

Enhance Code Virtualization Protections Via Diversity

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Code virtualization built upon virtual machine (VM) technologies are emerging as a viable method for implementing code obfuscation to protect programs against unauthorized analysis. State-of-the-art VM-based protection approaches use a fixed set of virtual instructions and bytecode interpreters across programs. This, however, opens up a security hole where an experienced attacker can use knowledge extracted from other programs to quickly uncover the mapping between virtual instructions and native code for applications protected under the same scheme. In this paper, we propose a novel VM-code obfuscation system to address this problem. The core idea of our approach is to obfuscate the mapping between the opcodes of bytecode instructions and their semantics. We achieve this by partitioning each protected code region into multiple segments where the mapping of opcodes and their semantics is randomized in different ways in different segments. In this way, each bytecode instruction will be translated into different native code in different sections of the obfuscated code. This significantly increases the diversity of the program behavior. As a result, the knowledge of bytecode to native code mappings obtained from other programs is unlikely to be useful for a new program. We evaluate our approach on a set of real-world applications and compare it against two state-of-the-art VM-based code obfuscation approaches. Experimental results show that our simple approach is effective, which provides stronger protection at the cost of little extra overhead.

CCS Concepts: •**Security and privacy** → **Software security engineering**; *Software reverse engineering*;

Additional Key Words and Phrases: Virtualized obfuscation, reverse engineering, instruction set randomization, analysis knowledge

1. INTRODUCTION

Unauthorized code reverse engineering is a major concern for software developers. This technique is widely used by adversaries to perform various attacks, including removing copyright protection to obtain an illegal copy of the software, taking out advertisement from the application, or injecting malicious code into the program. By making the program harder to be traced and analyzed, code obfuscation is a viable means to protect software against unauthorized code modification [Barak et al. 2001; Lynn et al. 2004; Linn and Debray 2003; Preda and Giacobazzi 2005; Van Oorschot 2003; Wu et al. 2010].

Code virtualization based on a virtual machine (VM) is emerging as a promising way for implementing code obfuscation [Oreans-Technologies 2016a; VMProtect-Software 2016; Oreans-Technologies 2016b; Fang et al. 2011; Wang et al. 2014; Wang et al. 2013].

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The underlying principal of VM-based protection is to replace the program instructions with bespoke virtual instructions and eventually encode into a bytecode program. These virtual bytecodes will then be translated into native machine code at runtime to execute on the underlying hardware platform. This forces the attacker to move from a familiar instruction set to an unfamiliar environment, which can significantly increase the time and effort involved in the attack.

Reverse engineering of VM-obfuscated code typically follows a number of steps. The attack first reverse-engineers the virtual interpreter to understand the semantics of individual bytecode instructions, i.e. how will a bytecode map be translated to native code. The attacker then translates the bytecode back to native machine instructions or even high-level program languages to understand the program logic [Falliere et al. 2009; Rolles 2009]. Among these steps, understanding the semantics of individual bytecode instructions is often the most-consuming process, which is involved in analysing the handler that used to interpret every bytecode instruction.

Numerous approaches have been proposed to protect VM handlers from reverse engineering. Most of them increase the diversity of program behavior by obfuscating the handler implementation [Wang et al. 2014] or iteratively transforming a single program multiple times using different interpretation techniques. However, all prior work employ a fixed strategy that each bytecode will be deterministically translated to a fixed set of native code. Such techniques are vulnerable for programs protected under the same obfuscation technique. In particular, an attacker can reuse the knowledge (termed *analysis knowledge* in this paper) of the handler implementation obtained from one program to attack another program.

To mitigate the effect of reuse of *analysis knowledge*, we propose DCVP (Code Virtualization Protection with Diversity), an enhanced VM-based code obfuscation system that obscures the semantics of bytecode instructions. We employ a technique called Instruction Set Randomization (ISR) [Kc et al. 2003] to randomly change the *opcodes* of bytecode instructions and their semantics. The randomization itself, however, is not sufficient for providing stronger protection, because it is similar to monoalphabetic substitution encryption and is easy to be bypassed according to the non-uniform frequencies of bytecode instructions. To overcome this issue, DCVP further partitions the bytecode program into several parts where the semantics of bytecode instructions in each part are randomized in different ways. As a result, the same bytecode instruction in different parts of the bytecode program is likely to have different semantics.

