data Flow Analysis for Binary Differencing

by

Benjamin Denton

A dissertations submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 2, 2014

Keywords: Binary Differencing, Reverse Engineering, Data flow Analysis, Static Analysis, Disassembly

Abstract

Differencing in computer science is often used to quickly determine differences between two files. While this works well for plain text files, such as source code, applying differencing to binary executable files is more difficult. Compiled binary files contain lists of instructions that when executed, perform operations using functions and data specified by a higher level programming language, such as C++. Syntactic changes to these instructions, changes in the form of an instruction, do not always reflect semantic changes, changes in the behavior of an instruction. Depending on the settings and optimizations of the compiler, a series of instructions from a binary executable could perform the same function as a different series of instructions from a different binary. These types of differences are difficult to detect using current binary differencing methods.

This dissertation explores software reverse engineering, binary differencing, and software semantics vs. syntax. We define a framework, we call Data Flow Binary Differencing, for performing binary differencing using data flow analysis and comparing the semantics of the data flow within a pair of functions. We discuss three use cases that illustrate how to implement the Data Flow Binary Differencing framework and show how our technique stands up against challenges faced by other binary differencing techniques.

Our major contribution of this research is using data flow and assembly language semantics to define a method to compare a pair of functions and test for similarities. We also discover that testing for semantic differences versus syntactic differences within a binary can expose semantic differences introduced by an optimizing compiler.

Acknowledgments

"For the Lord gives wisdom; from his mouth come knowledge and understanding."

Proversb 2:6

It cannot be understated how grateful I am to my adviser, Dr. David Umphress, for his patience, support, and encouragement, without which I would not have finished this dissertation. I also would like to thank my committee members, Dr. Overbey, Dr. Cross, and Dr. Hamilton for their time and support of this research. Auburn is an excellent university because of professors like you.

At times this road became lonely and frustrating, I would like to thanks my labmates for providing encouragement, entertainment, and sometimes just an attentive ear to whatever problem I was facing, even though you probably didn't care. Thank you Devin, Patrick, Chris, Sarah, and Jim for all the laughs and for letting me hang out in your lab. Special thanks to C.W Perr for pushing me through the final months and weeks of this dissertation.

If anyone ever asks me why I did this, I'll answer to make my Mom and Dad proud. Thank you, Mom and Dad, for all your encouragement and prayer, even when you didn't understand what I was talking about. I would also like to thank my twin sister, Jeni. You inspire me so much!

The real person that earned this dissertation is my wife, Selena. I just wrote the paper. She has been there through the tears, tantrums, and thwarted attempts to give up. You define me hun! Thanks you for believing in me and always having my back. I love you more everyday!

My most important recognition belong to my Heavenly Father for forgiveness, wisdom, and putting all the people I just mentioned in my life. Thank you God for everything!

Table of Contents

List of Figures

List of Tables

List of Listings

Chapter 1
Introduction

Software engineering is the process followed by a development team to create well-structured, intuitively designed, and easily maintainable software. There are many different approaches to software engineering, but, in general, each approach includes iterating through phases dedicated to specifying requirements, designing, writing code, testing, and maintaining. The output of each of these phases is an refinement of the previous phase. Software is designed based on requirements, but the design will not necessarily reveal the requirements. The same can be said of the source code and resulting executable binary file: these products do not always reveal the thought put into the requirements and design and in some cases do not even follow the agreed upon requirements and design.

1.1 Software Reverse Engineering

Software reverse engineering takes the *reverse* approach from the software engineering process. “Reverse engineering is the process of analyzing a subject system to create representations of the system at a higher level of abstraction.”[Chikofsky and Cross 1990] Another way to describe reverse engineering is “the process of extracting the knowledge or design blueprints from anything man-made.”[Eilam 2005] The goal of software reverse engineering is to recover the higher level information that is typically lost in the refinement of the software engineering process. Working typically only with the software executable binary, the software reverse engineer wants to discover the requirements and design of a software product.

The purpose of the software reverse engineering process depends on the goal of the reverse engineering project. In the field of cybersecurity, software reverse engineering is extremely useful in malware analysis, bug hunting, and software exploitation. Software reverse engineering is also used to re-engineer legacy software where the source code has been lost or is inaccurate. Another important use of software reverse engineering is to implement interoperability between software products. In the absence of source code, software reverse engineering is often the only solution to maintenance and modification of software.

1.1.1 Binary Differencing

Detecting differences in source code, also called 'diffing', has been studied extensively [Fluri et al. 2007; Maletic and Collard 2004; Thummalapenta et al. 2009; Kagdi et al. 2007]. Many techniques and tools are available to allow a software engineer to take two versions of the same source code and quickly find the changes between the two versions, such as treating the source code as a sequence of lines and applying a sequence-comparison algorithm [Hirschberg 1977; Hunt and Szymanski 1977; Miller and Myers 1985].

Binary differencing is a much less studied area, since comparing binary files can be difficult. This research focuses on comparing binary executable files. By definition, a binary file is simply a large file of data represented in bytes. A binary executable file contains a list of simple machine instructions that move data between memory and registers, perform mathematical operations, and modify the order of execution of future instructions. These instructions are intermingled with data, so it can be difficult to compare binary executable files directly. A binary analysis tool, called a disassembler, is needed to extract the list of instructions from the other data contain in a binary file.

Once we have a list of instructions, comparing two lists of instructions can also be difficult. Small changes in source code can cause a much larger number of changes in the resulting compiled binary. Understanding where a direct source code change originally occurred can be hidden by these indirect changes. For example, [Gao et al. 2008] reports that changes to 5 lines of source code in a security patch to the *gzip* application changed all 75 non-empty functions in the resulting binary. Compiler optimizations or changes to local variables in a source file can effect how registers are allocated in the binary and cause many changes to register usage throughout the binary file. The same is true for memory and data locations in a binary: immediate values and memory addresses are calculated at compile time and changes to source code or compiler settings that shift data or memory locations can change every other memory address in the binary. Each of these changes to registers, immediate values, or addresses in an instruction is easy to detect but do not always map directly to an actual change in the source code.

Binary differencing in software is important to combating the spread of malicious software. Malware often exhibits the same behavior and functionality with small differences between versions and reverse engineering a new version of a piece of malware often requires duplication of effort. A reverse engineer has to re-discover functions and design details already found in the original version. Little effort is required to change source code and recompile. Malware authors take advantage of this problem to evade detection by signature based anti-malware software, which uses a *hash* or *signature* of the binary file's bytes to identify malicious binary files. Malware on Windows and Android platforms are created using modular frameworks that make designing new variations of a single piece of malware easy by providing commonly used functions and utilities. The malware author simply needs to fill in specific details to create unique binaries [Barat et al. 2013; Jiang and Zhou 2013]. Being able to identify these families of malware quickly allows a defender to focus on specific changes between a new variant and a known sample.

Being able to determine changes in software is also important to testing software patches. Proprietary software patch notes often do not fully describe the security problem fixed by the binary patch. Software patches also should be tested prior to deployment to mission critical systems. Using binary differencing techniques, a reverse engineer can determine the changes between the patched and unpatched software and determine if applying the software patch is necessary. Patching software in production systems can be expensive, time consuming, and can run the risk of introducing new software bugs [Cavusoglu et al. 2006]. Binary differencing can help determine the necessity of a software patch to help justify the expense and to lower the risk of a patch introducing a new bug.

In order to compare binaries, the reverse engineer needs to break the executable binary file into objects suitable for comparison and apply structure to these objects. Using this structure, the reverse engineer can determine which objects exist in both versions and which do not. This is not a simple task since the high-level language constructs and structure are not found in the compiled version of the software.

1.1.2 Program Structure

Programming has evolved from sequential statements with the occasional IF-ELSE and DO constructs to Object-Oriented Design. Program structure is what makes software manageable by humans, whereas computers execute millions of instructions without concern for where they come from or how they are related. Software developers typically break down atomic functionality of a large software product into *chunks* and implement each *chunk* using whatever is provided by the software language. Each *chunk* accomplishes a specific task and can often be developed by different developers or teams of developers. The only requirement of each *chunk* is that it accomplishes its specific task and communicates well with the other *chunks*.

The largest *chunks* that make up a software product are *steps*, which are collections of independently executable code commonly called *libraries*. *Libraries* often represent a specific feature or area of functionality of a program.

The next level of *chunks* are *functions* and *objects*. *Functions* are sections of code with a well-defined purpose that can be executed from other areas within the program and, optionally, take input from the caller or return data to the caller. *Objects* extend the idea of functions by limiting code to the data it manipulates. *Procedures* and *objects* require data which comes in many different representations such as arrays, linked lists, or trees. Finally, each of these *chunks* is arranged inside the program using conditional blocks, switch blocks, and loops that controls the flow of the program. These *chunks* make developing and understanding the software easier for the development team.

When software is compiled, much of this well thought-out structure can be destroyed by the compiler and linker. Source code files and static system libraries are linked into the same file. Small functions may be inlined, creating one larger *chunk* out of two smaller *chunks*. Inefficient code may be optimized by the compiler, such as unrolling a loop where the setup and branching statements cost more than the internal statements. Redundancies within the code may be removed by the compiler to make the resulting binary code smaller or faster. Further, [Balakrishnan and Reps 2010] has shown that the compiler cannot be completely trusted because it and its optimizer tools may subtly, yet significantly, alter the behavior of the program, a phenomenon knows as "What you see is not what you execute". Ultimately, the executable binary file loses much of the structure of the source code and becomes one large *chunk* of executable statements represented in a machine language.

This transformation from source code to machine language makes software reverse engineering difficult. The software reverse engineer needs to recreate some structure in order to aid in the understanding of the design, functionality, and requirements of the software. Mining meaning from a binary is time consuming without source code and requires the reverse engineer to have knowledge about low-level software, such as assembly language, and computer architecture concepts, such as memory management, in addition to programming knowledge.

To begin creating structure, the executable binary file is disassembled into basic blocks and functions. In general, a basic block is defined as a group of instructions which are always executed together. Functions begin at the target of `call` statements and end at a `retn` instruction. In practice, this process can be difficult and is best performed by a disassembler such as IDA Pro [Hex Rays 2014]. The full details of the disassembly process are described further in [Eagle 2011].

Using call graphs and control flow graphs, the disassembly process creates a graph of graphs of a binary that provides the reverse engineer a view that contains functions, loops, and conditional execution paths. Figure 1.1 shows the full call graph of a simple "Hello World!" program. The full call graph is quite large even though the *_main* function only makes two calls, one to a local function called *_getNext()* and the other to a library function *_printf()*, which can be seen in Figure 1.2. Figure 1.3 shows the control flow graph for the *_main* function. Each node in the call graph represents a control flow graph. These nested graphs are what is meant by graph of graphs. Source code for this program can be found in Appendix A, Listing A.1.

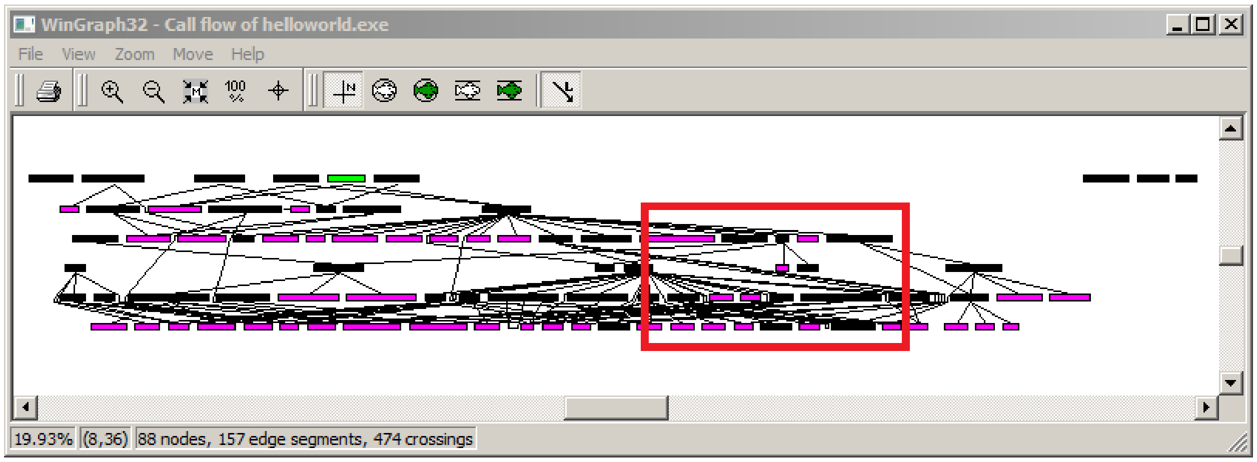

WinGraph32 - Call flow of helloworld.exe
File View Zoom Move Help
19.93% (8,36) 88 nodes, 157 edge segments, 474 crossings

Figure 1.1: Full call graph of helloworld.c

These graphs, a listing of instructions, and other data provided by the disassembly tool are usually the starting point for a reverse engineering project. This process can require much less work if the reverse engineer has already analyzed a similar binary with similar functions by using binary differencing techniques to detect the functions that have changed between the versions. The goal of binary differencing is to recognize functions and basic blocks that exist in a previous version of the binary, thus cutting down on the effort required to reverse engineer the binary. This allows the reverse engineer to focus on the functions that contain changes in the binary without having to determine which functions have not changed.

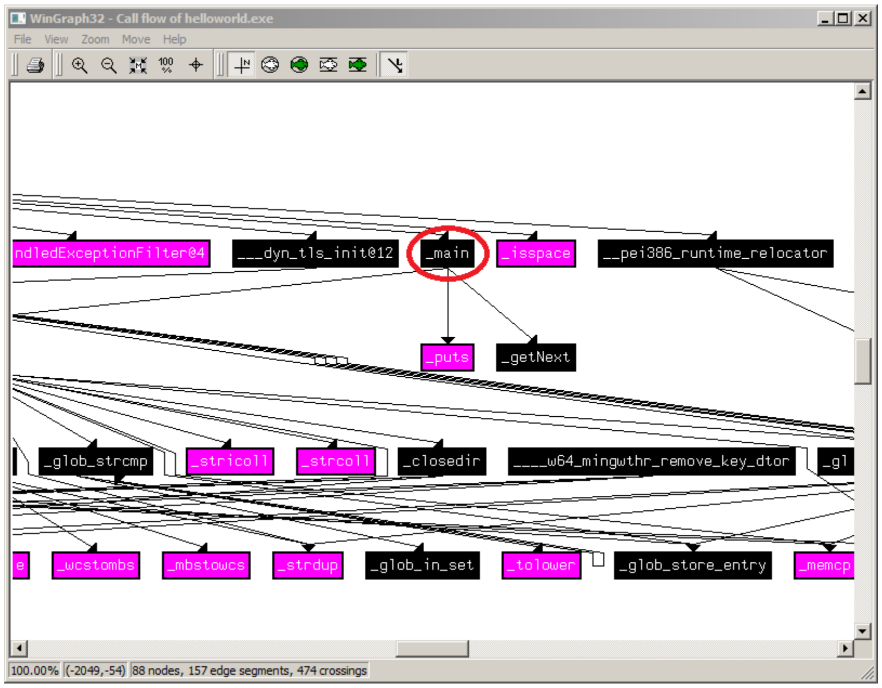
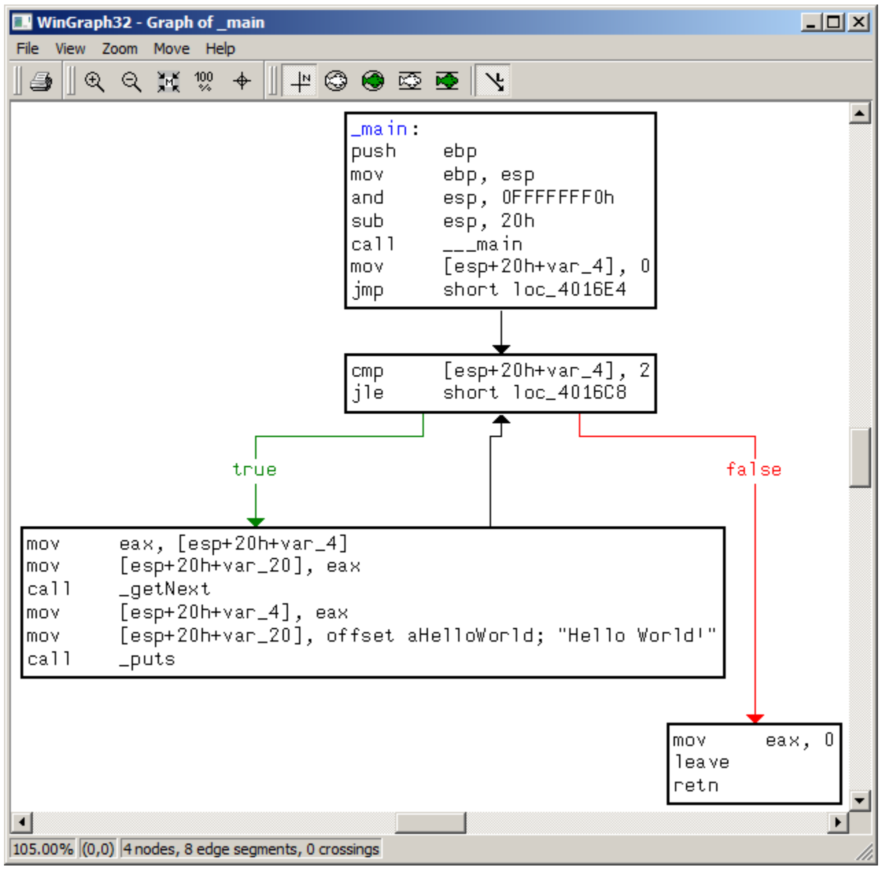


Figure 1.2: Close up of helloworld.c call graph showing _main function


WinGraph32 - Graph of _main
File View Zoom Move Help
true
false
105.00% (0,0) 4 nodes, 8 edge segments, 0 crossings

```
_main:
push    ebp
mov     ebp, esp
and     esp, 0FFFFFFF0h
sub     esp, 20h
call    ___main
mov     [esp+20h+var_4], 0
jmp     short loc_4016E4
```

```
cmp     [esp+20h+var_4], 2
jle     short loc_4016C8
```

```
mov     eax, [esp+20h+var_4]
mov     [esp+20h+var_20], eax
call    _getNext
mov     [esp+20h+var_4], eax
mov     [esp+20h+var_20], offset aHelloWorld; "Hello World!"
call    _puts
```

```
mov     eax, 0
leave
retn
```

Figure 1.3: Control flow graph for _main function of helloworld.c

1.2 Problem Statement

Existing methods to detect changes between different versions of the same binary use static and dynamic techniques. Static techniques include function name matching; matching functions and blocks based on characterizing "signatures"; and structural matching of functions and blocks. These techniques are limited in their ability to discriminate differences in functionality versus differences in form, such as syntactic changes introduced by an optimizing compiler. Such false negatives represent time wasting changes that the reverse engineer must investigate.

Dynamic techniques, on the other hand can detect semantic differences using symbolic execution [Schwartz et al. 2010], but these techniques can be computationally intensive and are typically employed when static techniques have been exhausted. [Gao et al. 2008]

Detecting semantic differences in binaries, as opposed to syntactic differences, is the goal of binary differencing since semantic differences represent a change in functionality. This is a difficult task since syntactic and semantic differences are difficult to tell apart with current binary differencing techniques. Binary differencing techniques need the capability to distinguish between changes that are a direct result of a source code change that modifies program behavior from indirect changes, such as compiler optimizations, that do not affect program behavior.