Of course, we have to admit that some malware authors also will use the above code virtualization technology to “protect” their malicious code and program. For example, Themida [Oreans-Technologies 2016b] is a popular tool of choice. In the same way, the reverse engineer isn’t always the bad guy. However, in this paper, we put ourselves in the perspective of code protection, and aims to provide a mechanism for code protection to protect the legitimate interests of users from malicious infringement.

The key contribution of this paper is a countermeasure to address the issue of reusing *analysis knowledge* to perform code reverse engineering across programs. This is achieved by first partitioning the bytecode programs into several parts and randomizing the semantics of bytecode instructions in each part in different ways. We compare our approach against VMProtect [VMProtect-Software 2016] and Themida [Oreans-Technologies 2016b] on md5.exe, gzip.exe, bcrypt.exe and mat_mul.exe applications. Experimental results show that DCVP is able to provide stronger protection at the cost of little extra overhead.

The rest of the paper is organized as follows. In Section 2, we illustrate the internals of VM-based obfuscation. Section 4 gives our threat model, which describes the analyst’s capabilities and goals, and we illustrate the process of reverse engineering a VM-obfuscated program. In Section 5, 6, 7 and 8, we present the details of DCVP.

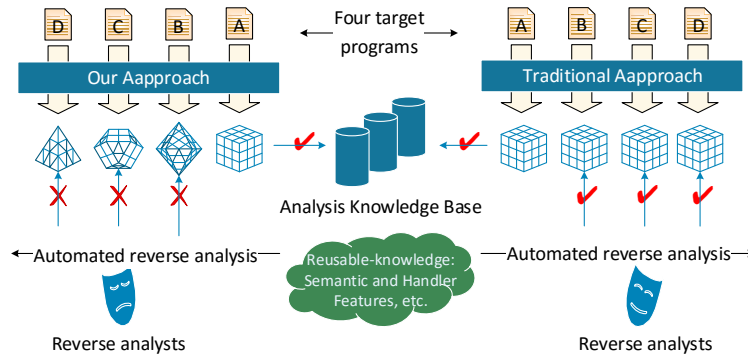


Fig. 1. The process of reusing attacking knowledge for code reverse engineering. Here we have four different target programs, A, B, C and D. In the right side of the scenario, all programs are obfuscated with a code obfuscation scheme that a virtual instruction will be deterministically translated to a fixed set of native code. This allows an attacker to reuse knowledge obtained from one program to efficiently reverse engineer other programs. In another scenario, the mapping between virtual instructions and native code is different for different programs. In this way, the attacker is unable to reuse the previously extracted knowledge to perform reverse analysis across programs.

Section 9 evaluates DCVP for its effectiveness and its spatial and temporal overhead. Section 10 presents the related work, and finally presents the conclusion and discusses the future work.

2. MOTIVATION

Figure 2 depicts an reverse analysis scenario where an analyst can reuse the *analysis knowledge* to attack applications protected by the same VM-based code obfuscation scheme. In this example, there are four different programs to be protected, labelled as A, B, C and D. In the right side of the diagram, all the four programs are protected using an identical set of virtual instructions and bytecode handlers. Under this setting, an experienced analyst would be able to use the knowledge of the mapping of virtual instructions and bytecode handlers obtained from one program to reverse-engineer the other three programs. Bear in mind that, uncovering the mapping between virtual instructions and native code is often the most time-consuming process for attacking VM-based code obfuscation. Having able to reuse the attacking knowledge thus can significantly reduce the cost involved in the attack. In another scenario, the translations between virtual instructions and native code vary among programs. Therefore, the knowledge obtained from one program will be inapplicable to others. This forces the analyst to start from the scratch when reverse engineering a new program. This example shows that shuffle the relationship between the virtual instructions and bytecode handlers can significantly increase the effort and cost involved in performing the attack. In the remainder section, we describe how we can construct such as scheme in details.

3. BACKGROUND

Virtualization technique has been used in many fields, e.g. virtual memory for resource virtualization, VMware and VirtualBox for CPU virtualization, and Java bytecode and .Net CIL for application virtualization. This paper discusses another application of virtualization technique in protecting software programs from unauthorized analyses, namely code virtualized obfuscation or VM-based obfuscation, like VMProtect [VMProtect-Software 2016] and Code Virtualizer [Oreans-Technologies 2016a].