1.3 Research Summary

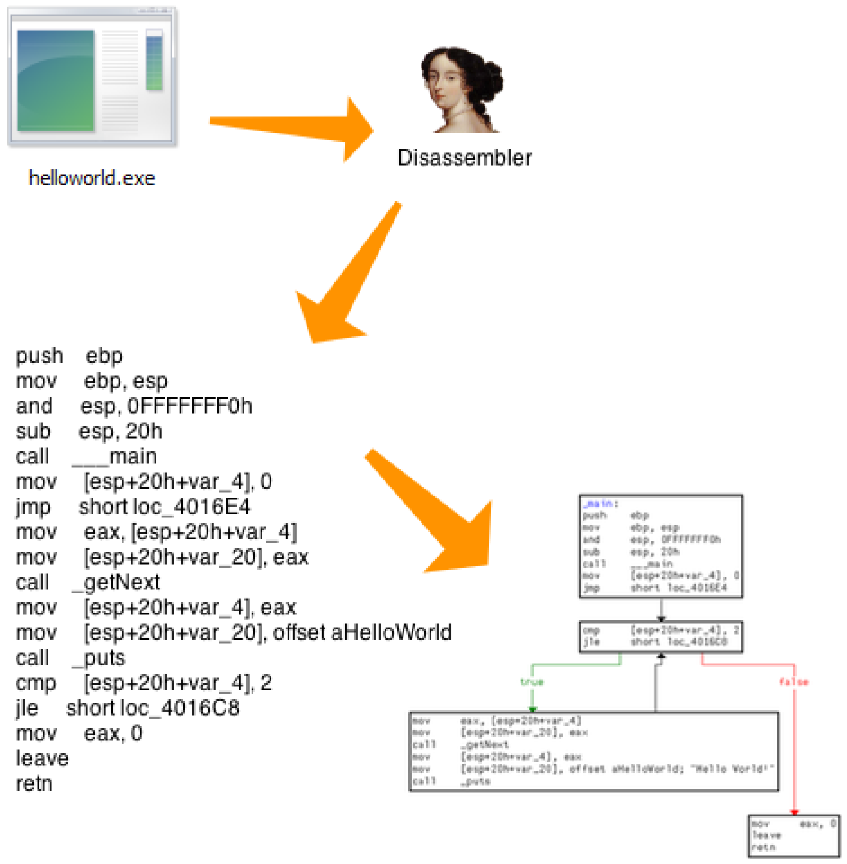
This dissertation describes Data Flow Binary Differencing, a technique we developed for use in reverse engineering software. The technique is enabled by data flow analysis over a disassembled binary executable file. By identifying data flows, we are able to translate the series of instructions that represent a data flow into another representation that allows us to compare two data flows from different binary files. If we determine the two data flows are identical, we have shown the binaries that contain these data flows are similar.

The major contribution of this research is the blending of data flow analysis, assembly language semantics, and symbolic execution to create a three step framework for testing functions from separate binary files for similarities. We implement the Data Flow Binary Differencing technique using three use cases of increasing complexity that illustrate the application of the three step framework. For each use case, we create binaries that fail current binary matching techniques by introducing non-semantic differences in the source code or by compiling the source code at different optimization levels. We successfully identify similarities between the binaries from each use case. We also identify semantic differences introduced by an optimizing compiler as limitations of the Data Flow Binary Differencing technique.

Chapter 2

Literature Survey

Binary differencing begins with disassembling a binary file into a series of instructions, basic blocks, and functions. Figure 2.1 shows a simplified overview of this process. A binary file is disassembled by a disassembly tool (in this example IDA Pro) to instructions, then a control flow graph is created from these instructions. The disassembler performs the analysis required to separate instructions into basic block and functions.



```
push   ebp
mov    ebp, esp
and    esp, 0FFFFFFF0h
sub    esp, 20h
call   ___main
mov    [esp+20h+var_4], 0
jmp    short loc_4016E4
mov    eax, [esp+20h+var_4]
mov    [esp+20h+var_20], eax
call   _getNext
mov    [esp+20h+var_4], eax
mov    [esp+20h+var_20], offset aHelloWorld
call   _puts
cmp    [esp+20h+var_4], 2
jle    short loc_4016C8
mov    eax, 0
leave
retn
```

Figure 2.1: Overview of the disassembly process

2.1 Symbol Name Matching

The simplest way to match functions between binaries is to match symbol names found in the listing of disassembled instructions. [Wang et al. 2000] demonstrates this by using the symbol names in a binary to match functions with the same symbol name in a similar binary. This can be a fast technique to determine if two binaries contain the same or different functions, but it is dependent on the existence of symbols within a binary. Even if symbols are available in a binary, differences in symbols may indicate only a function name change and does not always reflect a change in the function, thus rendering this approach ineffective.

2.2 Signature Hash Map Matching

To overcome the inability to match functions when symbol names contain small changes, [Wang et al. 2000] uses a hashing-based basic block matching algorithm between basic blocks and functions to create a signature that can be used to check for identical blocks and functions in another binary. [Oh 2009] uses a similar approach by creating a fingerprint hash map of basic blocks, then comparing basic blocks using the computed fingerprints. Both of these techniques depend on creating a unique signature resilient to simple changes such as symbol renaming and register allocation. Signatures are created using instructions inside each basic block, but volatile instruction element, such as address offsets, registers used, and immediate operands, might need to be ignored since they can be changed by the compiler between builds, even without source code changes [Wang et al. 2000].

The signature hash map matching technique depends on the contents of a basic block to detect differences. Source code modifications or compiler or linker optimizations that change instructions such that a different signature is calculated will cause false negatives in the output of this technique when trying to match functions between two binaries. Some of these weaknesses can be overcome, such as instruction reordering implemented by [Oh 2009]. By executing an instruction order normalizing routine in which instructions are ordered by dependency on each other and sorted by number of bytes, the signature hash map matching technique can increase matching of basic blocks when instructions have simply been reordered inside a basic block. Other weaknesses that do not reflect semantic differences, such as compiler optimizations, cannot be corrected using signature hash map matching.

Signature hash map matching also suffers from collisions when an executable contains short basic blocks. This means identical signatures are calculated over two separate basic blocks within the same executable. The blocks may only differ in elements ignored by the signature calculating algorithm, so they end up having the same signature. [Oh 2009] simply ignores these collisions but suggests that associating signatures with adjacent signatures in the control flow graph, a linked block signature can be checked against colliding block signatures, potentially elimination single block collisions.

2.3 Structural Analysis Matching

Another approach to detect similarities and differences between binaries is to ignore the instructions completely and focus solely on the control flow and call graphs of two binaries as a means to determine similarities between them. Using the call graph, the executable is visualized as a directed graph with functions represented as nodes and the call relationships between functions as edges. The control flow graph for each function is then used to create a directed graph with nodes representing basic blocks and edges representing jump statements. These graphs can be compared for isomorphism, indicating a match between functions.

Comparing undirected graphs can be computationally expensive so [Flake 2004] introduces a simpler method that compares the number of nodes and edges within a graph. This is a fast, although imprecise, technique to test for isomorphism between two graphs. If two graphs contain a different number of nodes and edges, they cannot be isomorphic. This is a quick technique to generate a small subset of potential graph based matched functions for further analysis.

[Flake 2004] and [Dullien and Rolles 2005] both implement a more precise structural analysis matching technique by generating metadata about each function. [Flake 2004] uses a triplet to record the number of basic blocks in a function, number of edges in the function, and number of edges in the call tree starting at the function. For example, the *_main* function of helloworld.c in figure 1.3 would have a triplet of {4,4,2}, corresponding to its 4 nodes, 4 edges (2 conditional, 2 unconditional), and 2 calls (to *_getNext* and *_puts*). Functions then are matched according to their metadata represented by this triplet.

[Dullien and Rolles 2005] extends this idea of a triplet by creating what they call selectors. A selector is an algorithm that, given two sets of nodes, returns either a node from each set (indicating a match) or the empty set (no matching nodes found). These two sets of nodes represent basic blocks, functions, and call graphs from the two binaries being tested. Selectors are run iteratively over a collection of nodes until no more matches are made between the two sets. Example of selectors from [Dullien and Rolles 2005] include: k-indegree/k-outdegree selector (which selects nodes that contain k indegree or outdegree edges), recursive node selector (which selects nodes that link to themselves), same name selector (selects nodes with identical symbol name), same string selector (selects nodes that reference the same string), and call graph node selector (selects nodes from the call graph which have the same triplet describe by [Flake 2004]).

Structural analysis matching will not detect small changes to source code such as changing a "less-than" comparison to a "less-than or equal" or the modification of a data type such as changing a local variable from an *int* to an *unsigned int*. Either of these changes could represent a security flaw in the application. [Economou 2009] uses structural analysis but also applies heuristics such as instruction counting and calculating a checksum over the basic block, to increase the possibility of detecting small source code changes. Adding introspective analysis to each function and basic block improves structural code analysis techniques but still can falsely identify changes within a function that do not actually change the program behavior.

Another problem for this technique is that small source code changes or compiler optimization might completely rearrange basic blocks, changing the control flow graph. Optimizing compilers can also break apart a single block, adding unconditional jump statements between these sub-blocks. This is especially true of Microsoft's linker. [Flake 2004] The other code changes are harder to detect without including the actual instructions in the analysis or extending the analysis method.

Structural analysis matching techniques also tend to break down when the binary contains a number of small functions. In general, basic blocks tend to have exactly two children, which represents conditional branches. For a binary with many small functions, multiple function can have the same structure, number of blocks, and call graphs. This makes it difficult for structural analysis matching to distinguish differences between small functions. [Dullien and Rolles 2005]

2.4 Semantic Matching using Symbolic Execution

[Gao et al. 2008] implemented symbolic execution and theorem proving as a dynamic binary differencing technique to test basic blocks for semantic differences. This technique can differentiate between syntactic and semantic differences, but due to computation requirements, is only useful for matching individual basic blocks and not functions.

In order to perform symbolic execution, this technique operates on a simple intermediate language. The process takes two basic blocks, identifies the input and output registers, and represents the instructions of each in the intermediate language, which may or may not fully represent the semantics of a machine language. Next, symbolic execution is used to represent the final values of the output registers using the input registers symbols. The two basic block are functionally equivalent if a theorem prover is able to show that the symbolic output values are the same for both. [Gao et al. 2008] never found an example where the simplicity introduced by utilizing an intermediate language hid a semantic change in the machine language, but the possibility exists. Using symbolic execution to detect semantic differences between binary is a good possibility but can be computationally intensive.

The largest weakness of [Gao et al. 2008]'s method is that it only allows for the comparison of basic blocks. When comparing two functions using this method, the basic block could be determined to be different, when the functions, in fact, may be functionally equivalent. This could be due to compiler optimization that has modified the function's structure so that the semantics of a basic block in one of the functions is split between two basic block in the other function.

2.5 Summary

In practice, some or all of these techniques are incorporated into tools when used on practical reverse engineering exercises. All static techniques share a weakness of difficult in determining is a change in a binary is a semantic change or a syntactic change. This is often left up to the reverse engineer, who can waste time and resources determining an identified change by one of these methods is actually not a functional change at all.

Chapter 3

Using Data Flow for Function Matching

Considering the limitations of the binary differencing techniques discussed in Chapter 2, our approach shifted the focus from program structure to data structure as a source of comparison. We accomplish this by looking at data flow through a function and comparing the data flow to another function to determine if the two functions are similar. We call this method Data Flow Binary Differencing. This research applies the data flow concepts of dynamic analysis to static analysis so as to identify behavior changes in binaries which may also have structural changes that do not affect behavior. Using data flow analysis to determine function and basic block matching between binaries allows for syntactic differences in implementation, but is able to use the program's data to determine if any semantic changes occurred between the binaries. Focusing on data flow allows for syntactic differences to exist in the machine languages of two binary executables while preserving the semantics of the intent of the instructions.

We limit the application of our research to comparing two function to determine if they contain similar behavior, regardless of syntactic differences. We assume that, as part of an analysis of a binary executable file we have discovered two functions we believe to contain similarities, but applying the differencing techniques discussed in Chapter 2 suggests the two function are different. Our research begins at this point in the analysis and attempts to prove the two functions contain similarities. Our research does not attempt to replace existing binary differencing methods, but to provide another technique for determining matches between functions.

3.1 A Framework for Data Flow Binary Differencing

Our Data Flow Binary Differencing framework consists of three different steps. Both binaries under comparison are processed in the first two steps and the comparison occurs in the third. The first step identifies slices of instructions within a function, where a slice is a series of instructions. Each slice begins with a data read (load mnemonic) or as the return value of a `call` instruction, and ends with either a data write (store mnemonic) or at the end of the data flow, the data flow we are following is no longer used. The second step translates the series of instructions to a representation that explicitly represents the semantics. From the semantics, the stream of instructions is represented as a logical formula. In the final step, this logical formula is compared to another logical formula to test for equality. Overall this framework allows for comparison of data usage between binaries with similar functions. We make the assumption that the behavior of a function is exposed by how it interacts with data and we represent this interaction with a logical formula that can be compared to another formula to test for similar behavior.

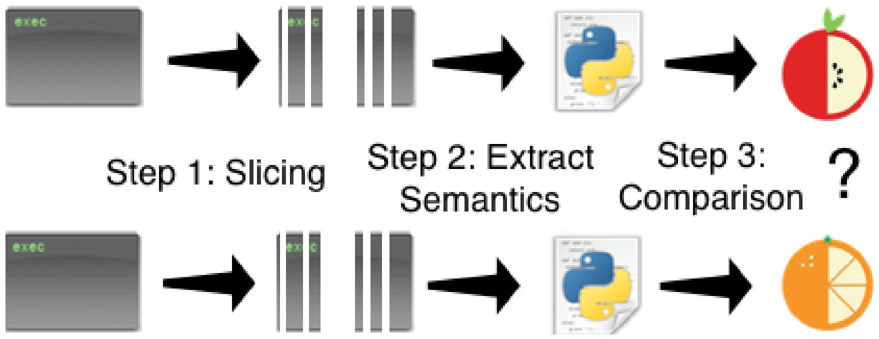


Figure 3.1: Overview of the Data Flow Binary Differencing process

Data Flow Binary Differencing addresses the limitation of the existing structural, signature, and symbolic analysis methods described in Chapter 2. This technique is not dependent on the control flow graph of a function, a weakness of the Structural Analysis Matching method, nor does this technique depend on syntactic signatures used by the Signature Hash Map Matching technique. Our technique is very similar to the Semantic Matching using

Symbolic Execution although by focusing on data we are able to generate semantic representations across basic blocks without creating computationally intensive requirements.

3.1.1 Step 1: Slicing Instructions

The first step takes the idea of slicing from [Jackson and Rollins 1994], who implement two sets of variable instances, *sources* and *sinks*, to create a linear graph showing the instructions that cause the definition of a *source* to affect the use of a *sink*. A slice represents the list of instructions that affect the value of the data use at the *sink* starting at the data definition at the *source*. The purpose of slicing in our research is to extract from a binary a subset of instructions that define a data flow. We use both forward and backward slicing from [Jackson and Rollins 1994]. Slicing follows the data uses from the *source*, ending at the *sink* for forward slicing, and follows data definitions from the *sink* backward through the instruction flow to the *source* for backward slicing. Both methods record each instruction that contains a data dependency, generating a series of instruction that represent a data flow.

The primary means of identifying *sources* and *sinks* is memory reads and memory writes, respectively defined in our research by a `mov` instruction with an operand that references a memory location. By slicing between these two points, we obtain the list of instructions that operate on a piece of data. The other primary means of identifying *sources* and *sinks* are `call` instructions. Viewed from the perspective of the calling code, *sources* can be defined as the return value from a subroutine and *sinks* can be defined as the arguments to a subroutine.

Using `call` instructions to identify *sources* and *sinks* allows us to model data flow to and from a subroutine. For well known subroutines, such as standard library functions and system calls, we look up the number of arguments so we know which data definitions belong to the slice. We then introduce constraints on the *sources* and *sinks* from the `call` instruction to simplify the matching in the third step. For example, if we know the return value of a standard library function is always '1' or '0', then we can simplify the comparisons in Step 3 by only considering '1' or '0' as potential values for this variable within a data flow. We also do this for conditional branching conditions. For a data flow that follows a conditional path, we record the condition and, in Step 3, use this as a constraint for the data along this path. An example is a jump condition that is dependent on the value of one symbolic variable being less than another. We include this constraint in our comparison of these data flows which decreases the possible values the symbolic variable can represent.

3.1.2 Step 2: Extracting Semantics

In contrast to high level languages such as C++ and Java, machine languages do not differentiate between data types, such as Int or Bool. Data is simply an n-bit binary value where n is determined by the operation of the instructions and width of addressable memory. Instructions perform logical or arithmetic transformations on these n-bit binary values and move them between memory locations or registers. These logical transformations consist of bitwise operations such as `and`, `or`, `shl` (unsigned left shift), and `sar` (signed right shift). Arithmetic transformation are mathematic calculations over bit vectors such as `add`, `sub`, and `imul` (integer multiply). The goal of this step is to extract the semantics of the series of instructions created in Step 1. This means explicitly representing the behavior of instructions belonging to complex architectures, where the result of an instruction depends on the contents of the EFLAGS register, the size of the operands, and the mnemonic of the instruction. Each data flow identified in the slicing step is processed in the extracting step.

Some instructions do not contribute to data flow analysis. These instructions can be discarded within the slicing step, but often it is useful to maintain full knowledge of semantics since this could lead to simplification in the comparison step. For example, a `test` instruction performs a bitwise `and` on the two operands and modifies the Adjust Flag (AF), Carry Flag (CF), Overflow Flag (OF), Parity Flag (PF), Sign Flag (SF), and Zero Flag (ZF). The CF and OF flags are set to zero. The SF is set to the most significant bit of the result of the `and` operation. The ZF flag is set to 1 if the result of the `and` is 0, otherwise the ZF flag is set to 0. The parity flag is set to 1 if the result of the `and` operation has an even number of 1 bits. The value of the AF flag is undefined after a `test` instruction. The result of the `and` operation is discarded.[Intel Corporation 2014] Subsequent instructions, such as `jle` (jump less than or equal), use these flags to modify control flow. Using this control flow information we can create constraints for program slices that simplify the comparison between data flows, but we do not need the control flow information to represent the data flow. This is further illustrated in Chapter 4.

3.1.3 Step 3: Testing for Equality

Once we extract the semantics of a series of instructions that represent a single data flow, we test it against data flows in another function we believe contains similar behavior by symbolically representing input to the data flows and testing both flows to see if they produce the same results. We translate the semantics to a single logical expression with symbolic bit vector inputs that evaluates to a single output. We do this for each series of instructions that we would like to test against each other for similarities. We then attempt to prove the logical expressions obtained from the semantics of each series of instruction is equal for the possible values of the symbolic bit vectors. Otherwise, we know the series of instructions contain a semantic difference.

3.2 Conclusion

Our approach to solve the problems identified in Chapter 2 with current binary differencing techniques entails using data flow to characterize the behavior of functions. Using data flow circumvents dependencies on program flow as well as internal structure of a binary or function. We build our research on symbolic execution but focus wholly on data flow as the source of our symbols, allowing us to overcome the computationally requirements of traditional symbolic execution.

Chapter 4

Implementing Data Flow Binary Differencing

4.1 Research Objective

The primary research goal is to determine if syntactic differences between two function represent semantic differences. If we determine that syntactic differences between two functions are not semantic differences, we have confidence that the function are similar, meaning, although the functions look different in their assembly language representation, they perform the same action or actions. We compare the Data Flow Binary Differencing method to the other differencing methods discussed in Chapter 2, specifically Signature Hash Map Matching and Structural Analysis Matching, since these matching techniques perform the same basic action of testing two functions for similarities. We ignore Symbol Name Matching since the matching criteria for this method has nothing to do with the syntax or semantic of a function.

We operate under the assumption that we have two functions that we want to test for differences, ultimately deciding if the functions contain similar behavior. Having some knowledge about the binaries we are testing and an indication that two functions might be equal is the starting point for our research. We do not attempt to solve the complete problem of performing binary differencing without any prior knowledge about the binaries or functions, only to provide another matching technique to test functions that will be used alongside existing techniques. Any difference that cannot be successfully matched semantically between functions is reported to the reverse engineer for further analysis.

4.2 Research Overview

To demonstrate proof of feasibility of our approach, we use IDA Pro ver. 6.6 [Hex Rays 2014] and Python ver. 2.7.3 to execute the first two steps of the Data Flow Binary Differencing Framework and then use the Z3 SMT solver ver. 4.3.2 [Microsoft Research 2014] to test for equality in the third step. From the available tools, this approach provided the greatest flexibility while meeting our research goals.

The process begins by compiling the use cases using GCC 4.7.2 on Debian 7 (Linux kernel 3.2.0-4-amd64). Once we have creating sample binaries, we use IDA Pro to disassemble the binaries to assembly language instructions. After disassembly, IDA performs a number of static analyses on the instructions including identifying local variables, auto-generating and populating names for known symbols, and creating a graph view of basic blocks and control flow of the instructions. Using this information, we create slices of instructions based on the method discussed in Section 3.1.1. Next, we extract the semantics of each instruction contained within each slice and explicitly represent the behavior of each instruction using Python. We test the two outputs for equality using Z3, a software solver for SMT (Satisfiability Modulo Theories), an extension of the Satisfiability (SAT) problem.

The assembly language listing and control flow graph figures presented in this dissertation are generated by IDA Pro. For local variables located on the stack, IDA Pro assigns a label to that variable relative to the position of the variable on the stack. For example, a variable located at the offset `-Ch` from the base of the stack, usually the value of the `ebp` register, would be referenced in IDA Pro as `[ebp+var_C]`. To represent hexadecimal in this dissertation we follow the format used by IDA Pro and represent hexadecimal values with "h" and hexadecimal addresses with"0x", such as `-Ch` is a value and [0x080486A3] is an address.

The following sections describe three use cases, each illustrating increasing complexity and achieving slightly different research objectives. These uses cases were selected to cover the three fundamental program flow constructs found in programming languages, sequential execution, conditional execution, and looping.

4.3 Use Case 1: Simple Arithmetic Calculation

Our first use case illustrates the approach using a simple mathematic example and allows us to show how the Data Flow Binary Differencing technique is applied. We create two functions that add two numbers together. The second function adds these two numbers in a different order and has an additional addition and subtraction operation but ultimately arrives at the same result as the first function. The goal of this use case is to show that our technique can be applied to syntactically different functions with semantically equal functionality.

Listings 4.1 and 4.2 are compiled using `gcc`, resulting in the 32-bit assembly language shown in Listings 4.3 and 4.4.

Listing 4.1: SimpleMath.c Source Code

```
#include <stdlib.h>

int main(int argc, char *argv[]){
        int w, x, y, z;
        x = 2;
        y = 3;
        w = 5;
        z = x + y;
        return z;}
```

Listing 4.2: SimpleMath2.c Source Code

```
#include <stdlib.h>

int main(int argc, char *argv[]){
        int x, y, z;
        x = 2;
        y = 3;
        z = y + x + x - x;
        return z;}
```

Listing 4.3: SimpleMath disassembled by IDA Pro

```
; int __cdecl main(int argc, const char **argv, const char **envp)
public main
main proc near

var_10= dword ptr -10h
var_C= dword ptr -0Ch
var_8= dword ptr -8
var_4= dword ptr -4
argc= dword ptr  8
argv= dword ptr  0Ch
envp= dword ptr  10h

push    ebp
mov     ebp, esp
sub     esp, 10h
mov     [ebp+var_4], 2
mov     [ebp+var_8], 3
mov     [ebp+var_C], 5
mov     eax, [ebp+var_8]
mov     edx, [ebp+var_4]
add     eax, edx
mov     [ebp+var_10], eax
mov     eax, [ebp+var_10]
leave
retn
main endp
```

Listing 4.4: SimpleMath2 disassembled by IDA Pro

```
; int __cdecl main(int argc, const char **argv, const char **envp)
public main
main proc near

var_C= dword ptr -0Ch
var_8= dword ptr -8
var_4= dword ptr -4
argc= dword ptr  8
argv= dword ptr  0Ch
envp= dword ptr  10h

push    ebp
mov     ebp, esp
sub     esp, 10h
mov     [ebp+var_4], 2
mov     [ebp+var_8], 3
mov     eax, [ebp+var_4]
mov     edx, [ebp+var_8]
add     edx, eax
mov     eax, [ebp+var_4]
add     eax, edx
sub     eax, [ebp+var_4]
mov     [ebp+var_C], eax
mov     eax, [ebp+var_C]
leave
retn
main endp
```

4.3.1 Analysis & Observations

The source code of SimpleMath and SimpleMath2 contain minor syntactic differences shown using the `diff` command in Listing 4.5. Since this function contains only one basic block, the Structural Analysis Matching technique alone attempts to match this function to any other function with a single basic block. The Signature Hash Map Matching technique fails because the additional instructions in SimpleMath2 will cause the Signature Hash Map Matching technique to generate a different signature than SimpleMath.

Listing 4.5: Difference between source code of Simplemath and SimpleMath2

```
$ diff SimpleMath.c SimpleMath2.c
4c4
<        int w, x, y, z;
---
>        int x, y, z;
7,8c7
<        w = 5;
<        z = x + y;
---
>        z = y + x + x - x;
```

SimpleMath includes an additional local variable declaration on line 4, `int w`, and an additional assignment on line 7 of Listing 4.1, `w = 5`. IDA Pro identifies the additional local variable `w` in SimpleMath and assigns it the label `var_C` (Listing 4.3 line 6 and 18). We can see from the assembly in Listing 4.3, after the definition of `var_C` on line 18 the data is never used so this variable does not contribute to a data flow.

SimpleMath adds the local variables `x` and `y` on line 8 of Listing 4.1. SimpleMath2 does the same but also performs an additional addition and subtraction on line 7 of Listing 4.2. The value assigned to the local variable `z` is the same as the value returned by the `main` function in both programs despite the additional mathematic operations on line 7 of SimpleMath2. We know that, semantically, `x + y == y + x + x - x` is true. Our technique will prove the semantic equality of these calculation by proving these output values are equal.

4.3.2 Step 1: Creating Slices

Sources are defined as memory load operations. Lines 19, 20, and 23 in SimpleMath[1] read data from memory (the stack in this case) and load that value into a register. Lines 17, 18, 19, and 24 in SimpleMath2[1] also read data from memory. *Sinks* are defined as memory store instructions and as the return value of the function (the value in `eax` at `retn`). Also depending on the memory usage of the function, the return value could also be a source, as it is in this case. Data is written to the stack at lines 16, 17, 18, and 22 in SimpleMath[1] and lines 15, 16, and 23 in SimpleMath2[1] so we consider these instructions as *sinks*. The return value of both functions is also a *sink*, line 23 in SimpleMath[1] and line 24 in SimpleMath2[1]. Table 4.1 lists all *sources* and *sink* in both programs' main() functions.

Table 4.1: Use Case 1: Sources and Sinks for SimpleMath and SimpleMath2

File	Line	Type	Instruction
SimpleMath	19	Source	mov eax, [ebp+var_8]
SimpleMath	20	Source	mov edx, [ebp+var_4]
SimpleMath	23	Source	mov eax, [ebp+var_10]
SimpleMath	16	Sink	mov [ebp+var_4], 2
SimpleMath	17	Sink	mov [ebp+var_8], 3
SimpleMath	18	Sink	mov [ebp+var_C], 5
SimpleMath	22	Sink	mov [ebp+var_10], eax
SimpleMath	23	Sink	mov eax, [ebp+var_10]
SimpleMath2	17	Source	mov eax, [ebp+var_4]
SimpleMath2	18	Source	mov edx, [ebp+var_8]
SimpleMath2	20	Source	mov eax, [ebp+var_4]
SimpleMath2	24	Source	mov eax, [ebp+var_C]
SimpleMath2	15	Sink	mov [ebp+var_4], 2
SimpleMath2	16	Sink	mov [ebp+var_8], 3
SimpleMath2	23	Sink	mov [ebp+var_C], eax
SimpleMath2	24	Sink	mov eax, [ebp+var_C]

We can see from Table 4.1, a few *sinks* are found at higher line numbers than any of the identified *sources*. Without a prior *source*, we cannot create a slice that includes these

[1]Line numbers reference Listings 4.3 and 4.4

sinks, so we must ignore them. We also ignore the the last *source* in both functions since no corresponding *sink* exists.

We use both forward and backward slicing to calculate slices. Listings 4.6 and Listings 4.7 illustrate the difference between forward and backward slicing.

To calculate a backward slice, we look for all data dependencies between the *source* and *sink* that influence the value at the *sink*. Conceptually, we start at the *sink* and follow use-define chains backward through the instruction flow until we reach the *source*. Starting at the *sink* in Listing 4.6, the instruction `mov eax, [ebp+var_10]` defines `eax` using `[ebp+var_10]`. So we look backwards through the instruction flow for a definition of `[ebp+var_10]` and add the instruction to the slice. The previous instruction, `mov [ebp+var_10], eax`, is added to the slice because it defines `[ebp+var_10]` and uses `eax`. Now we look for instructions that define `eax`. The `add eax, edx` instruction defines `eax` and uses `eax` and `edx`, so we now look for definitions of `eax` and `edx`. The next two previous instructions `mov eax, [ebp+var_8]` and `mov edx, [ebp+var_4]` define `eax` and `edx`, so they are also added to the slice. The instruction `mov eax, [ebp+var_8]` is also the *source* so we have finished calculating this slice.

Listing 4.6: Backwards Slicing SimpleMath with source at line 19 and sink at line 23

```
mov      eax, [ebp+var_8]
mov      edx, [ebp+var_4]
add      eax, edx
mov      [ebp+var_10], eax
mov      eax, [ebp+var_10]
```

Calculating a forward slice is similar, but follows define-use chains from the *source* to the *sink*. The *source* instruction on line 19[1], `mov eax, [ebp+var_8]`, defines `eax` using the data from `[ebp+var_8]`, so we look for uses of `eax` in the following instructions. The next instruction, `mov edx, [ebp+var_4]` is not added to the slice because it does not use `eax`. The `add eax, edx` instruction uses `eax`, so it is added to the slice. The `add eax, edx` redefines `eax` so we continue looking for uses of `eax` until we reach the *sink*. The remaining instructions including the *sink* are part of the use-define chain with `add eax, edx`, so they are also added to the slice. The final resulting slice is shown in Listing 4.7. The slice obtained from forward slicing is missing an instruction included in the backward slice, Listing 4.6.

Listing 4.7: Forward Slicing SimpleMath with source at line 19 and sink at line 23

```
mov      eax, [ebp+var_8]

add      eax, edx
mov      [ebp+var_10], eax
mov      eax, [ebp+var_10]
```

Our method allows for the creation of forward or backward slices. In Steps 2 and 3 of our framework, we test if either slicing method matches a slice from another binary, with a successful match representing a semantic match between data flows.

Continuing with our process, we calculate a backward slice from SimpleMath2, Listing 4.4. The resulting slice is show in Listing 4.8.

Listing 4.8: Backwards Slicing SimpleMath2 with source at line 17 and sink at line 24

```
mov      eax, [ebp+var_4]
mov      edx, [ebp+var_8]
add      edx, eax
mov      eax, [ebp+var_4]
add      eax, edx
sub      eax, [ebp+var_4]
mov      [ebp+var_C], eax
mov      eax, [ebp+var_C]
```

Looking back at Table 4.1, we see that the slice from SimpleMath, shown in Listing 4.6, contains all possible *sources* and *sinks* in the function, so any other slice generated from this table would be a subset of this slice. The same is true for the slice in Listing 4.8 from SimpleMath2.

4.3.3 Step 2: Extracting Semantics

We extract the behavior of each slice in preparation for symbolic execution, modeling the behavior in Python. Listings 4.9, 4.10, and 4.11 contain the results of extracting semantics for each slice in SimpleMath and SimpleMath2. Actual instructions appear as comments in the Python code for reference.

Listing 4.9: Semantics for Listing 4.6

```
eax = var_8         #mov  eax, [ebp+var_8]
edx = var_4         #mov  edx, [ebp+var_4]
eax = eax + edx     #add  eax, edx
var_10 = eax        #mov  [ebp+var_10], eax
eax = var_10        #mov  eax, [ebp+var_10]
```

Listing 4.10: Semantics for Listing 4.7

```
eax = var_8         #mov  eax, [ebp+var_8]
eax = eax + edx     #add  eax, edx
var_10 = eax        #mov  [ebp+var_10], eax
eax = var_10        #mov  eax, [ebp+var_10]
```

Listing 4.11: Semantics for Listing 4.8

```
eax = var_4         #mov  eax, [ebp+var_4]
edx = var_8         #mov  edx, [ebp+var_8]
edx = edx + eax     #add  edx, eax
eax = var_4         #mov  eax, [ebp+var_4]
eax = eax + edx     #add  eax, edx
eax = eax - var_4   #sub  eax, [ebp+var_4]
var_C = eax         #mov  [ebp+var_C], eax
eax = var_C         #mov  eax, [ebp+var_C]
```

Extracting semantics was performed manually by translating each instruction to the equivalent Python expression. [Intel Corporation 2014] We chose Python as the intermediate language is it allows us to use the Python API for the Z3 solver, discussed in the next step.

Other tools are available that implement an intermediate language such as S2E [Chipounov et al. 2011] and BAP [Brumley et al. 2011], but none of these tools are designed to allow analysis over multiple binary files at the same time.

All of our use cases employ x86 machine language instructions that could be modeled explicitly in the Python programming language.

4.3.4 Step 3: Testing Equality

After obtaining the semantics for each slice, we symbolically execute the slices and test if it matches the behavior of another slice. We implement this using the Microsoft Z3 solver's Python API. We use the *prove()* function from Z3's Python API, which creates an assert statement that attempts to disprove the equality of the two input statements. The *prove()* function takes a single input argument, for example `prove (P)`, and tries to solve the negation of that equation, `Not(P) == True` . If the solver cannot prove `Not(P)`, then it has indirectly proven `P == True` .

Listing 4.12 shows a simple example using the *prove* function from the Z3 Python API. Here we create two symbolic bit vectors, both 32-bit in length, and instruct *prove* to test if they are equal. Since both values are symbolic, Z3 is free to chose any value for each value. We do not provide any constraints for the variables so Z3 chooses different values which invalidates the statement `a == b`.

Listing 4.12: The Z3 Python API prove() function

```
Python 2.7.3 (default, Mar 13 2014, 11:03:55)
[GCC 4.7.2] on linux2
Type "help", "copyright", "credits" or "license" for more information.
>>> from z3 import *
>>> a = BitVec("a",32)
>>> b = BitVec("b",32)
>>> prove (a == b)
counterexample
[b = 0, a = 4294967295]
```

For our use cases, we pass *prove()* a statement representing testing two slices for equality, `prove (slice1 == slice2)`. *prove()* tells us that it has "proven" the statement (our slices are equal) or it provides a counterexample showing us the symbolic values in the counterexample that invalidate our statement.

Our goal is to prove that slices in SimpleMath are equal to slices from SimpleMath2. We compare both Listing 4.6 and 4.7 to Listing 4.8. We test both the forward and backward slices calculated from SimpleMath to the backward slice calculated from SimpleMath2. The complete Python script that implements these tests is shown in Listing 4.13. Running this script produces the output in Listing 4.14.

Listing 4.13: Testing slices of SimpleMath and SimpleMath2 for equality.

```python
from z3 import *

s = Solver()
var_4 = BitVec("var_4", 32)
var_8 = BitVec("var_8", 32)


#Semantics of backward slicing SimpleMath from line 19 to line 23
eax = var_8           #mov  eax, [ebp+var_8]
edx = var_4           #mov  edx, [ebp+var_4]
eax = eax + edx       #add  eax, edx
var_10 = eax          #mov  [ebp+var_10], eax
eax = var_10          #mov  eax, [ebp+var_10]
sm_slice1 = eax

#Semantics of forward slicing SimpleMath from line 19 to line 23
#We don't know the value of eax, so it is replaced with a symbol
edx = BitVec("edx", 32)

eax = var_8           #mov  eax, [ebp+var_8]
eax = eax + edx       #add  eax, edx
var_10 = eax          #mov  [ebp+var_10], eax
eax = var_10          #mov  eax, [ebp+var_10]
sm_slice2 = eax

#Semantics of backward slicing SimpleMath2 from line 17 to line 24
eax = var_4           #mov  eax, [ebp+var_4]
edx = var_8           #mov  edx, [ebp+var_8]
edx = edx + eax       #add  edx, eax
eax = var_4           #mov  eax, [ebp+var_4]
eax = eax + edx       #add  eax, edx
eax = eax - var_4     #sub  eax, [ebp+var_4]
var_C = eax           #mov  [ebp+var_C], eax
```

```
eax = var_C           #mov  eax, [ebp+var_C]
sm2_slice1 = eax


print "sm_slice1 :", sm_slice1
print "sm_slice2 :", sm_slice2
print "sm2_slice1 :", sm2_slice1

print "Testing sm_slice1 == sm2_slice1 :"
prove (sm_slice1 == sm2_slice1)

print "Testing sm_slice2 == sm2_slice1 :"
prove (sm_slice2 == sm2_slice1)
```

Listing 4.14: Output of Listing 4.13

```
1 sm_slice1 : var_8 + var_4
2 sm_slice2 : eax + var_4
3 sm2_slice1 : var_4 + var_8 + var_4 - var_4
4 Testing sm_slice1 == sm2_slice1 :
5 proved
6 Testing sm_slice2 == sm2_slice1 :
7 counterexample
8 [var_8 = 0, eax = 4294967295]
```

From lines 4 and 5 of Listing 4.14, we see that the Z3 solver is able to prove the backward slice from SimpleMath, `sm_slice1` in Listing 4.14, matches the backward slice from SimpleMath2, `sm2_slice1` in Listing 4.14. The symbolic representation of `sm_slice1` is `var_8 + var_4` and the symbolic representation of `sm2_slice1` is `var_4 + var_8 + var_4 - var_4`. Z3 is able to prove `var_8 + var_4 == var_4 + var_8 + var_4 - var_4`.

Lines 6 and 7 of Listing 4.14 show the result of comparing the forward slice from SimpleMath to the backward slice from SimpleMath2. The solver is unable to prove these two slices are equal and provides a counterexample. Symbolically, the solver tries to prove `eax + var_4 == var_4 + var_8 + var_4 - var_4`. The left side of this equation has an extra variable not present on the right side, `eax`. The solver returns values for `var_8` and `eax` that invalidate this equation for all values of `var_4`.

4.3.5 Conclusion

The SimpleMath use case illustrates each step of the Data Flow Binary Differencing framework by creating slices of instructions based on sinks and sources, extracting the semantics from these instructions, and then symbolically testing slices from both programs for equality. When creating slices, forward and backward techniques do not always produce the same slice, so we should test both methods when calculation slices. By comparing the backward slice from SimpleMath and the backward slice from SimpleMath2, we have shown the Data Flow Binary Differencing method for detecting semantically equal, yet syntactically different, functions is successful with this simple example.

4.4 Use Case 2: Exploring limitations of Data Flow Binary Differencing

Use Case 2 demonstrates the validity of our approach on artifacts that contain conditional program flow in the form of loops. This use case is designed to test the limitations of Binary Data Flow Differencing, specifically to see how our approach handles looping. We know that symbolic execution for program analysis tends to have trouble with loops. This was a major limitation of using S2E [Chipounov et al. 2011] or BAP [Brumley et al. 2011] for this research because both implementations require the intermediate language to unroll loops before invoking the SMT solver.

We chose to illustrate the use case with a program that calculates Fibonacci numbers, creating different versions by compiling it with different optimization levels. The use of different optimization levels introduces syntactic differences without modifying the semantics of the program.

GCC supports 4 levels of optimizations. Level 0 instructs the compiler to generate machine instructions without reordering statements or enabling optimizations. At level 1, the compiler tries to reduce code size and execution time without performing any optimizations that increase compilation time. Level 2 includes all the optimizations at level 1 plus optimizations that do not involve a space-speed tradeoff, so the resulting executable will not increase in size. Level 3 optimizes beyond level 2 by turning on more expensive optimization that can increase compile time and the resulting file size. We used these optimization levels to created semantically identical binaries with syntactic differences.

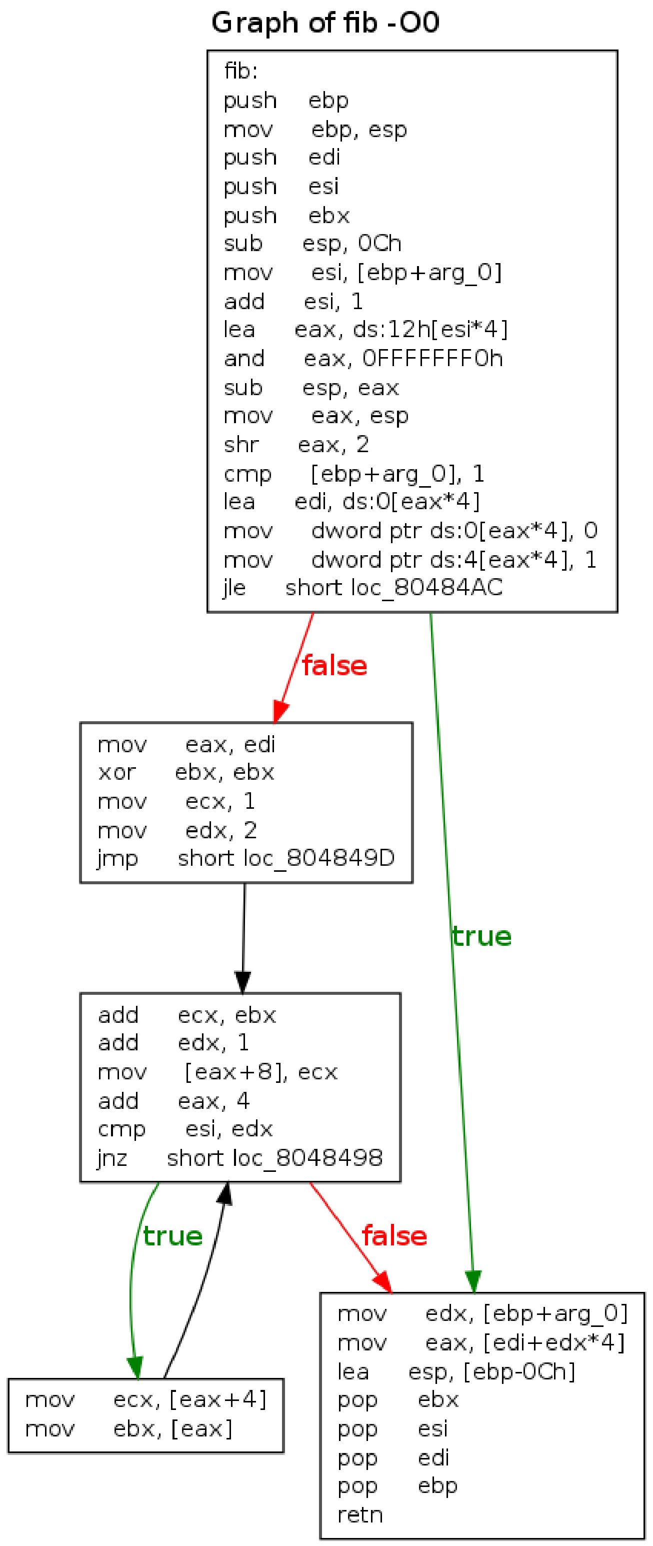
The source code for our Fibonacci program can be found in Appendix A, Listing A.2. As with our first use case, we build Fibonacci with GCC 4.7.2 on Debian 7 using all four of the optimization levels. Our Fibonacci function takes one argument, `n`, calculates an array of Fibonacci values, and returns the requested value, the n-th Fibonacci number. The *fib()* function calculates the array of Fibonacci values by setting the first and second Fibonacci numbers to `0` and `1`, respectively, and then loops over an addition operation that adds the previous two Fibonacci numbers and stores the result in the next array location.