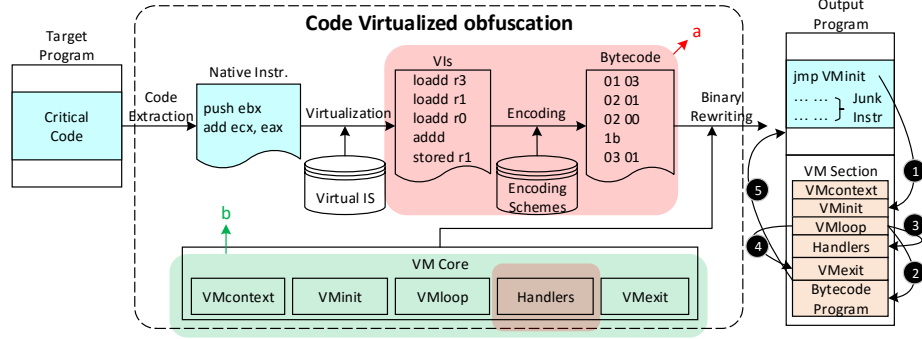


Fig. 2. The architecture of code virtualized obfuscation and the execution view of a VM-obfuscated program. The main work of this paper is to improve the core steps of VM-based protection (areas of “a” and “b”). In the “a” region, we adopt the partition bytecode encoding schemes, and obfuscate handlers to generate multiple sets of handlers. In the “b” region, we use a variety of methods of obfuscation and anti-taint analysis technology to protect the important components of virtual interpreter.

As software does not have uniform security requirements throughout its execution [Geneiatakis et al. 2012] and protecting the whole program is too costly, code virtualized obfuscation usually protects only the critical part(s) of the whole software program, which could be a critical algorithm or a processing logic. VM-based obfuscation protects a target program by transforming its native machine code into bytecode for a self-defined virtual instruction set architecture. At runtime, the execution instruction semantics of the original program are fulfilled by a native interpreter bundled with the bytecode. In this section, we will look into the internal working mechanism of VM-based obfuscation.

Figure 1 shows the architecture of a VM-based obfuscation system. The core of a VM-based obfuscation are the virtual IS (Instruction Set) and the native interpreter. Virtual instructions are used to emulate native instructions. It is required that virtual IS be able to emulate all the semantics of native IS, or formally speaking, virtual IS should be Turing-equivalent to the native IS. The native interpreter is to fetch and execute bytecode instructions. It follows the *decode-dispatch* approach [Ghosh et al. 2012], and consists of a bundle of handlers and a VMloop. VMloop is the main *decode-dispatch* loop and for each loop, VMloop fetches a bytecode instruction, decodes it, and dispatches a Handler to interpret it. Different from native instructions, bytecode instructions are specific for a virtual context, namely VMcontext, which contains the virtual registers and flags. Virtual registers and flags are related to the native registers and flags. At runtime, VMinit first saves native context and uses them to initialize the virtual context. In the simplest implementation, the virtual context could be a block of memory and stores the exact values of the native context; this could be more complex [Falliere et al. 2009], but it should be guaranteed that the converting between native context and virtual context is reversible, since VMexit will restore the native context from the virtual context upon exiting the virtual interpreter.

Figure 1 also depicts the workflow of the obfuscation process. It starts from extracting the critical code from the target program. This is typically done with the help of the program author who will mark the location and scope of the critical code to be protected during programing; the obfuscation system then will search for the marks to locate the critical code at obfuscation time. The critical code is disassembled into native disassembly instructions to enable later conversion from native instructions to virtual instructions in an instruction-by-instruction fashion. The rules of conversions

are set ahead of protection and are stable inside a VM-based obfuscation system. These rules depend on the semantics of the virtual IS and guarantee that the semantics of the resulted virtual instructions are equivalent to the native ones. Subsequently, virtual instructions are encoded into bytecode program. Finally, the bytecode program and other VM components are assembled into the target program through binary rewriting. This paper improves the core steps of code virtualization protection. We modify the encoding schemes and adopt the partition bytecode programming, and generate multiple sets of handlers. So the bytecodes will have different semantics in different parts of bytecode program. We also use a variety of methods of obfuscation and anti-taint analysis technology to protect the critical components of virtual interpreter (section 8).

At runtime, upon executing the “critical code”, an instruction, `jmp VMin`, transfers the control to `VMin` (Step ❶). `VMin` saves the native context and initializes the virtual context. Next, `VMloop` starts to work. It fetches a bytecode instruction, decodes it (Step ❷) and dispatches a handler to interpret it (Step ❸). Step ❷ and Step ❸ are iterated until all the bytecode instructions are interpreted. Then, `VMloop` transfers the execution to `VMexit` (Step ❹), where the native context is restored and the program jumps back to the native instruction following the critical code (Step ❺) and continue to execute the rest of the program code.

4. THREAT MODEL

In our threat model, an analyst owns a copy of the target VM-obfuscated software program and runs it in a malicious host environment [Collberg and Thomborson 2002]. In a malicious host environment, also referenced as the white-box attack context [Chow et al. 2003; Liem et al. 2008], an analyst has full privileged accesses to the system, and she can execute the software program at will and take advantages of any static and dynamic analysis tools (such as, “IDA”¹, “OllyDbg”² and “Sysinternals Suite”³) to help to trace and analyze instructions, monitor registers and process memory, and even change instruction bytes and control flows at runtime, etc. The analyst in our threat model is defined as an entity that seeks to reverse engineer and understand a software program’s inner implementation and logic details, since code understanding is the basis for later tampering, cracking, or behavior pattern extraction. The ultimate goal of the analyst is to automate the entire analysis process. At present, there are two mainly types of methods to attack VM-based protection system. The first is based on the virtual execution analysis, the other is based on the behavior and semantic analysis.

4.1. Attack based on the virtual execution analysis

This method is proposed by Rolles et al. [Rolles 2009], which is based on the analysis of the interpretation process of the bytecode program, and requires an attacker to have a certain understanding of the principle of code virtualization.

It can be summarised as the following three steps. First, reverse engineering the virtual interpreter. The purpose of this step is to get the location and interaction information of each component of the virtual interpreter and the mapping relationship between the real CPU environment and `VMcontext`. Then using these informations to work out the semantics of individual bytecode instructions. Finally, recovering original program’s logic embedded in the bytecode program, eliminating redundant information and restoring a program that is similar to the original program. Nicolas Falliere

¹IDA Pro, <https://www.hex-rays.com/index.shtml>.

²OllyDbg, <http://www.ollydbg.de/>.

³Sysinternals Suite, <https://technet.microsoft.com/en-us/sysinternals/bb842062/>.

[Falliere et al. 2009] presented an example of the above analysis process which is used to analyze the Trojan.Clampi protected by VMProtect [VMProtect-Software 2016].

Since the virtual interpreter consists of VMloop and Handlers, an analyst needs to locate them and analyze how VMloop works and what each handler does. By tracing the *decode-dispatch* loop in VMloop, the analyst could figure out the correspondences between bytecode instructions and handlers, and thus the semantics of individual bytecode instructions. Combining the above information, the analyst can figure out what the bytecode program does, and after some simplification (constant folding and dead code elimination for example [FightingOreans'VM 2008]), she could reveal the original program's logic.

In the classical code virtualized obfuscation, the relationships between the opcodes of bytecode instructions and their semantics (the handlers) are stable, which means that a bytecode instruction in different obfuscated programs has identical semantics. Once an analyst gets aware of such relationships and semantics of each handler from previous analysis work or materials published by another analyst, she could reuse them for analyzing another VM-obfuscated program more efficiently, just like the first scenario in figure 2.

4.2. Attack based on the behavior and semantic analysis

This type of attack method can be used to attack not only code virtualization protection but also other confusion methods. Coogan et al. [Coogan et al. 2011] puts forward a behavior based analysis method, which aims to analyze the important behavior of code, but it does not pay attention to how to restore the original code. Its implementation steps are as follows: (1) Dynamically trace program execution process by using debugging tools, and collect some instruction execution information, such as the address of the instructions and register values. (2) Analyze and identify the system calls and its related parameters from the above information. (3) Further mark all of instructions that influence on the system calls. (4) Extract these labeled instructions and analyze their behavior.

This type of approach is usually used for malicious code analysis because it is based on analysis of the interaction between the program and system. The malicious code will interact with the system frequently in order to achieve a malicious purpose, but it is not necessary for the benign code. In other words, if the protected code does not interact with the system frequently, this approach will not be very effective on reverse analysis.