We use optimization levels 0, 1, and 2 for our analysis. The binary resulting from optimization level 3 was almost identical to level 2 so we exclude it from the analysis. After compiling the source code at each of the optimization levels 0, 1, and 2, we use IDA Pro to disassemble the resulting binaries. In Appendix B we show the disassembled *fib()* functions from each optimization level. Each binary contains a *main()* function as well as other imported standard library functions not shown, since these additional functions are not relevant to our research.

Figures 4.1, 4.2, and 4.3 show the Control Flow Graph (CFG) of *fib()* at each optimization level 0, 1, and 2.

4.4.1 Analysis & Observations

In looking at the conventional function matching techniques, the Structural Analysis technique depends on similarities between the CFGs to detect similar functions. Table 4.2 shows a way to perform structural analysis on *fib()*. The matching algorithm attempts to match functions that contain the closest number of basic blocks, edges, and calls. None of the functions under analysis from the three optimization levels contain the same number of basic blocks, edges, or calls so Structural Analysis matching fails.



```
fib:
push    ebp
mov     ebp, esp
push    edi
push    esi
push    ebx
sub     esp, 0Ch
mov     esi, [ebp+arg_0]
add     esi, 1
lea     eax, ds:12h[esi*4]
and     eax, 0FFFFFFF0h
sub     esp, eax
mov     eax, esp
shr     eax, 2
cmp     [ebp+arg_0], 1
lea     edi, ds:0[eax*4]
mov     dword ptr ds:0[eax*4], 0
mov     dword ptr ds:4[eax*4], 1
jle     short loc_80484AC
```

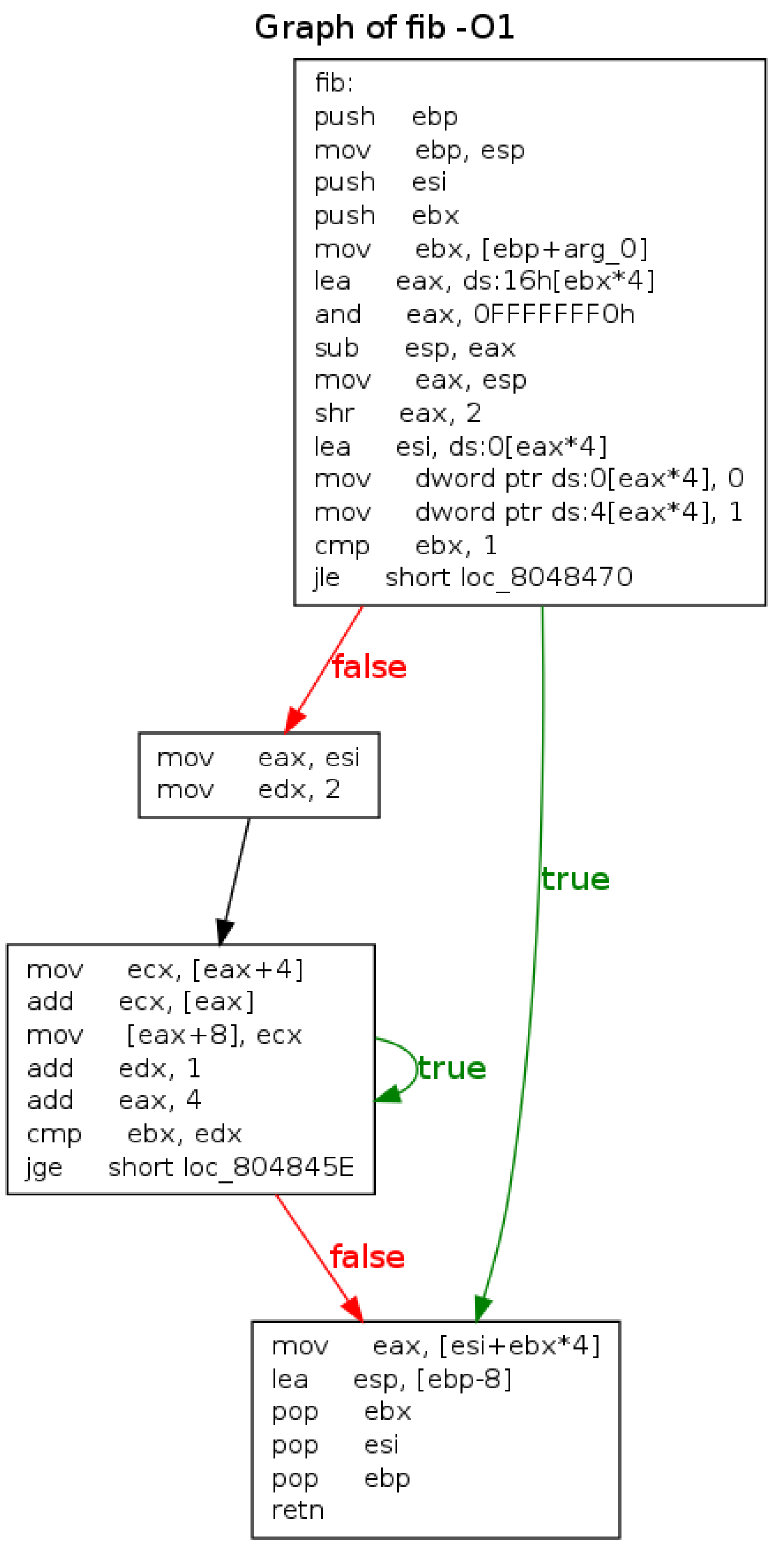
```
mov     eax, edi
xor     ebx, ebx
mov     ecx, 1
mov     edx, 2
jmp     short loc_804849D
```

```
add     ecx, ebx
add     edx, 1
mov     [eax+8], ecx
add     eax, 4
cmp     esi, edx
jnz     short loc_8048498
```

```
mov     ecx, [eax+4]
mov     ebx, [eax]
```

```
mov     edx, [ebp+arg_0]
mov     eax, [edi+edx*4]
lea     esp, [ebp-0Ch]
pop     ebx
pop     esi
pop     edi
pop     ebp
retn
```

Figure 4.1: Control Flow Graph of fib() optimization level 0



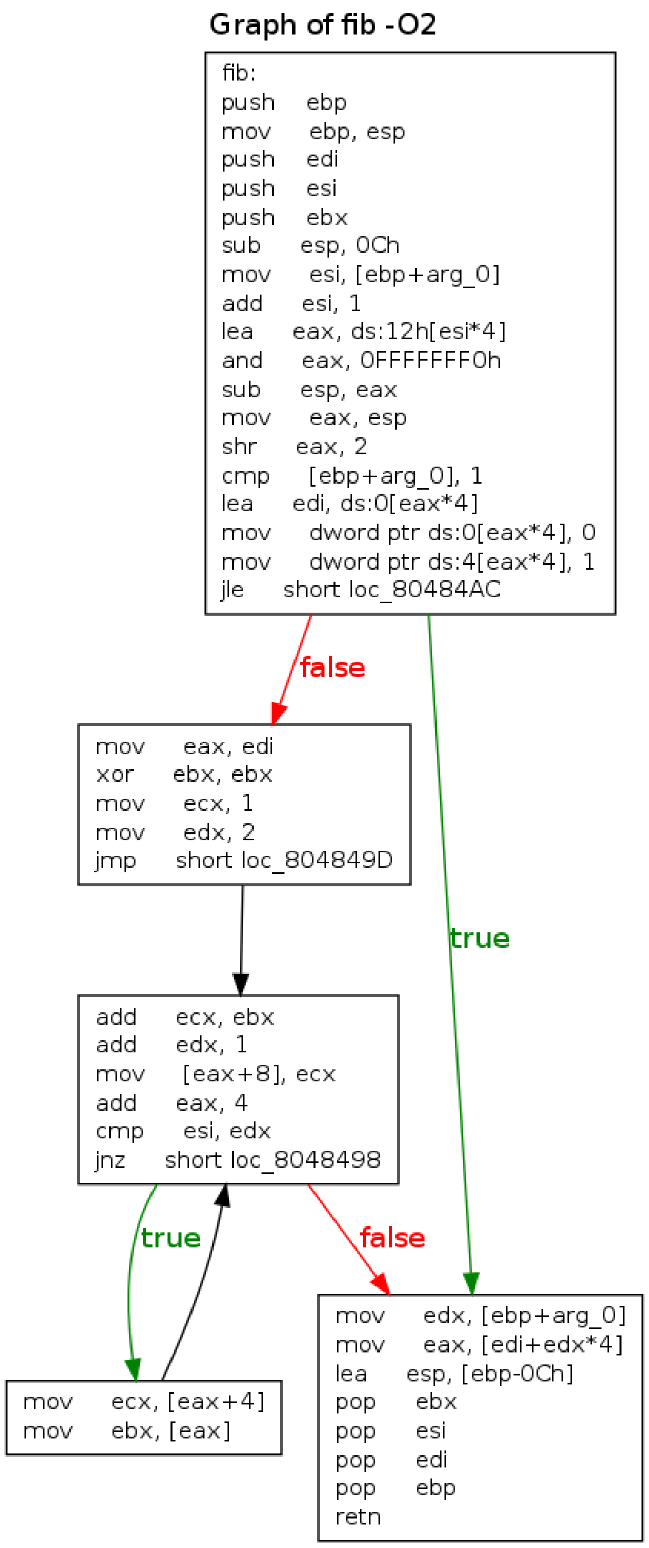
```
fib:
push    ebp
mov     ebp, esp
push    esi
push    ebx
mov     ebx, [ebp+arg_0]
lea     eax, ds:16h[ebx*4]
and     eax, 0FFFFFFF0h
sub     esp, eax
mov     eax, esp
shr     eax, 2
lea     esi, ds:0[eax*4]
mov     dword ptr ds:0[eax*4], 0
mov     dword ptr ds:4[eax*4], 1
cmp     ebx, 1
jle     short loc_8048470
```

```
mov     eax, esi
mov     edx, 2
```

```
mov     ecx, [eax+4]
add     ecx, [eax]
mov     [eax+8], ecx
add     edx, 1
add     eax, 4
cmp     ebx, edx
jge     short loc_804845E
```

```
mov     eax, [esi+ebx*4]
lea     esp, [ebp-8]
pop     ebx
pop     esi
pop     ebp
retn
```

Figure 4.2: Control Flow Graph of fib() optimization level 1



```
fib:
push    ebp
mov     ebp, esp
push    edi
push    esi
push    ebx
sub     esp, 0Ch
mov     esi, [ebp+arg_0]
add     esi, 1
lea     eax, ds:12h[esi*4]
and     eax, 0FFFFFFF0h
sub     esp, eax
mov     eax, esp
shr     eax, 2
cmp     [ebp+arg_0], 1
lea     edi, ds:0[eax*4]
mov     dword ptr ds:0[eax*4], 0
mov     dword ptr ds:4[eax*4], 1
jle     short loc_80484AC
```

```
mov     eax, edi
xor     ebx, ebx
mov     ecx, 1
mov     edx, 2
jmp     short loc_804849D
```

```
add     ecx, ebx
add     edx, 1
mov     [eax+8], ecx
add     eax, 4
cmp     esi, edx
jnz     short loc_8048498
```

```
mov     ecx, [eax+4]
mov     ebx, [eax]
```

```
mov     edx, [ebp+arg_0]
mov     eax, [edi+edx*4]
lea     esp, [ebp-0Ch]
pop     ebx
pop     esi
pop     edi
pop     ebp
retn
```

Figure 4.3: Control Flow Graph of fib() optimization level 2

Table 4.2: Structural Analysis of fib()

Optimization Level	Number of Blocks	Edges	Calls
-O0	4	4	0
-O1	4	5	0
-O2	5	6	0

The Signature Hash Map matching technique attempts to create signatures of each basic block using the mnemonics and operands of the instructions. None of the basic blocks in Figures 4.1, 4.2, and 4.3 contain identical instructions so each basic block will have a different signature. Figures 4.2 and 4.3 both contain a basic block with exactly two `mov` instructions, but with different operands. Ignoring the operands, Signature Hash Map Matching could generate a signature that matches basic blocks containing two `mov` instructions, but every other basic block has a different signature so ultimately this matching technique could only match one of four or five basic blocks between these functions.

From a reverse engineering perspective, the *fib()* function is complicated. Each binary is compiled using the exact same source code but with different compiler optimization enabled, the disassembled instructions contain many syntactic differences that make understanding the behavior of each binary difficult.

As for the behavior of the functions, the first operation that occurs is the calculation of the array size and address to store the Fibonacci numbers. The number of Fibonacci numbers to calculate is passed to the function as `arg_0`. The function uses this value to calculate the number of bytes required to hold the Fibonacci array and subtracts that number from the current stack address to create space to store the array.

Optimization level 0 results in a complicated approach to calculate the Fibonacci array shown in Listing B.1,lines 17-35 whereas the other optimization levels use a much simpler approach to calculate the array shown in Listing B.2, lines 10-15 for optimization level 1 and Listing B.3, lines 12-18 for optimization level 2.

4.4.2 Step 1: Creating Slices

Tables 4.3, 4.4 and 4.5 show the *sources* and *sinks* from each binary. Without optimizations, the binary includes many memory operations. Optimization levels 1 and 2 have fewer memory load and stores that optimization level 0, which makes runtime faster.

Table 4.3: Use Case 2: Sources and Sinks for fib() optimization level 0

Line Number	Type	Instruction
17	Source	mov eax, [ebp+arg_0]
36	Source	mov eax, [ebp+var_14]
38	Source	mov eax, [ebp+var_14]
44	Source	mov eax, [ebp+var_C]
46	Source	mov eax, [ebp+var_14]
47	Source	mov edx, [eax+edx*4]
48	Source	mov eax, [ebp+var_C]
50	Source	mov eax, [ebp+var_14]
51	Source	mov eax, [eax+edx*4]
53	Source	mov edx, [ebp+var_14]
54	Source	mov edx, [ebp+var_C]
58	Source	mov eax, [ebp+var_C]
61	Source	mov eax, [ebp+var_14]
62	Source	mov edx, [ebp+arg_0]
63	Source	mov eax, [eax+edx*4]
65	Source	mov ebx, [ebp+var_4]
20	Sink	mov [ebp+var_10], edx
26	Sink	mov [ebp+var_1C], 0x10
35	Sink	mov [ebp+var_14], eax
37	Sink	mov dword ptr [eax], 0
41	Sink	mov dword ptr [eax+4], 1
40	Sink	mov [ebp+var_C], 2
55	Sink	mov [eax+edx*4], ebx
63	Sink	mov eax, [eax+edx*4]

There are many possible individual slices that can be calculated from Table 4.3 given the large number of *sources* and *sinks*. A much smaller number of slices can be calculated from the other two binaries. The slices that were relavent to this research were slices that captured the behavior of the array size calculation and the loop. Listings 4.15, 4.16, and 4.19 show the slices that capture the array size and address calculation for each binary.

Table 4.4: Use Case 2: Sources and Sinks for fib() optimization level 1

Line Number	Type	Instruction
10	Source	mov ebx, [ebp+arg_0]
24	Source	mov ecx, [eax+4]
32	Source	mov eax, [esi+ebx*4]
17	Sink	mov dword ptr ds:0[eax*4], 0
18	Sink	mov dword ptr ds:4[eax*4], 1
26	Sink	mov [eax+8], ecx
32	Sink	mov eax, [esi+ebx*4]

Table 4.5: Use Case 2: Sources and Sinks for fib() optimization level 2

Line Number	Type	Instruction
12	Source	mov esi, [ebp+arg_0]
32	Source	mov ecx, [eax+4]
33	Source	mov ebx, [eax]
42	Source	mov edx, [ebp+arg_0]
51	Source	mov eax, [edi+edx*4]
21	Sink	mov dword ptr ds:0[eax*4], 0
22	Sink	mov dword ptr ds:4[eax*4], 1
37	Sink	mov [eax+8], ecx
51	Sink	mov eax, [edi+edx*4]

We use two approaches to generate a slice that captures the loop instructions for each optimization level. The first is a naive approach in which we calculate a backward slice between the functions input value, `arg_0`, and the final assignment to `eax`, the return value. As explained in Section 4.4.4, we perform this analysis only on binaries compiled at optimization levels 1 and 2. Slicing between reading `arg_0` and writing the final `eax` represents a slice from the input to the output. Ultimately, we have to unroll each loop in order to model the linear execution of the assembly language. This is the same limitation we discovered trying to S2E [Chipounov et al. 2011] or BAP [Brumley et al. 2011] for this research. We discuss this further in Section 4.5.4. These slices are listing alongside their semantics in Appendix C.

The second approach takes a slice from the *source* and *sink* inside the loop. Listings 4.18 and 4.19 show these slices from optimization levels 1 and 2 binaries.

Listing 4.15: Backward slice of fib() optimization level 0 from line 17 to line 35

```
mov     eax, [ebp+arg_0]
add     eax, 1
lea     edx, [eax-1]
mov     [ebp+var_10], edx
shl     eax, 2
lea     edx, [eax+3]
mov     eax, 10h
sub     eax, 1
add     eax, edx
mov     [ebp+var_1C], 10h
mov     edx, 0
div     [ebp+var_1C]
imul    eax, 10h
sub     esp, eax
mov     eax, esp
add     eax, 3
shr     eax, 2
shl     eax, 2
mov     [ebp+var_14], eax
```

Listing 4.16: Backward slice of fib() optimization level 1 from line 10 to line 17

```
mov     ebx, [ebp+arg_0]
lea     eax, ds:16h[ebx*4]
and     eax, 0FFFFFFF0h
sub     esp, eax
mov     eax, esp
shr     eax, 2
lea     esi, ds:0[eax*4]
mov     dword ptr ds:0[eax*4], 0
```

Listing 4.17: Backward slice of fib() optimization level 2 from line 12 to line 21

```
mov     esi, [ebp+arg_0]
add     esi, 1
lea     eax, ds:12h[esi*4]
and     eax, 0FFFFFFF0h
sub     esp, eax
mov     eax, esp
shr     eax, 2
mov     dword ptr ds:0[eax*4], 0
```

Listing 4.18: Backward slice of fib() optimization level 1 from line 24 to line 26

```
mov     ecx, [eax+4]
add     ecx, [eax]
mov     [eax+8], ecx
```

Listing 4.19: Backward slice of fib() optimization level 2 from line 32 to line 37

```
mov     ecx, [eax+4]
mov     ebx, [eax]
add     ecx, ebx
add     edx, 1
mov     [eax+8], ecx
```

4.4.3 Step 2: Extracting Semantics

After calculating slices using forward and backward slicing between *sources* and *sinks*, we translate each statement into an intermediate representation using Python. Most of the instructions contained in the slices described above are assignments and mathematical calculations, which simplifies the translation process.

Using symbolic bit vectors to represent unknown register and memory values also simplifies the modeling of certain instructions since the Z3 Python API overloads the corresponding Python functions with functions that mimic the machine instruction. Examples of this are the shifting instructions, `shl` and `slr`, where we are able to model `shl` using the overloaded « operator and `shr` using the overloaded » operator. The Z3 Python API also provides functions such as unsigned division, `UDiv()`, used on line 24 of Listing 4.20 for use with symbolic bit vectors.

Listing 4.20 contains slices from optimization levels 0 and 1 that perform the array size and address calculation and Listing 4.23 contains the same slices from optimization levels 1 and 2. Listings C.1, C.2, C.3, and C.4 show the slices obtained from unrolling the loop in optimization levels 1 and 2, and Listing 4.25 contains the slices that capture the internal loop semantics from optimization levels 1 and 2. These listing also contain the Python code that executes the Z3 solver to test for equality between the pairs of slices.