Another attack method based on semantic is proposed by the Yadegari et al. [Yadegari et al. 2015], which use taint propagation to track the flow of inputs values, and semantics-preserving code transformations to simplify the logic of the instructions. The implementation steps are as follows: (1) Dynamically trace program execution process by using debugging tools, identify the input and output of the program. (2) With the input of the program as a taint source to perform the taint propagation, and extract the affected instruction sequence. (3) Simplify the above instruction sequences by using code simplification techniques, then construct the control flow graph of the program and optimize it, and finally get the final result.

For the results of a run obtained, the function is equivalent to the original program, but it is only for one implementation, and does not cover all the execution branches. So the final control flow graph is only part of the original program. We need to perform analysis through multiple tracking and specify different input values each time, then comprehensive analysis to get a more complete control flow graph.

In conclusion. The first type of attack method based on virtual execution is closely related to the principle and structure of the code virtualization, and has the most

realistic and comprehensive results. The second method has wider applicability, but it is hard to get a comprehensive analysis results. So this paper mainly aims at the first kind of attack, but also will provide some measures to prevent the second kind of attack. And in our threat model, we assume that the analyst is familiar with the mechanism of code virtualized obfuscation and follows the above steps while reverse engineering a VM-obfuscated program. The ultimate goal of the analyst is to fully reverse engineer the VM-obfuscated application and automate the reverse analysis process.

5. DESIGN DETAILS

As we have described, the reuse of *analysis knowledge* about the semantics of bytecode instructions can save an analyst much time and effort. Since the longer the software stay uncompromised, the more benefit the software authors will get, the naive idea to harden code virtualized obfuscation is to disable the *analysis knowledge* and force analysts to analyze the obfuscated software programs from scratch. Our solution is randomizing the relationships between the bytecode instructions and their semantics for each obfuscation instance. In this section, we will present the details about our solution. For better understanding, we will start from the design of virtual IS and handlers.

Virtual IS and Handlers. Virtual IS (Virtual Instruction Set) and handlers are the basis of the VM-based obfuscation system. First analysis of the native instructions, design complete virtual instruction set according to the classification of native instructions, and then design the handlers that used to interpret the VI (Virtual Instruction). The details are described as section 6.

Native Instructions to VIs. Extract the native instructions of key code segment from the target program, and then convert native instructions to the corresponding VIs according to designed virtual IS. The details are described as section 7.

VIs to Bytecode. It is a very important step that convert virtual instructions into a bytecode program in the process of code virtualization protection. System will generate a special bytecode program based on special encoding schemes, and these bytecodes can only be interpreted by the special interpreter of the system itself. This paper adopt the method of partitioning and randomization of virtual instruction semantics, and the different parts of the bytecode program will have different semantics. So different partitions need a set of specific interpretation procedures, the system will generate multiple sets of Handlers with same functions but different forms. Our approach will also adopt some anti-taint analysis techniques to protect Handlers and other components from taint analysis. The details are described as section 8.

DCVP will convert all of the critical instructions into bytecode program that can only be interpreted by the system itself. Finally the bytecode program and other VM components (such as, VMloop, VMcontext et al.) are assembled into the target program through binary rewriting.

6. VIRTUAL INSTRUCTION SET AND HANDLERS

As the basis of a VM-based obfuscation system, virtual IS and the handlers should be the first considerations when designing such a system. The challenge lies in devising a feature-complete virtual IS that is Turing-equivalent to native IS, which means that any native instructions could be substituted with the virtual instructions. Virtual instructions ultimately will be executed by the hand-crafted handlers; these handlers are written in native instructions.

There are two main VM architectures: stack-based, and register-based. Examples of stack-based virtual machines are the Java Virtual Machine and the .Net CLR, and examples of register-based virtual machines are the Lua VM, and the Dalvik VM. In this paper, we choose stack-based architecture for the VM-based obfuscation system for the following reasons:

- In a stack-based VM, operations are carried out with the help of stack, where operands and results of operations are stored. This simplifies the addressing of operands and ultimately simplifies the implementation of handlers.
- The process of converting native x86 instructions to virtual instructions is simpler.
- Stack-based VMs require more virtual instructions for a given computation; this makes the instructions more complex and conforms to our objective of impeding reverse analysis.