4.4.4 Step 3: Testing Equality

The first slices we compare are the slices that calculate the size and address for the `fib[]` array. Lines 21-39 of Listing B.1 and lines 14-21 of Listing B.2 calculate the array size and address for the unoptimized binary and the binary compiled at optimization level 1. After slicing and extracting the semantics, we obtain the equations in listing 4.21 as the symbolic values of the array address at the end of each slice. The solver cannot prove these slices are equal and outputs a counterexample of values for `arg_0` and `esp`.

Listing 4.20: Fibonacci array address calculation using optimization levels 0 and 1

```python
from z3 import *

s =  Solver()

esp = BitVec('esp', 32)
#Since both functions modify esp, we create copies
#for each function.
esp_0 = esp
esp_1 = esp
arg_0 = BitVec('arg_0',32)

#fib.c compiled with -m32 -O0
eax = arg_0                 # mov  eax, [ebp+arg_0]
eax = eax + 0x1             # add  eax, 1
edx = eax - 0x1             # lea  edx, [eax-1]
var_10 = edx                # mov  [ebp+var_10], edx
eax = eax << 0x2            # shl  eax, 2
edx = eax + 0x3             # lea  edx, [eax+3]
eax = 0x10                  # mov  eax, 10h
eax = eax -0x1              # sub  eax, 1
eax = eax + edx             # add  eax, edx
var_1C = 0x10               # mov  [ebp+var_1C], 10h
edx = 0                     # mov  edx, 0
eax = UDiv(eax, var_1C)     # div  [ebp+var_1C]
eax = eax * 0x10            # imul eax, 10h
esp_0 = esp_0 - eax         # sub  esp, eax
eax = esp_0                 # mov  eax, esp
#This add instruction is the only semantic difference
#between the two optimization levels.
#Uncommenting this line prevents the solver from
#proveing the equality of these two slices.
```

```
32 eax = eax + 0x3             # add  eax, 3
33 eax = eax >> 0x2            # shr  eax, 2
34 eax = eax << 0x2            # shl  eax, 2
35 fib0 = eax                  # mov  [ebp+var_14], eax
36
37
38 # fib.c -m32 -O1
39 ebx = arg_0                 # mov  ebx, [ebp+arg_0]
40 eax = ebx * 0x4 + 0x16      # lea  eax, ds:16h[ebx*4]
41 eax = eax & 0xFFFFFFF0      # and  eax, 0FFFFFFF0h
42 esp_1 = esp_1 - eax         # sub  esp, eax
43 eax = esp_1                 # mov  eax, esp
44 eax = eax >> 0x2            # shr  eax, 2
45 fib1 = eax * 0x4 + 0        # mov  dword ptr ds:0[eax*4], 0
46 print "Optimization Level 0:"
47 print "      ",fib0
48 print "Optimization Level 1:"
49 print "      ",fib1
50
51 prove (fib0 == fib1)
```

Listing 4.21: Output of Listing 4.20 including Line 32

```
Optimization Level 0:
      (esp - UDiv(15 + (arg_0 + 1 << 2) + 3, 16)*16 + 3 >> 2) << 2
Optimization Level 1:
      (esp - (arg_0*4 + 22 & 4294967280) >> 2)*4 + 0
counterexample
[arg_0 = 210894847, esp = 1016143305]
```

The reason these slices are not equal is that Line 32 of Listing 4.20, `add eax, 3`, causes the slice of instructions from the unoptimized binary to differ semantically from the binary compiled at optimization level 1. This was a calculation inserted by the compiler and, most likely, represents a rounding and byte alignment calculation. This is an example of a semantic area where the source code does not define behavior, but that the compiler is free to make a decision about memory locations and usage. This is a limitation we identified when comparing semantics extracted from data flow. Instructions resulting from a memory operation in a higher level source code language (where explicit memory control is not exposed to the developer) could contain semantic differences between non-optimized and optimized compilations. After removing the `add eax, 3` instruction from the unoptimized slice, the solver is able to prove the equations are equal, shown in Listing 4.22. We cannot definitely determine the significance of this addition instruction within the unoptimized slice, but it illustrates that testing for similar functions using semantics can fail when the compiler introduces differences not controlled by the source code.

Listing 4.22: Output of Listing 4.20 excluding Line 32

```
Optimization Level 0:
      (esp - UDiv(15 + (arg_0 + 1 << 2) + 3, 16)*16 >> 2) << 2
Optimization Level 1:
      (esp - (arg_0*4 + 22 & 4294967280) >> 2)*4 + 0
proved
```

To compare the array address calculation from optimization levels 1 and 2, we compare the slices from Listings 4.16 and 4.17. Listing 4.23 shows the python script that compares this slice with the same slice from the binary compiled at optimization level 1. Listing 4.24 contains the output from Listing 4.23 showing the “proved” result from the solver, meaning these slice are equal.

Listing 4.23: Fibonacci array address calculation using optimization levels 1 and 2

```python
from z3 import *

s = Solver()

############################################################
#fib.c compiled using -m32 -O1
#declare symbolic variables
arg_0 = BitVec("arg_0",32)
esp = BitVec("esp",32)

ebx = arg_0                # mov ebx, [ebp+arg_0]
eax = ebx * 4 + 0x16       # lea eax, ds:16h[ebx*4]
eax = eax & 0xfffffff0     # and eax, 0FFFFFFF0h
esp = esp - eax            #  sub esp, eax
eax = esp                  # mov eax, esp
eax = eax >> 0x2           # shr eax, 2
                           # lea esi, ds:0[eax*4]
fib1 = eax                 # mov dword ptr ds:0[eax*4], 0

############################################################
#fib.c compiled using -m32 -O2
```

```
#declare symbolic variables
arg_0 = BitVec("arg_0",32)
esp = BitVec("esp",32)

esi = arg_0                 # mov esi, [ebp+arg_0]
esi = esi + 1               # add esi, 1
eax = esi*4 + 0x12          # lea eax, ds:12h[esi*4]
eax = eax & 0xfffffff0      # and eax, 0FFFFFFF0h
esp = esp - eax             # sub esp, eax
eax = esp                   # mov eax, esp
eax = eax >> 0x2            # shr eax, 2
                            # cmp [ebp+arg_0], 1
                            # lea edi, ds:0[eax*4]
fib2 = eax                  # mov dword ptr ds:0[eax*4], 0

print "Optimization Level 1:"
print "      ",fib1
print "Optimization Level 2:"
print "      ",fib2

prove (fib1 == fib2)
```

Listing 4.24: Output of Listing 4.25

```
Optimization Level 1:
      esp - (arg_0*4 + 22 & 4294967280) >> 2
Optimization Level 2:
      esp - ((arg_0 + 1)*4 + 18 & 4294967280) >> 2
proved
```

Testing the looping behavior is more difficult than the array calculation. Creating slices according to our method that can be extracted to semantics and solved using an SMT solver is a difficult task because using a symbolic variable for a loop counter will cause the solver to run indefinitely. Our idea of using instructions that affect control flow to create constraints on the data flow was successful but required that we unroll the loop the same number of time in both functions before testing for equality. To our knowledge, no SMT solver supports looping in the way we would need to use it to model looping behavior using symbolic variables without unrolling loops to create non-cyclic models of the instructions.

For the naive slicing approach to capture the loop discussed in Section 4.4.2, We unroll the loop within the *fib()* function 0, 1, 2, and 3 times from the binaries compiled at optimization levels 1 and 2. We use the information gained from control flow to determine constraints for the symbolic variables and unroll the loop equal numbers of times in both binaries, verifying the output after each unrolling. The Python scripts in Appendix C model slices of instructions starting at `arg_0` and ending at the return value of the *fib()* function. Each of the Python scripts in Appendix C illustrates that manually unrolling the loop in the binaries compiled at optimization levels 1 and 2 can prove the slices are equal.

A better solution that does not require unrolling loops is to calculate smaller slices and try to determine if subsets of the function's behavior match. Using the slices from Listings 4.18 and 4.19 we are able to compare a data flow that performs the addition operation contain within the Fibonacci loop, reavealing that the behavior of these two slices is identical. Listing 4.25 shows a Python script testing the slices and semantics using the Z3 SMT solver. Listing 4.26 contains the output from this script.

Listing 4.25: Fibonacci loop semantics from optimization levels 1 and 2

```python
from z3 import *

s = Solver()

############################################################
#fib.c compiled using -m32 -O1
#declare symbolic variables
eax = BitVec("eax",32)
mem = Array("mem", BitVecSort(32), BitVecSort(32))
arg_0 = BitVec("arg_0",32)

ecx = mem[eax+4]                   # mov   ecx, [eax+4]
ecx = mem[eax] + ecx               # add   ecx, [eax]
mem = Store(mem, eax+8, ecx)       # mov   [eax+8], ecx

fib1 = mem

############################################################
#fib.c compiled using -m32 -O2
mem = Array("mem", BitVecSort(32), BitVecSort(32))

ecx = mem[eax+4]                   # mov   ecx, [eax+4]
ebx = mem[eax]                     # mov   ebx, [eax]
ecx = ecx + ebx                    # add   ecx, ebx
mem = Store(mem, eax+8, ecx)       # mov   [eax+8], ecx

fib2 = mem
```

```

print "Optimization Level 1:"
print "      ",fib1
print "Optimization Level 2:"
print "      ",fib2
prove (fib1 == fib2)
```

Listing 4.26: Output of Listing 4.25

```
Optimization Level 1:
      Store(mem, eax + 8, mem[eax] + mem[eax + 4])
Optimization Level 2:
      Store(mem, eax + 8, mem[eax + 4] + mem[eax])
proved
```

4.4.5 Conclusion

Use Case 2 includes a loop that is dependent on an input argument, which made calculating the exact behavior of the loop difficult since the input argument is represented as a symbolic variable. While we were able to prove the entire functions were semantically equal by unrolling the loop a static number of times, this also put unreasonable constraints on the input variable since the input variable decided the number of times the loop is unrolled. A better solution was to capture a smaller slice within the loop to compare the behavior inside the loop. The implications of this approach is that Data Flow Binary Matching is able to match some of the behavior of these functions, but not all of their behavior. This is an acceptable result for our research since a partial match is a better solution than no match at all, which is the result of the other binary matching techniques.

4.5 Use Case 3: Applying Data Flow Binary Differencing to Actual Malware

Use Case 3 applies our research to live malware. We chose this example to provide a real world look at how using Data Flow Binary Differencing might apply to a realistic problem faced by a reverse engineer. We compile the malware from source code at various optimization levels so we can introduce syntactic differences into the malware's functions without changing the semantics. Metamorphic malware uses these same techniques to evade signature-based anti-virus detection techniques without relying on encryption. [Walenstein et al. 2007]

The malware we are analyzing is sdbot version 0.5b. Sdbot is the client software installed on victim computer used to create a botnet, a large collection of infected computers an attacker can use for malicious actions such as launching a distributed denial of service (DDoS) attack. This malware is classified as a Trojan horse, a type of malware that tricks the user into installing itself usually through social engineering. Once installed and running on the victim computer, sdbot opens a backdoor that allows an attacker to perform various malicious actions on the infected system, such as stealing data or taking remote control of the victim computer. Sdbot is controlled through IRC (Internet Chat Relay), by connection to an IRC server and joining a chat room where the attacker is able to issue commands. IRC requires that each user connected to a server have a unique nickname so sdbot generates a random nickname before connecting to a IRC server. This nickname is the identity of each bot in the chat room and how the attacker can interact with each specific bot if desired. We chose the function that randomly generates this nickname as the target of our analysis. The source code for this function is shown in Listing 4.27.

The *rndnick()* function takes one argument, a pointer to a string buffer, returns a pointer to a string buffer, and contains 3 local variables, two integers and a 12 character length array. A number of system calls are used inside this functions. *GetTickCount()* is passed to *srand()* in order to initialize the random number generator. Next, *memset()* writes zeros to the 12 character long array, `nick[]`. A *for()* loop is used to fill the `nick[]` array using random ASCII characters between `nick[0]` and `nick[4]` to `nick[7]` depending on the value of `nl`, followed by a NULL string terminator. This results is a random string of lowercase ASCII character either between 4 and 7 character in length. Finally the 12 characters of `nick[]` are copied to strbuf and the pointer to strbuf is returned.

Listing 4.27: Source code for rndnick function

```c
char * rndnick(char *strbuf)
{
 int n, nl;
 char nick[12];

 srand(GetTickCount());
 memset(nick, 0, sizeof(nick));
 nl = (rand()%3)+4;
 for (n=0; n<nl; n++) nick[n] = (rand()%26)+97;
 nick[n+1] = '\0';

 strncpy(strbuf, nick, 12);
 return strbuf;
}
```

The full assembly language for *rndnick()* compiled at optimization level 0 is shown in Appendix B Listing B.4 and compiled at optimization level 1, in Listing B.5. Figures 4.4 and 4.5 show the Control Flow Graphs for these functions.

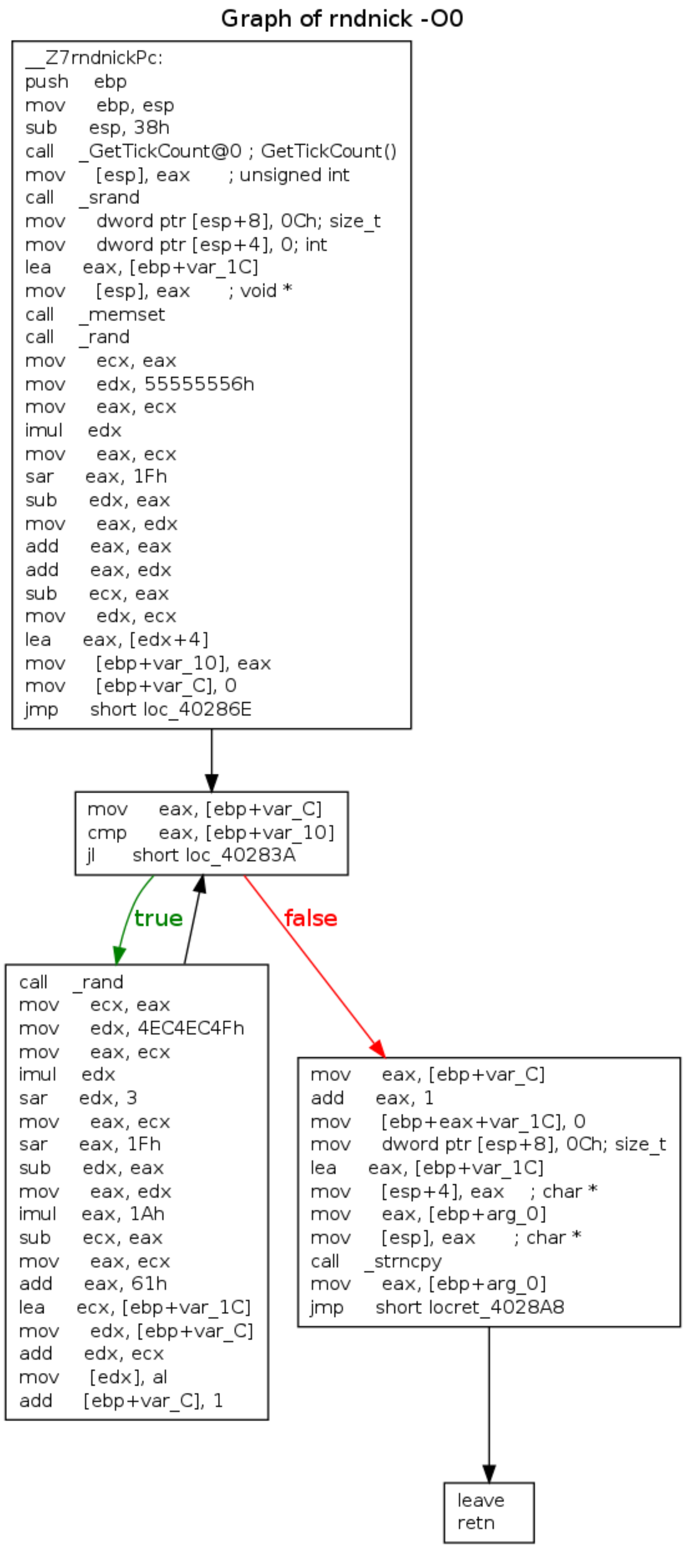
4.5.1 Analysis & Observations

Both *rndnick()* functions from optimization levels 1 and 2 have different control flow graphs so Structural Analysis Matching fails. Table 4.6 shows the structural metadata for *rndnick()*. Also both functions have different instructions for each of their basic blocks, therefore signatures generated for each basic block will be different and Signature Hash Map Matching also fails.

Table 4.6: Structural Analysis of rndnick()

Optimization Level	Number of Blocks	Edges	Calls
0	5	4	6
1	6	7	5

One syntactic and semantic difference we notice between the binaries is the systems call to `memset` has been removed from the binary compiled at optimization level 1. The compiler has decided since the *rndnick()* function does not use all 12 characters it allocates, and since



```
__Z7rndnickPc:
push    ebp
mov     ebp, esp
sub     esp, 38h
call    _GetTickCount@0 ; GetTickCount()
mov     [esp], eax      ; unsigned int
call    _srand
mov     dword ptr [esp+8], 0Ch; size_t
mov     dword ptr [esp+4], 0; int
lea     eax, [ebp+var_1C]
mov     [esp], eax      ; void *
call    _memset
call    _rand
mov     ecx, eax
mov     edx, 55555556h
mov     eax, ecx
imul    edx
mov     eax, ecx
sar     eax, 1Fh
sub     edx, eax
mov     eax, edx
add     eax, eax
add     eax, edx
sub     ecx, eax
mov     edx, ecx
lea     eax, [edx+4]
mov     [ebp+var_10], eax
mov     [ebp+var_C], 0
jmp     short loc_40286E
```

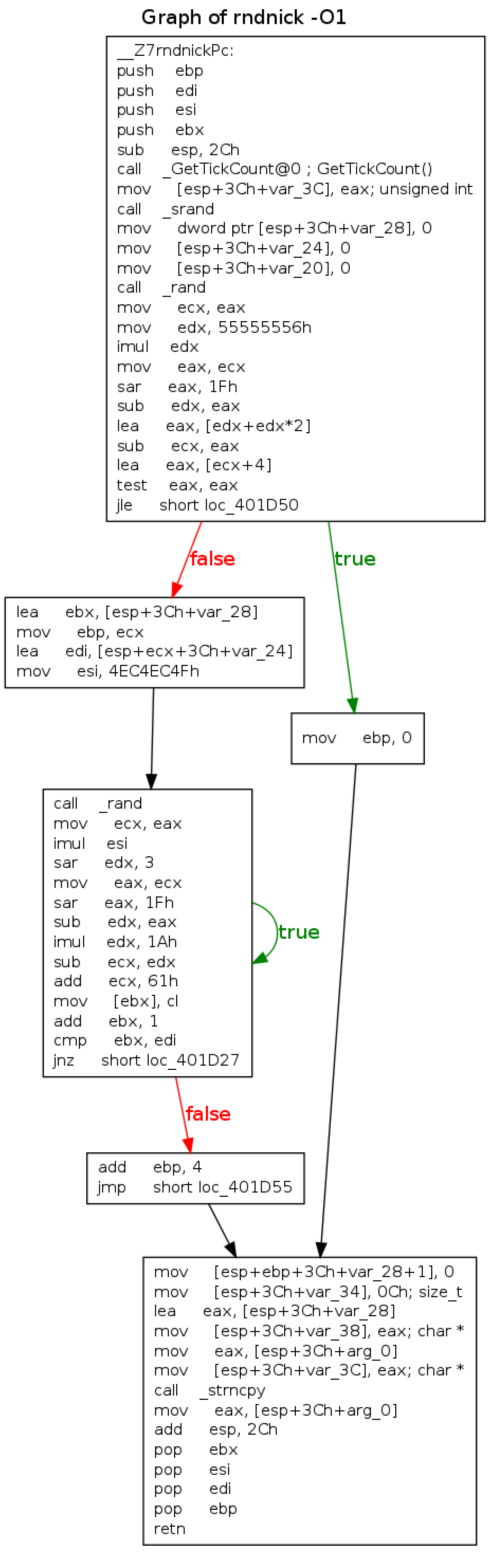
```
mov     eax, [ebp+var_C]
cmp     eax, [ebp+var_10]
jl      short loc_40283A
```

```
call    _rand
mov     ecx, eax
mov     edx, 4EC4EC4Fh
mov     eax, ecx
imul    edx
sar     edx, 3
mov     eax, ecx
sar     eax, 1Fh
sub     edx, eax
mov     eax, edx
imul    eax, 1Ah
sub     ecx, eax
mov     eax, ecx
add     eax, 61h
lea     ecx, [ebp+var_1C]
mov     edx, [ebp+var_C]
add     edx, ecx
mov     [edx], al
add     [ebp+var_C], 1
```

```
mov     eax, [ebp+var_C]
add     eax, 1
mov     [ebp+eax+var_1C], 0
mov     dword ptr [esp+8], 0Ch; size_t
lea     eax, [ebp+var_1C]
mov     [esp+4], eax    ; char *
mov     eax, [ebp+arg_0]
mov     [esp], eax      ; char *
call    _strncpy
mov     eax, [ebp+arg_0]
jmp     short locret_4028A8
```

```
leave
retn
```

Figure 4.4: Control Flow Graph of rndnick() optimization level 0



```
__Z7rndnickPc:
push    ebp
push    edi
push    esi
push    ebx
sub     esp, 2Ch
call    _GetTickCount@0 ; GetTickCount()
mov     [esp+3Ch+var_3C], eax; unsigned int
call    _srand
mov     dword ptr [esp+3Ch+var_28], 0
mov     [esp+3Ch+var_24], 0
mov     [esp+3Ch+var_20], 0
call    _rand
mov     ecx, eax
mov     edx, 55555556h
imul    edx
mov     eax, ecx
sar     eax, 1Fh
sub     edx, eax
lea     eax, [edx+edx*2]
sub     ecx, eax
lea     eax, [ecx+4]
test    eax, eax
jle     short loc_401D50
```

```
lea     ebx, [esp+3Ch+var_28]
mov     ebp, ecx
lea     edi, [esp+ecx+3Ch+var_24]
mov     esi, 4EC4EC4Fh
```

```
mov     ebp, 0
```

```
call    _rand
mov     ecx, eax
imul    esi
sar     edx, 3
mov     eax, ecx
sar     eax, 1Fh
sub     edx, eax
imul    edx, 1Ah
sub     ecx, edx
add     ecx, 61h
mov     [ebx], cl
add     ebx, 1
cmp     ebx, edi
jnz     short loc_401D27
```

```
add     ebp, 4
jmp     short loc_401D55
```

```
mov     [esp+ebp+3Ch+var_28+1], 0
mov     [esp+3Ch+var_34], 0Ch; size_t
lea     eax, [esp+3Ch+var_28]
mov     [esp+3Ch+var_38], eax; char *
mov     eax, [esp+3Ch+arg_0]
mov     [esp+3Ch+var_3C], eax; char *
call    _strncpy
mov     eax, [esp+3Ch+arg_0]
add     esp, 2Ch
pop     ebx
pop     esi
pop     edi
pop     ebp
retn
```

Figure 4.5: Control Flow Graph of rndnick() optimization level 1

line 10 of source code, Listing 4.27, adds a string terminating NULL, zeroing out the array isn't necessary. At optimization level 1, the compiler removes this system call replacing it with a couple of `mov` instructions writing zeros to the start of the `nick[]` array. The intent of the source code was to write zeros to all 12 memory addresses of the `nick[]` array. This is a semantic change internal to the function although is remedied by the `call _strncpy` at the end of the function. The function `_strncpy` will write zeros to the end of the destination if the source string is less than the number of bytes passed as an argument to `_strncpy`. In this case, `_strncpy` is called with 12 bytes as the `num` argument. The `_memset` functions actually performs redundant actions with `_strncpy` so the compiler has removed it.

4.5.2 Step 1: Slicing Instructions

We perform slicing on both binaries in the same way as the previous two use cases. We begin by identifying the *sources* and *sinks* within both binaries. Tables 4.7 and 4.8 show the *sources* and *sinks* from the unoptimized and level 1 optimized binaries, respectively. Line number are from Listings B.4 and B.5.

The `call` instructions are identified as *sources* in both functions. More specifically, the value of `eax` after the call is executed is the data we use when slicing the instructions following the `call` instruction and the arguments used by the `call` instructions are *sinks*. This allows for the capture of data flow to and from a sub-function.

Listings 4.28, 4.29, 4.30, 4.31, 4.32, 4.33, and 4.34 contain the slices obtained from the unoptimized binary and Listings 4.35, 4.36, 4.37, 4.38, and 4.39 show the slices from the level 1 optimized binary.

Listing 4.28, 4.29, 4.33, 4.35, and 4.38 all result from backward slicing from identified input argument to the listed `call` instruction. Backward slicing is the only slicing technique that works for capturing data flow to a called sub-function. We do not initially know how

Table 4.7: Use Case 3: Sources and Sinks for rndnick() optimization level 0

Line number	Type	Instruction
16	Source	call _GetTickCount
17	Source	call _srand
22	Source	call _memset
23	Source	call _rand
43	Source	call _rand
58	Source	mov edx, [ebp+var_C]
64	Source	mov eax, [ebp+var_C]
67	Source	mov eax, [ebp+var_C]
73	Source	mov eax, [ebp+arg_0]
75	Source	call _strncpy
76	Source	mov eax, [ebp+arg_0]
16	Sink	mov [esp], eax
18	Sink	mov dword ptr [esp+8], 0Ch
19	Sink	mov dword ptr [esp+4], 0
21	Sink	mov [esp], eax
37	Sink	mov [ebp+var_10], eax
38	Sink	mov [ebp+var_C], 0
60	Sink	mov [edx], al
69	Sink	mov [ebp+eax+var_1C], 0
70	Sink	mov dword ptr [esp+8], 0Ch
72	Sink	mov [esp+4], eax
74	Sink	mov [esp], eax
76	Sink	mov eax, [ebp+arg_0]

Table 4.8: Use Case 3: Sources and Sinks for rndnick() optimization level 1

Line Number	Type	Instruction
20	Source	call _GetTickCount
22	Source	call _srand
26	Source	call _rand
44	Source	call _rand
70	Source	mov edx, [esp+3Ch+arg_0]
72	Source	call _strncpy
73	Source	mov eax, [esp+3Ch+arg_0]
21	Sink	mov [esp+3Ch+var_3C], eax
23	Sink	mov dword ptr [esp+3Ch+var_28], 0
24	Sink	mov [esp+3Ch+var_24], 0
25	Sink	mov [esp+3Ch+var_20], 0
54	Sink	mov [ebx], cl
66	Sink	mov [esp+ebp+3Ch+var_28+1], 0
67	Sink	mov [esp+3Ch+var_34], 0Ch
69	Sink	mov [esp+3Ch+var_38], eax
71	Sink	mov [esp+3Ch+var_3C], eax
73	Sink	mov eax, [esp+3Ch+arg_0]

far back the arguments are calculated so we must follow the identified input arguments backwards until no more use-define pairs exist in the slice.

Listing 4.30, 4.31, 4.32, 4.36, and 4.37 were generated using forward slicing between a *source* and *sink*. This creates a series of instructions where the definition of the data at the *source* and subsequent use-define pairs influence the data use at the *sink*.

Listing 4.34 and 4.39 are obtained by slicing between the function's input arguments `arg_0` and the function's return values.

Listing 4.28: Optimization Level 0: Slice created from return value of _getTickCount@0 and argument of _srand

```
call  _GetTickCount@0
mov     [esp], eax ; unsigned int
call    _srand
```

Listing 4.29: Optimization Level 0: Slice created from arguments to _memset

```
mov     dword ptr [esp+8], 0Ch ; size_t
mov     dword ptr [esp+4], 0 ; int
lea     eax, [ebp+var_1C]
mov     [esp], eax      ; void *
call    _memset
```

Listing 4.30: Optimization Level 0: Slice created from return value of _rand at line 23

```
call    _rand
mov     ecx, eax
mov     eax, ecx
imul    edx
mov     eax, ecx
sar     eax, 1Fh
sub     edx, eax
mov     eax, edx
add     eax, eax
add     eax, edx
sub     ecx, eax
mov     edx, ecx
lea     eax, [edx+4]
mov     [ebp+var_10], eax
```

Listing 4.31: Optimization Level 0: Slice created from return value of _rand on line 43

```
call    _rand
mov     ecx, eax
mov     eax, ecx
imul    edx
sar     edx, 3
mov     eax, ecx
sar     eax, 1Fh
sub     edx, eax
mov     eax, edx
imul    eax, 1Ah
sub     ecx, eax
mov     eax, ecx
add     eax, 61h
mov     [edx], al
```

Listing 4.32: Optimization Level 0: Slice created from source at line 67

```
mov     eax, [ebp+var_C]
add     eax, 1
mov     [ebp+eax+var_1C], 0
```

Listing 4.33: Optimization Level 0: Slice created from the arguments to _strncpy at line 75

```
mov     dword ptr [esp+8], 0Ch ; size_t
lea     eax, [ebp+var_1C]
mov     [esp+4], eax    ; char *
mov     eax, [ebp+arg_0]
mov     [esp], eax      ; char *
call    _strncpy
```

Listing 4.34: Optimization Level 0: Slice created from `arg_0` and return value.

```
mov     eax, [ebp+arg_0]
retn
```

Listing 4.35: Optimization Level 1: Slice created from return value of _getTickCount@0 and argument of _srand

```
call  _GetTickCount@0
mov     [esp+3Ch+var_3C], eax ; unsigned int
call    _srand
```

Listing 4.36: Optimization Level 1: Slice created from return value of _rand at line 26

```
call    _rand
mov     ecx, eax
imul    edx
mov     eax, ecx
sar     eax, 1Fh
sub     edx, eax
lea     eax, [edx+edx*2]
sub     ecx, eax
lea     eax, [ecx+4]
```

Listing 4.37: Optimization Level 1: Slice created from return value of _rand at line 44

```
call     _rand
mov      ecx, eax
imul     esi
sar      edx, 3
mov      eax, ecx
sar      eax, 1Fh
sub      edx, eax
imul     edx, 1Ah
sub      ecx, edx
add      ecx, 61h
mov      [ebx], cl
```

Listing 4.38: Optimization Level 1: Slice created from arguments to _strncpy

```
mov      [esp+3Ch+var_34], 0Ch ; size_t
lea      eax, [esp+3Ch+var_28]
mov      [esp+3Ch+var_38], eax ; char *
mov      eax, [esp+3Ch+arg_0]
mov      [esp+3Ch+var_3C], eax ; char *
call     _strncpy
```

Listing 4.39: Optimization Level 1: Slice created from `arg_0` and return value

```
mov      eax, [esp+3Ch+arg_0]
retn
```

4.5.3 Step 2: Extracting Semantics

As with the previous use cases, we take each line of the slice and transform its behavior into Python code using symbolic variables where we do not know actual values. We compare and analyze each slice from Listings 4.28 to 4.39 in Section 4.5.4.

Translating the `imul` instruction to Python was cumbersome since the semantics of the instruction differ depending on the number of operands and the operands are symbolic. According to [Intel Corporation 2014], the `imul` instruction, when used with a single operand, takes the operand and multiplies it with the contents of the `eax` register placing the result in the concatenation of the edx and eax registers. In mathematical terms, for imul esi this looks like esi*eax = [edx:eax] where : represents concatenation of the two registers. This was difficult to model explicitly in Python since we are using symbolic variables, but the Z3 solver's Python API provides a few functions that allow us to implement the imul instruction accurately. We were able to zero extend the two factors so that the result product was actually 64-bits wide. Then we extracted the two 32-bit halves of the product into the edx and eax registers. Listing 4.40 shows the results of this implementation.

Listing 4.40: Modeling the x86 “imul esi” instruction in Python

```
r = ZeroExt(64,esi) * ZeroExt(64,eax)
edx = Extract(63,32,r)
eax = Extract(31,0,r)
```

4.5.4 Step 3: Testing for Equality

Comparing the slices from Listings 4.28 to 4.35, 4.33 to 4.38,and 4.34 to 4.39, we can see that these slices are identical, if certain variables are equal between the two optimization levels, assuming data exists at the same location in both functions.

Comparing Listings 4.28 to 4.35, if esp from 4.28 equals esp+3Ch+var_3C in 4.35, the slices are identical. The label var_3C is inserted by IDA and represents a constant value, -3Ch. 3Ch+var_3C means 3Ch-3Ch = 0 so these slices are equal since esp is the same as esp+0

Considering 4.33 and 4.38, if the equations in table 4.9 are valid, with values on the left from 4.33 and values on the right from 4.38, these slices are also equal.

We have already discussed that the var_ labels followed by a hex value represents subtraction by that hex value, so we can the the first, third, and last equations in Table 4.9 are equal when we replace the var_ with the negative hex value and solve.

Table 4.9: Equations that make Listings 4.33 and 4.38 equal.

esp+8	==	esp+3Ch+var_34
ebp+var_1C	==	esp+3Ch+var_28
esp+4	==	esp+3Ch+var_38
ebp+arg_0	==	esp+3Ch+arg_0
esp	==	esp+3Ch+var_3C

We can confirm the second and fourth equations are equal by looking at the instructions that modify `esp` at the start of the *rndnick()* function from the binary compiled at optimization level 0 shown in Listing 4.41. At the start of the *rndnick()* function, the `ebp` and `esp` registers point to the base of the stack. Once data is pushed on the stack the `esp` register will be decremented so that it points to the next free memory address on the stack. The `push` instruction in Listing 4.41 subtracts 4 bytes from `esp` and the `sub exp, 38h` instruction subtracts `38h` bytes from `esp`. The difference between `ebp` and `esp` is now `-3Ch` bytes. This means `ebp` in the *rndnick()* function from the unoptimized binary is equal to `esp+3Ch` in *rndnick()* from the level 1 optimized binary. This proves the second and fourth equations in Table 4.9 are equal. By solving each of the equations in Table 4.9 we prove the slices in Listings 4.33 and 4.38 are equal, meaning both *rndnick()* functions pass the same arguments to `_strncpy`.

The slices in Listings 4.34 and 4.39 are equal if `epb` in 4.34 equals `esp+3Ch` in 4.39. We just proved this from the previous analysis so we know these slices are also equal.

Listing 4.41: Calculating esp in unoptimized rndnick()

```
push     ebp
mov      ebp, esp
sub      esp, 38h
```

Next we compare the slices in Listings 4.30 and 4.31 from the unoptimized binary to the slices in Listings 4.36 and 4.37 from the level 1 optimized binary. These slice represent the data flow resulting from the `call _rand` instructions. After translating these slices to Python, we were able to prove their equality using the same process described in the other use cases. Listing 4.42 and 4.43 contain the full Python scripts these slices and Listing 4.44 and 4.45 show the output of these scripts.

Listing 4.42: Python script that compares first _rand call in the unoptimized rndnick() to optimization level 1 rndnick()

```
from z3 import *

rand = BitVec('rand', 32)
unk = BitVec('unk', 32)
s.add(rand >= 0)
########################################
# sdbox05b -O0

eax = rand                          # call _rand
ecx = eax                           # mov ecx, eax
edx = unk                           # edx is unknown
# assume edx matches unknown input from other function
                                    # imul edx
r = ZeroExt(64,edx) * ZeroExt(64,eax)
edx = Extract(63,32,r)
eax = Extract(31,0,r)

eax = ecx                           # mov eax, ecx
eax = LShR(eax, 31)                 # sar eax, 1Fh
edx = edx - eax                     # sub edx, eax
eax = edx                           # mov eax, edx
eax = eax + eax                     # add eax, eax
eax = eax + edx                     # add eax, edx
ecx = ecx - eax                     # sub ecx, eax
edx = ecx                           # mov edx, ecx
eax = eax + 4                       # lea eax, [edx+4]
var_10 = eax                        # mov [ebp+var_10], eax
rndnick0 = var_10
print "Optimization level 0: "
print rndnick0
########################################
# sdbox05b -O1

eax = rand                          # call _rand
ecx = eax                           # mov ecx, eax
edx = unk                           # edx is unknown
# assume edx matches unknown input from other function
                                    # imul edx
r = ZeroExt(64,edx) * ZeroExt(64,eax)
edx = Extract(63,32,r)
eax = Extract(31,0,r)

eax = ecx                           # mov eax, ecx
eax = LShR(eax, 31)                 # sar eax, 1Fh
edx = edx - eax                     # sub edx, eax
eax = edx + edx*2                   # lea eax, [edx+edx*2]
```

```
ecx = ecx - eax                   # sub ecx, eax
eax = eax + 4                     # lea eax, [ecx+4]
rndnick1 = eax
print "Optimization level 1: "
print rndnick1

prove (rndnick0 == rndnick1)
```

Listing 4.43: Python script that compares the second _rand call in the unoptimized rndnick() to optimization level 1 rndnick()

```
from z3 import *

s = Solver()

var_1C = BitVec('var_1C', 32)
var_C = BitVec('var_C', 32)
rand = BitVec('rand', 32)
mem = Array("mem", BitVecSort(32), BitVecSort(8))

unk = BitVec("unk",32)

s.add(rand >= 0)
########################################
# sdbox05b -O0
eax = rand                        # call rand
ecx = eax                         # mov  ecx, eax
edx = unk                         # edx is undefined
# assume edx matches unknown input from other function
eax = ecx                         # mov  eax, ecx
                                  # imul edx
r = ZeroExt(64,edx) * ZeroExt(64,eax)
edx = Extract(63,32,r)
eax = Extract(31,0,r)

edx = LShR(edx, 3)                # sar  edx, 3
eax = ecx                         # mov  eax, ecx
eax = LShR(eax,31)                # sar  eax, 1Fh
edx = edx - eax                   # sub  edx, eax
eax = edx                         # mov  eax, edx
eax = eax * 0x1A                  # imul eax, 1Ah
ecx = ecx - eax                   # sub  ecx, eax
eax = ecx                         # mov  eax, ecx
eax = eax + 0x61                  # add  eax, 61h
ecx = var_1C                      # lea  ecx, [ebp+var_1C]
edx = var_C                       # mov  edx, [ebp+var_1C]
edx = edx + ecx                   # add  edx, ecx
                                  # mov  [edx], al
mem = Store(mem, edx, Extract(7,0,eax))
rndnick0 = Extract(7,0,eax)
print "Optimization level 0: "
print rndnick0
```

```
##########################################
# sdbox05b -O1
ebx = BitVec('var_28', 32)
mem = Array("mem", BitVecSort(32), BitVecSort(8))

eax = rand                          # call _rand
ecx = eax                           # mov  ecx, eax
                                    # imul esi
esi = unk                           # esi is unknown
# assume esi matches unknown input from other function
r = ZeroExt(64,esi) * ZeroExt(64,eax)
edx = Extract(63,32,r)
eax = Extract(31,0,r)

edx = LShR(edx, 3)                  # sar  edx, 3
eax = ecx                           # sub  edx, eax
eax = LShR(eax,31)                  # sar  eax, 1Fh
edx = edx - eax                     # sub  ecx, edx
edx = edx * 0x1A                    # imul edx, 1Ah
ecx = ecx - edx                     # sub  ecx, edx
ecx = ecx + 0x61                    # add  ecx, 61h
                                    # mov  [ebx], cl
mem = Store(mem,ebx,Extract(7,0,ecx))

rndnick1 = Extract(7,0,ecx)
print "Optimization level 1: "
print rndnick1

prove (rndnick0 == rndnick1)
```

Listing 4.44: Output of Listing 4.42

```
Optimization level 0:
Extract(63, 32, ZeroExt(64, unk)*ZeroExt(64, rand)) -
LShR(rand, 31) +
Extract(63, 32, ZeroExt(64, unk)*ZeroExt(64, rand)) -
LShR(rand, 31) +
Extract(63, 32, ZeroExt(64, unk)*ZeroExt(64, rand)) -
LShR(rand, 31) +
4
Optimization level 1:
Extract(63, 32, ZeroExt(64, unk)*ZeroExt(64, rand)) -
LShR(rand, 31) +
(Extract(63, 32, ZeroExt(64, unk)*ZeroExt(64, rand)) -
 LShR(rand, 31))*
2 +
4
proved
```

Listing 4.45: Output of Listing 4.43

```
Optimization level 0:
Extract(7,
        0,
        rand -
        (LShR(Extract(63,
                      32,
                      ZeroExt(64, unk)*ZeroExt(64, rand)),
              3) -
         LShR(rand, 31))*
        26 +
        97)
Optimization level 1:
Extract(7,
        0,
        rand -
        (LShR(Extract(63,
                      32,
                      ZeroExt(64, unk)*ZeroExt(64, rand)),
              3) -
         LShR(rand, 31))*
        26 +
        97)
proved
```

We have proven equality of all the slices created from the level 1 optimized binary, but we have two slices, Listing 4.29 and 4.32, remaining from the unoptimized binary that we could not match. This means the data flow identified by these two slices was either not captured by the slices we created in the optimized binary or a semantic change exists. For an automated implementation of our technique, we would alert the user of these non-matched slices as well as the *sources* and *sinks* that do not belong to a matched slice.