To devise a virtual IS that is Turing-equivalent to the native IS, one naive approach is devising a virtual instruction for every single native instruction. However, this results in a very large size of handlers. As the basic idea of stack-based VMs implies, a native operation are carried out or virtualized by virtual instructions in a three-phase fashion: pushing operands into the stack, executing the aimed operation, and storing the result into the virtual context. Therefore, it is sufficient for the virtual IS to include the following instructions:

- load instructions and store instructions for data transfers. load instructions are for pushing operands into stack, and store instructions are for popping results out of the stack and store the results into the virtual context.
- Arithmetical and logical instructions. The variants of these kind of instructions are much smaller than their native ones, as the addressing mode of operands is simpler and uniform, i.e., stack-based addressing.
- Branch instructions for changing the control flow of bytecode program.

Other instructions that are not included in the above categories are defined as special virtual instruction - undef, which we will discuss later. We first discuss the different formats of these instructions and how to implement the handlers of them.

6.1. "load" and "store" Instructions

load and store instructions are used for preparing operands and storing the results of operations. They are used in the first and third phases of virtualizing a native instruction. In our virtual IS, they are the only ones that have operands. For a load instruction, the operand could be a virtual register, a memory addresses, or an immediate value, and for a store instruction, the operand is a virtual register or a memory address. Virtual registers are stored in the virtual context, i.e., the VMcontext. A naive construction of VMcontext is simply copying the values of native registers into the VMcontext. But the mapping between the virtual registers and the native registers is not necessarily one-to-one. To further impede the reverse analysis, the mapping mechanism could be made purposely more complex, as NISLVMP [Wang et al. 2013] does. In this section, we only consider the one-to-one mapping between the virtual registers and the native ones.

Besides the operand type, the operand size matters as well. In x86 architecture, the size of an operand could be 8-bit, 16-bit, and 32-bit. For example, given a memory address, the load instruction could fetch the first 8-bit, or the lower 16-bit value, or the entire 32-bit value that stored in that address. Therefore, it is better to design a virtual instruction for every distinct combination of operand type and size. However, in x86 architecture, push and pop operations do not support 8-bit operations. We decide to delay distinguishing different size operands to the second phase of virtualizing native

Table I. The Virtual Instructions and Corresponding Handlers of load and store.

VI	Handler
load_r reg	movzx eax, byte [VPC] ;get vr index add VPC, 1 push dword [VMcontext+eax*4]
load_r8h reg	movzx eax, byte [VPC] ;get vr index add VPC, 1 movzx eax, byte [VMcontext+eax*4+1] push eax
load_m mem	mov eax, dword [VPC] ;get memory addr add VPC, 4 push dword [eax]
load_i8 imm8	movzx eax, byte [VPC] ;get 8-bit imm value add VPC, 1 push eax
load_i16 imm16	movzx eax, word [VPC] ;get 16-bit imm value add VPC, 2 push eax
load_i32 imm32	mov eax, dword [VPC] ;get 32-bit imm value add VPC, 4 push eax
load_ms	pop eax push dword [eax]
store_r reg	movzx eax, byte [VPC] ;get vr index add VPC, 1 pop dword [VMcontext+eax*4]
store_r8h reg	movzx eax, byte [VPC] ;get vr index add VPC, 1 pop edx mov byte [VMcontext+eax*4+1], dl
store_m mem	mov eax, dword [VPC] ;get memory addr add VPC, 4 pop dword [eax]
store_ms	pop eax pop ebx mov dword [eax], ebx

Note: In the table, reg means register, mem memory address, imm immediate value, and vr virtual register. VPC is short for Virtual Program Counter and represents the address of the next bytecode instruction to interpret.

instructions. Table I shows the virtual instructions of load and store and their corresponding handlers. In table I, there exists four special virtual instructions: load_r8h and store_r8h are used when we encounter an operation that manipulate the second least significant byte of a register, i.e., ah, dh, ch, bh. load_ms and store_ms have no operands and are used to process instructions with indirect memory addressing mode (memory address is stored in a register or presented as an expression). An example in table V illustrates the situation of using of load_ms.

6.2. Arithmetical and Logical Instructions

Arithmetical and logical virtual instructions are used to execute the aimed operations and they need not to worry about operands, since their operands have been pushed into the stack by load instructions. However, as we said before, these instructions must consider the size of the operands. These instructions are in similar forms and we take

Table II. The Virtual Instructions and Handlers of add Virtual Instructions.