We manually analyze these slices to understand the reason they were not matched. The slice in Listing 4.32 represents writing a zero to the end of the `nick[]` array. This same behavior is represented at line 66 of *rndnick()* from the level 1 optimized binary. Employing the same approach we used to prove Listing 4.33 and 4.38 are equal, we test that the calculated addresses this slice and this instruction are equal. This means solving the equation `ebp + ebp +var_C + 1 + var_1C == esp + ebp + 3Ch + var_28 +1`. Setting `ebp` as constant, the only remaining variable is `esp` from the optimization level 1 binary. By analyzing the instructions at the top of *rndnick()* that manipulate `esp`, we determine that `ebp = esp - 3Ch`, which plugged into the equation above satisfies the equally statement, meaning the slice represents the same behavior as the instruction.

The remaining slice, Listing 4.29, contains the list of instructions that setup the call to `_memset` discussed in Section 4.5.1. This missing data flow does represent a semantic difference, but after further analysis we determine that the behavior of these instructions were actually redundant with the `call _strncpy` instructions which explains why the compiler removed this data flow. Ultimately, this change did not represent a significant difference but is a semantic difference that exists between the two binaries.

4.5.5 Conclusion

This use case illustrates that semantic differencing can be used on real world problems faced by real world security engineers and reverse engineers. We were able to show how Data Flow Binary Differencing handles the `call` instruction and creates slices to capture behavior surrounding the use of sub-procedures. Although this use case also includes looping, we were able to prove the compared functions contained the same data flows without having to unroll the loops since linear slices within the loops were captured by the use of *sources* and *sinks*.

Chapter 5

Research Conclusion and Future Work

Our research goal was to provide another means of testing two functions to determine if they are similar, a common requirement in reverse engineering binary software. We compared our research to fundamental, yet very different, approaches used to compare functions, Symbol Name Matching, Signature Hash Matching, and Structural Analysis Matching. Specifically, our research goal was to be able to prove that two functions were actually similar after these matching techniques failed to show the function's similarities. By focusing on data flow, we were able to use the semantics of the function to test if they perform the same actions.

5.1 Research Contributions

Our research fills a gap in the currently available techniques for binary differencing. Table 5.1 compares the three techniques discussed in Chapter 2 with our technique. Symbol Name Matching is useful for analysis that focuses on the symbol names, but does not have the capability to detect differences within Functions, Instructions, or Semantics. Signature Hash Map Matching, Structural Analysis Matching, and Data Flow Binary Differencing can detect differences present in the Functions, but Structural Analysis Matching fails for functional changes that do not alter the control flow graph. Only Signature Hash Map Matching and Data Flow Binary Differencing are able to detect differences within a basic block. Finally, our technique is the only available approach that allow for comparing semantics using data flow.

Table 5.1: Summary of Binary Differencing Techniques

Technique	Compares				
	Symbols	Functions	Basic Blocks	Instructions	Semantics
Symbol Name Matching	Y	N	N	N	N
Signature Hash Map Matching	N	Y	Y	Y	N
Structural Analysis Matching	N	Y	N	N	N
Data Flow Binary Differencing	N	Y	Y	Y	Y[1]

Using data flow to identify semantically identical behavior is the key contribution for our research. Our technique does not depend on the structure or the syntax of the instructions, only the effects of the structure and syntax on the data. We do not consider this to be "the" answer to binary differencing, yet it can be an additional tool to aid the reverse engineering of software. When used along side other binary matching technique, Data Flow Binary Differencing can be applied where other techniques fail, to gain a higher confidence that two functions contain similarities or differences. We also were able to discover semantic differences introduced by the compiler due to optimization. Both Use Cases 2 and 3 contained semantic differences between compiled binaries. While the primary use of Data Flow Binary Matching is to detect semantic similarities between binaries, we also show that this technique can detect semantic differences.

5.2 Limitations and Challenges

The largest challenge our research faced was figuring out how to deal with the loops in Use Case 2 (Fibonacci) and Use Case 3 (sdbot's *rndnick()* function). Our solutions for Use Case 2 were, first unroll the loops and compare each unrolling to each other starting at the input argument and ending with the return value of the function, and second to calculate a slice from within the loop and representing unknown values as symbolic variables. Both methods were able to prove the calculated slices were equal. By unrolling the loop, we were able to symbolically execute the entire data flow from input to output of the function. A better solution was to look inside the loops for data flow and compare the semantics of

[1]Using data flow.

the data flow inside each loop. This does not give us a complete view of the behavior of the functions, but is enough to determine that the two functions are similar, achieving our research goal.

The loop contained in Use Case 3 did not create the same level of challenge as the loop in Use Case 2. The primary reason for this difference is the loop index in Use Case 2 was derived from the input argument for the function and had to be represented using a symbolic variable in our analysis. Had we implement the loop in Use Case 2 as it was derived directly from the semantics of the assembly language and if the SMT solver was able to loop over these statements, the solver would never finish since the loop terminating condition is symbolic. The same problem did not occur in Use Case 3 because the semantics within the loop of Use Case 3 could be contained within a single data flow. The loop index and the loop terminating condition are not part of the data flow inside the loop statements.

Another challenge we faced and were not able to overcome was comparing the calculation of the memory array in Use Case 2 between the optimization level 0 and 1 binaries. Our conclusion is that the two calculations are actually different. The compiler is freely able to calculate memory locations and addresses as long as the end result follows the intent of the source code. In Use Case 2, the unoptimized binary uses a slightly different method to calculate the starting memory address for the local array than the optimized binaries. Although this is a limitation of the Data Flow Binary Differencing technique, this is still a semantic difference discovered by our technique.

5.3 Future Work

The next step of our research is to automate the process of creating slices, transforming slices to an intermediate language, and then testing the slices for equality. The most likely path for this continuation of our research would be to incorporate Data Flow Binary Differencing into a tool like S2E [Chipounov et al. 2011] and BAP [Brumley et al. 2011], but these tools would need to be modified to add the ability for to analyze multiple binaries at one time or be able to extract semantics and reuse them in the analysis of a different binary.

We believe that using semantic for reverse engineering is a very important research topic for the future. Our look at using semantics for binary differencing is just one area where applying semantics to reverse engineering can be used. Our work could be expanded to look at creating signatures based on semantics to be able to detect the presence of similar code in many binaries and allow a reverse engineer to detect code reuse or the theft of proprietary algorithms.

An area we did not include in this research was inter-procedural slicing. Future research should include research on how to implement inter-procedural slicing for Data Flow Binary Differencing so that we could also detect function in-lining. Currently we can only detect this as a semantic difference, but for a completely in-lined function, we should be able to use semantics to determine if the in-lining actually creates any differences. In order to do this we need to be able to begin a slice prior to a `call` instruction, follow the execution through the sub-procedure, and, using the return value of the sub-procedure, continue slicing until our *sink* is reached.

Beyond expanding the scope of this research, we also identified a few more narrow opportunities for further research. As we discuss in Section 5.1, an interesting contribution of this research was the discovery of semantical differences introduced by the compiler. The potential exists for compiler optimizations to introduce security vulnerabilities detectable as semantic differences. This research area could help discover very hard to detect vulnerabilities that result from optimizations, as well as classifying "safe" and "unsafe" compiler optimization and under what circumstances certain optimization could introduce vulnerabilities.

We could also further investigate semantic differences, such as the array address calculation in Use Case 2, that do not affect the program state. Being able to identify these types of differences could allow for a more precise implementation of Data Flow Binary Differencing that is able to ignore these slight differences or at least report their existence to the reverse engineer. Knows that a semantic difference exists but that it doesn't not affect the program state, such as placing a data structure at a byte higher address than a non-optimized implementation, allows the reverse engineer to focus on other important differences or at least judge the impact of this semantic change in the context of the rest of the program state.

Beyond Data Flow Binary Differencing, we also identified a few areas related to symbolic execution that warrant further research. Currently, an SMT solver designed for reverse engineering does not exist. There are many assembly language constructs that are difficult to translate into the solver specific language such as loops and jumps. Having a more natural means of expressing these constructs in a language an SMT solver can reason about would be a good addition to the currently available tools for program analysis using symbolic execution.

Bibliography

[Balakrishnan and Reps 2010] Gogul Balakrishnan and Thomas Reps. 2010. WYSINWYX: What you see is not what you eXecute. *ACM Transactions on Programming Languages and Systems* 32, 6 (8 2010), 1–84.

[Barat et al. 2013] Marius Barat, Dumitru-Bogdan Prelipcean, and DragoÅ§ Teodor GavriluÅč. 2013. A study on common malware families evolution in 2012. *Journal of Computer Virology and Hacking Techniques* 9, 4 (10 2013), 171–178.

[2011] David Brumley, Ivan Jager, Thanassis Avgerinos, and Edward J. Schwartz. 2011. BAP: a binary analysis platform, In Computer Aided Verification. *Computer Aided Verification* (7 2011), 463–469.

[Cavusoglu et al. 2006] Huseyin Cavusoglu, Hasan Cavusoglu, and Jun Zhang. 2006. Economics of Security Patch Management. (2006).

[Chikofsky and Cross 1990] E.J. Chikofsky and J.H. Cross. 1990. Reverse engineering and design recovery: a taxonomy. *IEEE Software* 7, 1 (1 1990), 13–17.

[Chipounov et al. 2011] Vitaly Chipounov, Volodymyr Kuznetsov, and George Candea. 2011. S2E: a platform for in-vivo multi-path analysis of software systems, In Proceedings of the 16th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS XVI). *Proceedings of the 16th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS XVI)* (3 2011), 265–278. http://dl.acm.org/citation.cfm?id=1961296.1950396

[Dullien and Rolles 2005] Thomas Dullien and Rolf Rolles. 2005. Graph-based comparison of Executable Objects, In SÃĽcuritÃĽ des Technologies de lâĂŹInformation et des Communications (SSTIC). *SÃĽcuritÃĽ des Technologies de lâĂŹInformation et des Communications (SSTIC)* (2005).

[Eagle 2011] Chris Eagle. 2011. *The IDA Pro Book: The Unofficial Guide to the World's Most Popular Disassembler.* No Starch Press, San Francisco. 672 pages.

[Economou 2009] Nicolas Economou. 2009. Heuristics applied to Binary Diffing, In EkoParty. *EkoParty* (2009).

[Eilam 2005] Eldad Eilam. 2005. *Reversing: Secrets of Reverse Engineering.* Wiley. 624 pages.

[Flake 2004] Halvar Flake. 2004. Structural Comparison of Executable Objects, In Detection of Intrusions and Malware & Vulnerability Assessment (DIMVA), GI SIG SIDAR Workshop. *Detection of Intrusions and Malware & Vulnerability Assessment (DIMVA), GI SIG SIDAR Workshop* 46 (2004), 161–173.

[Fluri et al. 2007] Beat Fluri, Michael Wuersch, Martin PInzger, and Harald Gall. 2007. Change Distilling:Tree Differencing for Fine-Grained Source Code Change Extraction. *IEEE Transactions on Software Engineering* 33, 11 (11 2007), 725–743.

[Gao et al. 2008] Debin Gao, Michael K Reiter, and Dawn Song. 2008. BinHunt : Automatically Finding Semantic Differences in Binary Programs. *International Conference on Information and Communication Security* (2008), 238–255.

[Hex Rays 2014] Hex Rays. 2014. IDA Pro. (2014). `https://www.hex-rays.com/products/ida/` https://www.hex-rays.com/products/ida/.

[Hirschberg 1977] Daniel S. Hirschberg. 1977. Algorithms for the Longest Common Subsequence Problem. *J. ACM* 24, 4 (10 1977), 664–675.

[Hunt and Szymanski 1977] James W. Hunt and Thomas G. Szymanski. 1977. A fast algorithm for computing longest common subsequences. *Commun. ACM* 20, 5 (5 1977), 350–353.

[Intel Corporation 2014] Intel Corporation. 2014. *Intel 64 and IA-32 Architectures Software Developer's Manual Combined Volumes 2A, 2B, and 2C: Instruction Set Reference, A-Z.* Vol. 2. `http://www.intel.com/content/www/us/en/processors/architectures-software-developer-manuals.html`

[Jackson and Rollins 1994] Daniel Jackson and Eugene J. Rollins. 1994. Chopping: A Generalization of Slicing. *Carnegie Mellon Technical Paper* CMU-CS-94, 169 (7 1994). `http://dl.acm.org/citation.cfm?id=865125`

[Jiang and Zhou 2013] Xuxian Jiang and Yajin Zhou. 2013. *Android Malware.* Springer New York, New York, NY. 44 pages.

[Kagdi et al. 2007] Huzefa Kagdi, Michael L. Collard, and Jonathan I. Maletic. 2007. A survey and taxonomy of approaches for mining software repositories in the context of software evolution. *Journal of Software Maintenance and Evolution: Research and Practice* 19, 2 (3 2007), 77–131.

[Maletic and Collard 2004] J.I. Maletic and M.L. Collard. 2004. Supporting source code difference analysis, In 20th IEEE International Conference on Software Maintenance, 2004. Proceedings. *20th IEEE International Conference on Software Maintenance, 2004. Proceedings.* (2004), 210–219.

[Microsoft Research 2014] Microsoft Research. 2014. Z3. (2014). `http://z3.codeplex.com/` Z3 is a high-performance theorem prover being developed at Microsoft Research.

[Miller and Myers 1985] Webb Miller and Eugene W. Myers. 1985. A file comparison program. *Software: Practice and Experience* 15, 11 (11 1985), 1025–1040.

[Oh 2009] Jeongwook Oh. 2009. Fight against 1-day exploits : Diffing Binaries vs Anti-diffing Binaries, In Black Hat. *Black Hat* (2009).

[Schwartz et al. 2010] Edward J. Schwartz, Thanassis Avgerinos, and David Brumley. 2010. All You Ever Wanted to Know about Dynamic Taint Analysis and Forward Symbolic Execution (but Might Have Been Afraid to Ask). *2010 IEEE Symposium on Security and Privacy* (2010), 317–331.

[Thummalapenta et al. 2009] Suresh Thummalapenta, Luigi Cerulo, Lerina Aversano, and Massimiliano Di Penta. 2009. An empirical study on the maintenance of source code clones. *Empirical Software Engineering* 15, 1 (3 2009), 1–34.

[Walenstein et al. 2007] Andrew Walenstein, Rachit Mathur, Mohamed R. Chouchane, and Arun Lakhotia. 2007. The Design Space of Metamorphic Malware, In 2nd International Conference on i-Warfare and Security (ICIW 2007). *2nd International Conference on i-Warfare and Security (ICIW 2007)* (2007), 241–248. `http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.69.486`

[Wang et al. 2000] Zheng Wang, Ken Pierce, and Scott McFarling. 2000. BMAT - A Binary Matching Tool for Stale Profile Propagation. *Journal of Instruction-Level Parallelism* 2 (2000).

Appendices

Appendix A

Source Code

Listing A.1: Hello World source code

```c
#include<stdio.h>

int getNext(int num);

int main(){
    int i=0;

    while (i < 3){
      i = getNext(i);
      printf("%s", "Hello World!\n");
        }
        return 0;
}

int getNext(int num){
        return num++;
}
```

Listing A.2: Source code for fib.c

```c
#include<stdio.h>

int fib(int n)
{
  /* Declare an array to store fibonacci numbers. */
  int f[n+1];
  int i;

  /* 0th and 1st number of the series are 0 and 1*/
  f[0] = 0;
  f[1] = 1;

  for (i = 2; i <= n; i++)
  {
      /* Add the previous 2 numbers in the series
         and store it */
      f[i] = f[i-1] + f[i-2];
  }

  return f[n];
}

int main ()
{
  int n = 12;
  printf("%d", fib(n));
  return 0;
}
```

Appendix B
Assembly Language

Listing B.1: Assembly of fib.c compiled with -O0

```
; =========== S U B R O U T I N E =============
; Attributes: bp-based frame
                public fib
fib             proc near
var_1C          = dword ptr -1Ch
var_14          = dword ptr -14h
var_10          = dword ptr -10h
var_C           = dword ptr -0Ch
var_4           = dword ptr -4
arg_0           = dword ptr  8
                push    ebp
                mov     ebp, esp
                push    ebx
                sub     esp, 24h
                mov     eax, esp
                mov     ecx, eax
                mov     eax, [ebp+arg_0]
                add     eax, 1
                lea     edx, [eax-1]
                mov     [ebp+var_10], edx
                shl     eax, 2
                lea     edx, [eax+3]
                mov     eax, 10h
                sub     eax, 1
                add     eax, edx
                mov     [ebp+var_1C], 10h
                mov     edx, 0
                div     [ebp+var_1C]
                imul    eax, 10h
                sub     esp, eax
                mov     eax, esp
                add     eax, 3
                shr     eax, 2
                shl     eax, 2
                mov     [ebp+var_14], eax
                mov     eax, [ebp+var_14]
                mov     dword ptr [eax], 0
                mov     eax, [ebp+var_14]
                mov     dword ptr [eax+4], 1
                mov     [ebp+var_C], 2
                jmp     short loc_80484A9
; ----------------------------------------------
loc_8048481:
```

```
                  mov     eax, [ebp+var_C]
                  lea     edx, [eax-1]
                  mov     eax, [ebp+var_14]
                  mov     edx, [eax+edx*4]
                  mov     eax, [ebp+var_C]
                  lea     ebx, [eax-2]
                  mov     eax, [ebp+var_14]
                  mov     eax, [eax+ebx*4]
                  lea     ebx, [edx+eax]
                  mov     eax, [ebp+var_14]
                  mov     edx, [ebp+var_C]
                  mov     [eax+edx*4], ebx
                  add     [ebp+var_C], 1
loc_80484A9:
                  mov     eax, [ebp+var_C]
                  cmp     eax, [ebp+arg_0]
                  jle     short loc_8048481
                  mov     eax, [ebp+var_14]
                  mov     edx, [ebp+arg_0]
                  mov     eax, [eax+edx*4]
                  mov     esp, ecx
                  mov     ebx, [ebp+var_4]
                  leave
                  retn
fib               endp
```

Listing B.2: Assembly of fib.c compiled with -O1

```
; =========== S U B R O U T I N E ===============
; Attributes: bp-based frame
                  public fib
fib               proc near
arg_0             = dword ptr  8
                  push    ebp
                  mov     ebp, esp
                  push    esi
                  push    ebx
                  mov     ebx, [ebp+arg_0]
                  lea     eax, ds:16h[ebx*4]
                  and     eax, 0FFFFFFF0h
                  sub     esp, eax
                  mov     eax, esp
                  shr     eax, 2
                  lea     esi, ds:0[eax*4]
                  mov     dword ptr ds:0[eax*4], 0
                  mov     dword ptr ds:4[eax*4], 1
                  cmp     ebx, 1
                  jle     short loc_8048470
                  mov     eax, esi
                  mov     edx, 2
loc_804845E:
                  mov     ecx, [eax+4]
                  add     ecx, [eax]
```

```
                mov     [eax+8], ecx
                add     edx, 1
                add     eax, 4
                cmp     ebx, edx
                jge     short loc_804845E
loc_8048470:
                mov     eax, [esi+ebx*4]
                lea     esp, [ebp-8]
                pop     ebx
                pop     esi
                pop     ebp
                retn
fib             endp
```

Listing B.3: Assembly of fib.c compiled with -O2

```
; ============ S U B R O U T I N E ============
; Attributes: bp-based frame
                public fib
fib             proc near
arg_0           = dword ptr  8
                push    ebp
                mov     ebp, esp
                push    edi
                push    esi
                push    ebx
                sub     esp, 0Ch
                mov     esi, [ebp+arg_0]
                add     esi, 1
                lea     eax, ds:12h[esi*4]
                and     eax, 0FFFFFFF0h
                sub     esp, eax
                mov     eax, esp
                shr     eax, 2
                cmp     [ebp+arg_0], 1
                lea     edi, ds:0[eax*4]
                mov     dword ptr ds:0[eax*4], 0
                mov     dword ptr ds:4[eax*4], 1
                jle     short loc_80484AC
                mov     eax, edi
                xor     ebx, ebx
                mov     ecx, 1
                mov     edx, 2
                jmp     short loc_804849D
; --------------------------------------------------
                align 8
loc_8048498:
                mov     ecx, [eax+4]
                mov     ebx, [eax]
loc_804849D:
                add     ecx, ebx
                add     edx, 1
                mov     [eax+8], ecx
                add     eax, 4
                cmp     esi, edx
                jnz     short loc_8048498
loc_80484AC:
                mov     edx, [ebp+arg_0]
                mov     eax, [edi+edx*4]
                lea     esp, [ebp-0Ch]
                pop     ebx
                pop     esi
                pop     edi
                pop     ebp
                retn
fib             endp
; ---------------------------------------------------
```

Listing B.4: Assembly of sdbot05b.cpp compiled with -O0

```
; =============== S U B R O U T I N E =================
; Attributes: bp-based frame
; _DWORD __cdecl rndnick(char *)
                public __Z7rndnickPc
__Z7rndnickPc   proc near

var_1C          = byte ptr -1Ch
var_10          = dword ptr -10h
var_C           = dword ptr -0Ch
arg_0           = dword ptr  8
                push    ebp
                mov     ebp, esp
                sub     esp, 38h
                call    _GetTickCount@0 ; GetTickCount()
                mov     [esp], eax      ; unsigned int
                call    _srand
                mov     dword ptr [esp+8], 0Ch ; size_t
                mov     dword ptr [esp+4], 0 ; int
                lea     eax, [ebp+var_1C]
                mov     [esp], eax      ; void *
                call    _memset
                call    _rand
                mov     ecx, eax
                mov     edx, 55555556h
                mov     eax, ecx
                imul    edx
                mov     eax, ecx
                sar     eax, 1Fh
                sub     edx, eax
                mov     eax, edx
                add     eax, eax
                add     eax, edx
                sub     ecx, eax
                mov     edx, ecx
                lea     eax, [edx+4]
                mov     [ebp+var_10], eax
                mov     [ebp+var_C], 0
                jmp     short loc_40286E
; ---------------------------------------------------------
loc_40283A:
                call    _rand
                mov     ecx, eax
                mov     edx, 4EC4EC4Fh
                mov     eax, ecx
                imul    edx
                sar     edx, 3
                mov     eax, ecx
                sar     eax, 1Fh
                sub     edx, eax
                mov     eax, edx
                imul    eax, 1Ah
                sub     ecx, eax
                mov     eax, ecx
                add     eax, 61h
                lea     ecx, [ebp+var_1C]
                mov     edx, [ebp+var_C]
                add     edx, ecx
                mov     [edx], al
                add     [ebp+var_C], 1
loc_40286E:
                mov     eax, [ebp+var_C]
                cmp     eax, [ebp+var_10]
                jl      short loc_40283A
                mov     eax, [ebp+var_C]
                add     eax, 1
                mov     [ebp+eax+var_1C], 0
                mov     dword ptr [esp+8], 0Ch ; size_t
                lea     eax, [ebp+var_1C]
                mov     [esp+4], eax    ; char *
                mov     eax, [ebp+arg_0]
                mov     [esp], eax      ; char *
                call    _strncpy
                mov     eax, [ebp+arg_0]
                jmp     short locret_4028A8
; ------------------------------------------------------
                dd 0E8240489h
                dd 7C58h
; ------------------------------------------------------
locret_4028A8:
                leave
                retn
__Z7rndnickPc   endp
```

Listing B.5: Assembly of sdbot05b.cpp compiled with -O1

```
; =============== S U B R O U T I N E ===================
; _DWORD __cdecl rndnick(char *)
                public __Z7rndnickPc
__Z7rndnickPc   proc near ;
```

```

var_3C          = dword ptr -3Ch
var_38          = dword ptr -38h
var_34          = dword ptr -34h
var_28          = byte ptr -28h
var_24          = dword ptr -24h
var_20          = dword ptr -20h
arg_0           = dword ptr  4
                push    ebp
                push    edi
                push    esi
                push    ebx
                sub     esp, 2Ch
                call    _GetTickCount@0 ; GetTickCount()
                mov     [esp+3Ch+var_3C], eax ; unsigned int
                call    _srand
                mov     dword ptr [esp+3Ch+var_28], 0
                mov     [esp+3Ch+var_24], 0
                mov     [esp+3Ch+var_20], 0
                call    _rand
                mov     ecx, eax
                mov     edx, 55555556h
                imul    edx
                mov     eax, ecx
                sar     eax, 1Fh
                sub     edx, eax
                lea     eax, [edx+edx*2]
                sub     ecx, eax
                lea     eax, [ecx+4]
                test    eax, eax
                jle     short loc_401D50
                lea     ebx, [esp+3Ch+var_28]
                mov     ebp, ecx
                lea     edi, [esp+ecx+3Ch+var_24]
                mov     esi, 4EC4EC4Fh
loc_401D27:
                call    _rand
                mov     ecx, eax
                imul    esi
                sar     edx, 3
                mov     eax, ecx
                sar     eax, 1Fh
                sub     edx, eax
                imul    edx, 1Ah
                sub     ecx, edx
                add     ecx, 61h
                mov     [ebx], cl
                add     ebx, 1
                cmp     ebx, edi
                jnz     short loc_401D27
                add     ebp, 4
                jmp     short loc_401D55
; ---------------------------------------------------
loc_401D50:
```

```
                mov     ebp, 0
loc_401D55:
                mov     [esp+ebp+3Ch+var_28+1], 0
                mov     [esp+3Ch+var_34], 0Ch ; size_t
                lea     eax, [esp+3Ch+var_28]
                mov     [esp+3Ch+var_38], eax ; char *
                mov     eax, [esp+3Ch+arg_0]
                mov     [esp+3Ch+var_3C], eax ; char *
                call    _strncpy
                mov     eax, [esp+3Ch+arg_0]
                add     esp, 2Ch
                pop     ebx
                pop     esi
                pop     edi
                pop     ebp
                retn
__Z7rndnickPc   endp
```

Appendix C
Python scripts for unrolling the Fibonacci loop

Listing C.1: Python script that compares fib() -O1 and -O2 by unrolling 0 times

```
from z3 import *

s = Solver()


############################################################
#fib.c compiled using -m32 -O1
#declare variables
mem = Array("mem", BitVecSort(32), BitVecSort(32))
arg_0 = BitVec("arg_0",32)
esp = BitVec("esp",32)

#assume arg_0 >= 0 and arg_0 <= 1
s.add(arg_0 >= 0)
s.add(arg_0 <= 1)

ebx = arg_0                      # mov  ebx, [ebp+arg_0]
eax = (ebx * 4) + 0x16           # lea  eax, ds: 16h[ebx*4]
eax = eax & 0xFFFFFFF0           # and  eax, 0FFFFFFF0h
esp = esp - eax                  # sub  esp, eax
eax = esp                        # mov  eax, esp
eax = eax >> 2                   # shr  eax, 2
esi = eax * 4                    # lea  esi, ds:0[eax*4]
mem = Store(mem, (eax*4)+0, 0)   # mov  dword ptr ds:0[eax*4]
mem = Store(mem, (eax*4)+4, 1)   # mov  dword ptr ds:0[eax*4]
                                 # cmp  ebx, 1
                                 # jle  short loc_804870
# assum ebx <= 1
#--------------
eax = mem[esi+ebx*4]             # mov  eax, [esi+ebx*4]

fib1 = eax
############################################################
#fib.c compiled using -m32 -O2
#declare variables
mem = Array("mem", BitVecSort(32), BitVecSort(32))
arg_0 = BitVec("arg_0",32)
esp = BitVec("esp",32)

esi = arg_0                      # mov  esi, [ebp+arg_0]
esi = esi + 1                    # add  esi, 1
eax = (esi * 4) + 0x12           # lea  eax, ds:12h[esi*4]
eax = eax & 0xFFFFFFF0           # and  eax, 0FFFFFFF0h
```

```
esp = esp - eax                  # sub  esp, eax
eax = esp                        # mov  eax, esp
eax = eax >> 2                   # shr  eax, 2
                                 # cmp  [ebx+arg_0], 1
edi = eax * 4 + 0                # lea  edi, ds: 0[eax*4]
mem = Store(mem, (eax*4)+0, 0)   # mov  dword ptr ds:0[eax*4], 0
mem = Store(mem, (eax*4)+4, 1)   # mov  dword ptr ds:0[eax*4], 1
                                 # jle  short loc_80484AC
# assume arg_0 <= 1
#--------------
edx = arg_0                      # mov  edx, [epb+arg_o]
eax = mem[edi+edx*4]             # mov  eax, [edi+edx*4]

fib2 = eax

############################################################
#Test for equality
prove (fib1 == fib2)
```

Listing C.2: Python script that compares fib() -O1 and -O2 by unrolling 1 time

```
from z3 import *

s = Solver()


############################################################
#fib.c compiled using -m32 -O1
#declare variables
mem = Array("mem", BitVecSort(32), BitVecSort(32))
arg_0 = BitVec("arg_0",32)
esp = BitVec("esp",32)

#assume arg_0 > 1 and arg_0 <= 2
s.add(arg_0 == 2)

ebx = arg_0                      # mov  ebx, [ebp+arg_0]
eax = (ebx * 4) + 0x16           # lea  eax, ds: 16h[ebx*4]
eax = eax & 0xFFFFFFF0           # and  eax, 0FFFFFFF0h
esp = esp - eax                  # sub  esp, eax
eax = esp                        # mov  eax, esp
eax = eax >> 2                   # shr  eax, 2
esi = eax * 4                    # lea  esi, ds:0[eax*4]
mem = Store(mem, (eax*4)+0, 0)   # mov  dword ptr ds:0[eax*4]
mem = Store(mem, (eax*4)+4, 1)   # mov  dword ptr ds:0[eax*4]
                                 # cmp  ebx, 1
                                 # jle  short loc_804870
# assum ebx <= 1
#--------------
eax = esi                        # mov  eax, esi
edx = 2                          # mov  edx, 2
#--------------
ecx = mem[eax+4]                 # mov  ecx, [eax+4]
ecx = ecx + mem[eax]              # add  ecx, [eax]
mem = Store(mem,eax+8,ecx)        # mov  [eax+8], ecx
edx = edx + 1                     # add  edx, 1
eax = eax + 4                     # add  eax, 4
                                  # cmp  ebx, edx
                                  # jle  short loc_804870
# assume ebx < edx (ebx == 2)
#--------------
eax = mem[esi+ebx*4]              # mov  eax, [esi+ebx*4]

fib1 = eax
##############################################################
#fib.c compiled using -m32 -O2
#declare variables
mem = Array("mem", BitVecSort(32), BitVecSort(32))
esp = BitVec("esp",32)

esi = arg_0                       # mov  esi, [ebp+arg_0]
esi = esi + 1                     # add  esi, 1
eax = (esi * 4) + 0x12            # lea  eax, ds:12h[esi*4]
eax = eax & 0xFFFFFFF0            # and  eax, 0FFFFFFF0h
esp = esp - eax                   # sub  esp, eax
eax = esp                         # mov  eax, esp
eax = eax >> 2                    # shr  eax, 2
                                  # cmp  [ebx+arg_0], 1
edi = eax * 4 + 0                 # lea  edi, ds: 0[eax*4]
mem = Store(mem, (eax*4)+0, 0)    # mov  dword ptr ds:0[eax*4], 0
mem = Store(mem, (eax*4)+4, 1)    # mov  dword ptr ds:0[eax*4], 1
                                  # jle  short loc_80484AC
# assume arg_0 <= 1
#--------------
eax = edi                         # mov  eax, edi
ebx = 0                           # xor  ebx, ebx
ecx = 1                           # mov  ecx, 1
edx = 2                           # mov  edx, 2
#--------------
ecx = ecx + ebx                   # add  ecx, ebx
edx = edx + 1                     # add  edx, 1
mem = Store(mem,eax+8, ecx)       # mov  [eax+8], ecx
eax = eax + 4                     # add  eax, 4
                                  # cmp  esi, edx
# assume esi == edx (esi == 2)
#--------------
edx = arg_0                       # mov  edx, [epb+arg_o]
eax = mem[edi+edx*4]              # mov  eax, [edi+edx*4]

fib2 = eax

##############################################################
#Test for equality
prove (fib1 == fib2)
```

Listing C.3: Python script that compares fib() -O1 and -O2 by unrolling 2 times

```
from z3 import *

s = Solver()


###########################################################
#fib.c compiled using -m32 -O1
#declare variables
mem = Array("mem", BitVecSort(32), BitVecSort(32))
arg_0 = BitVec("arg_0",32)
esp = BitVec("esp",32)

s.add(arg_0 == 3)

ebx = arg_0                          # mov  ebx, [ebp+arg_0]
eax = (ebx * 4) + 0x16               # lea  eax, ds: 16h[ebx*4]
eax = eax & 0xFFFFFFF0               # and  eax, 0FFFFFFF0h
esp = esp - eax                      # sub  esp, eax
eax = esp                            # mov  eax, esp
eax = eax >> 2                       # shr  eax, 2
esi = eax * 4                        # lea  esi, ds:0[eax*4]
mem = Store(mem, (eax*4)+0, 0)       # mov  dword ptr ds:0[eax*4]
mem = Store(mem, (eax*4)+4, 1)       # mov  dword ptr ds:0[eax*4]
                                     # cmp  ebx, 1
                                     # jle  short loc_804870
# assum ebx <= 1
#--------------
eax = esi                            # mov  eax, esi
edx = 2                              # mov  edx, 2
#--------------
ecx = mem[eax+4]                     # mov  ecx, [eax+4]
ecx = ecx + mem[eax]                 # add  ecx, [eax]
mem = Store(mem,eax+8,ecx)           # mov  [eax+8], ecx
edx = edx + 1                        # add  edx, 1
eax = eax + 4                        # add  eax, 4
                                     # cmp  ebx, edx
                                     # jle  short loc_804870
# assume ebx > edx (ebx == 3)
#--------------
ecx = mem[eax+4]                     # mov  ecx, [eax+4]
ecx = ecx + mem[eax]                 # add  ecx, [eax]
mem = Store(mem,eax+8,ecx)           # mov  [eax+8], ecx
edx = edx + 1                        # add  edx, 1
eax = eax + 4                        # add  eax, 4
                                     # cmp  ebx, edx
                                     # jle  short loc_804870
#ebx <= edx (ebx == 3)
#--------------
eax = mem[esi+ebx*4]                 # mov  eax, [esi+ebx*4]

fib1 = eax
###########################################################
#fib.c compiled using -m32 -O2
```

```
#declare variables
mem = Array("mem", BitVecSort(32), BitVecSort(32))
esp = BitVec("esp",32)

esi = arg_0                       # mov  esi, [ebp+arg_0]
esi = esi + 1                     # add  esi, 1
eax = (esi * 4) + 0x12            # lea  eax, ds:12h[esi*4]
eax = eax & 0xFFFFFFF0            # and  eax, 0FFFFFFF0h
esp = esp - eax                   # sub  esp, eax
eax = esp                         # mov  eax, esp
eax = eax >> 2                    # shr  eax, 2
                                  # cmp  [ebx+arg_0], 1
edi = eax * 4 + 0                 # lea  edi, ds: 0[eax*4]
mem = Store(mem, (eax*4)+0, 0)    # mov  dword ptr ds:0[eax*4], 0
mem = Store(mem, (eax*4)+4, 1)    # mov  dword ptr ds:0[eax*4], 1
                                  # jle  short loc_80484AC
# assume arg_0 <= 1
#--------------
eax = edi                         # mov  eax, edi
ebx = 0                           # xor  ebx, ebx
ecx = 1                           # mov  ecx, 1
edx = 2                           # mov  edx, 2
#--------------
ecx = ecx + ebx                   # add  ecx, ebx
edx = edx + 1                     # add  edx, 1
mem = Store(mem,eax+8, ecx)       # mov  [eax+8], ecx
eax = eax + 4                     # add  eax, 4
                                  # cmp  esi, edx
# assume esi != edx (esi == 3)
#--------------
ecx = mem[eax+4]                  # mov  ecx, [eax+4]
ebx = mem[eax]                    # mov  ebx, [eax]
#--------------
ecx = ecx + ebx                   # add  ecx, ebx
edx = edx + 1                     # add  edx, 1
mem = Store(mem,eax+8, ecx)       # mov  [eax+8], ecx
eax = eax + 4                     # add  eax, 4
                                  # cmp  esi, edx
# assume esi == edx (esi == 3)
#--------------
edx = arg_0                       # mov  edx, [epb+arg_o]
eax = mem[edi+edx*4]              # mov  eax, [edi+edx*4]

fib2 = eax

############################################################
#Test for equality
prove (fib1 == fib2)
```

Listing C.4: Python script that compares fib() -O1 and -O2 by unrolling 3 times

```
from z3 import *

```

```
s = Solver()


###############################################################
#fib.c compiled using -m32 -O1
#declare variables
mem = Array("mem", BitVecSort(32), BitVecSort(32))
arg_0 = BitVec("arg_0",32)
esp = BitVec("esp",32)

s.add(arg_0 == 4)

ebx = arg_0                         # mov  ebx, [ebp+arg_0]
eax = (ebx * 4) + 0x16              # lea  eax, ds: 16h[ebx*4]
eax = eax & 0xFFFFFFF0              # and  eax, 0FFFFFFF0h
esp = esp - eax                     # sub  esp, eax
eax = esp                           # mov  eax, esp
eax = eax >> 2                      # shr  eax, 2
esi = eax * 4                       # lea  esi, ds:0[eax*4]
mem = Store(mem, (eax*4)+0, 0)      # mov  dword ptr ds:0[eax*4]
mem = Store(mem, (eax*4)+4, 1)      # mov  dword ptr ds:0[eax*4]
                                    # cmp  ebx, 1
                                    # jle  short loc_804870
# assum ebx <= 1
#--------------
eax = esi                           # mov  eax, esi
edx = 2                             # mov  edx, 2
#--------------
ecx = mem[eax+4]                    # mov  ecx, [eax+4]
ecx = ecx + mem[eax]                # add  ecx, [eax]
mem = Store(mem,eax+8,ecx)          # mov  [eax+8], ecx
edx = edx + 1                       # add  edx, 1
eax = eax + 4                       # add  eax, 4
                                    # cmp  ebx, edx
                                    # jle  short loc_804870
# assume ebx > edx (ebx == 4)
#--------------
ecx = mem[eax+4]                    # mov  ecx, [eax+4]
ecx = ecx + mem[eax]                # add  ecx, [eax]
mem = Store(mem,eax+8,ecx)          # mov  [eax+8], ecx
edx = edx + 1                       # add  edx, 1
eax = eax + 4                       # add  eax, 4
                                    # cmp  ebx, edx
                                    # jle  short loc_804870
# assume ebx > edx (ebx == 4)
#--------------
ecx = mem[eax+4]                    # mov  ecx, [eax+4]
ecx = ecx + mem[eax]                # add  ecx, [eax]
mem = Store(mem,eax+8,ecx)          # mov  [eax+8], ecx
edx = edx + 1                       # add  edx, 1
eax = eax + 4                       # add  eax, 4
                                    # cmp  ebx, edx
                                    # jle  short loc_804870
# assume ebx <= edx (ebx == 3)
```

```
#--------------
eax = mem[esi+ebx*4]              # mov  eax, [esi+ebx*4]

fib1 = eax
############################################################
#fib.c compiled using -m32 -O2
#declare variables
mem = Array("mem", BitVecSort(32), BitVecSort(32))
esp = BitVec("esp",32)

esi = arg_0                       # mov  esi, [ebp+arg_0]
esi = esi + 1                     # add  esi, 1
eax = (esi * 4) + 0x12            # lea  eax, ds:12h[esi*4]
eax = eax & 0xFFFFFFF0            # and  eax, 0FFFFFFF0h
esp = esp - eax                   # sub  esp, eax
eax = esp                         # mov  eax, esp
eax = eax >> 2                    # shr  eax, 2
                                  # cmp  [ebx+arg_0], 1
edi = eax * 4 + 0                 # lea  edi, ds: 0[eax*4]
mem = Store(mem, (eax*4)+0, 0)    # mov  dword ptr ds:0[eax*4], 0
mem = Store(mem, (eax*4)+4, 1)    # mov  dword ptr ds:0[eax*4], 1
                                  # jle  short loc_80484AC
# assume arg_0 <= 1
#--------------
eax = edi                         # mov  eax, edi
ebx = 0                           # xor  ebx, ebx
ecx = 1                           # mov  ecx, 1
edx = 2                           # mov  edx, 2
#--------------
ecx = ecx + ebx                   # add  ecx, ebx
edx = edx + 1                     # add  edx, 1
mem = Store(mem,eax+8, ecx)       # mov  [eax+8], ecx
eax = eax + 4                     # add  eax, 4
                                  # cmp  esi, edx
# assume esi != edx (esi == 4)
#--------------
ecx = mem[eax+4]                  # mov  ecx, [eax+4]
ebx = mem[eax]                    # mov  ebx, [eax]
#--------------
ecx = ecx + ebx                   # add  ecx, ebx
edx = edx + 1                     # add  edx, 1
mem = Store(mem,eax+8, ecx)       # mov  [eax+8], ecx
eax = eax + 4                     # add  eax, 4
                                  # cmp  esi, edx
# assume esi != edx (esi == 4)
#--------------
ecx = mem[eax+4]                  # mov  ecx, [eax+4]
ebx = mem[eax]                    # mov  ebx, [eax]
#--------------
ecx = ecx + ebx                   # add  ecx, ebx
edx = edx + 1                     # add  edx, 1
mem = Store(mem,eax+8, ecx)       # mov  [eax+8], ecx
eax = eax + 4                     # add  eax, 4
                                  # cmp  esi, edx
# assume esi == edx (esi == 4)
#--------------
edx = arg_0                         # mov   edx, [epb+arg_o]
eax = mem[edi+edx*4]                # mov   eax, [edi+edx*4]

fib2 = eax

################################################################
#Test for equality
prove (fib1 == fib2)
```