VI	Handler
add8	pop eax add <i>byte</i> [esp], al
add16	pop eax add <i>word</i> [esp], ax
add32	pop eax add <i>dword</i> [esp], eax

Note: Since the operations of these instructions could be 8-bit, 16-bit, or 32-bit, we design a virtual instruction for each of the operations of different operand size.

add operation as an example to illustrate. Table II lists the virtual instructions and handling procedures of add operation. Since the operations of these instructions could be 8-bit, 16-bit, or 32-bit, we design a virtual instruction for each of the operations of different operand size.

6.3. Branch Instructions

In native IS, the commonly used branch instructions include `jmp`, `jcc` (conditional jump), `call`, and `retn`. It is a big challenge to virtualize these instructions, since they have many different variants and each of these variants needs a virtual instruction. Considering the destination of a jump (branch) instruction, if its destination also resides in the critical code, we call it an *inner jump*; otherwise, we call it an *outer jump*. Figure 3 illustrates these two kinds of branch instructions. In DCVP, we ignore the situation where the destination of a branch instruction outside the critical code resides in the critical code, the start instruction of the critical code excluded. This situation will not occur if the critical code to be protected is well-structured.

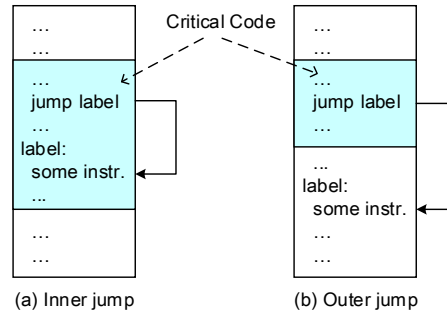


Fig. 3. The destination of a branch instruction could be in the critical code or outside the critical code. Branch instructions include `jmp`, `jcc`, `call`, and `retn`.

Besides the location of the destination instruction, we should also consider if the destination of a branch instruction can be determined statically. From this point of view, the branch instructions can be divided into two categories: one is *direct branches*, whose destinations are calculated in a PC (Program Counter)-relative mode and can be calculated statically. The other is *indirect branches*, whose destinations are stored in registers or memories. Their destinations are undefined statically and are determined

at runtime. Table III classifies different forms of `jmp/jcc/call/retn` instructions considering the above two categories.

Table III. Examples of Direct and Indirect Branches.

Direct Branches	<code>jmp rel8/16/32</code> <code>jcc rel8/16/32</code> <code>call rel16/32</code>
Indirect Branches	<code>jmp reg32/mem32</code> <code>call reg32/mem32</code> <code>retn</code>

Note: In this table, `rel` means a PC-relative address. The numbers (8, 16, and 32) are the size (in bit) of the operands.

Direct Branches. Since `jmp` instructions are the basis of the other branch instructions, we elaborate on the introduction of the virtual instructions and handlers of `jmp` instructions. As we have illustrated, the destination of a direct `jmp` instruction can be calculated statically. If the destination instruction of the `jmp` instruction resides in the critical code, the `jmp` is a *direct inner* `jmp`; otherwise a *direct outer* `jmp`. We designate virtual instructions for both of them, `jmp_di` for the former, and `jmp_do` for the latter. For *direct inner* `jmp`, it is able to obtain the corresponding bytecode instruction address of its native destination instruction during protection. Therefore, we set that bytecode instruction address as the operand of `jmp_di`, which is pushed into stack by `load_i`. The handler of `jmp_di` fetches the address from stack and assigns it to VPC (Virtual Program Counter). For *direct outer* `jmp`, we just need to jump to that destination instruction. Prior to that, we should restore the native context. Therefore, the operand of `jmp_do` is the address of the native destination instruction. Table IV presents the above two virtual instructions of *direct* `jmp` and their handlers.

Table IV. The Virtual Instructions and Handlers of `jmp` Instructions.

VI	Handler
<code>jmp_di</code>	<i>;operand: addr of the dest. bytecode instr.</i> <code>pop eax ;get operand</code> <code>mov VPC, eax</code>
<code>jmp_do</code>	<i>;operand: addr of the dest. native instr.</i> <code>pop [mem] ;get operand</code> <i>... ;restore native context</i> <code>jmp dword [mem]</code>

Note: `jmp_di` is for *direct inner* `jmp` and `jmp_do` for *direct outer* `jmp`.

`jcc` and *direct* `call` instructions are similar to *direct* `jmp`. `jcc` has many different kinds of instructions for different conditions, and each needs a specific virtual instruction. In the handlers, some extra instructions are needed to check the state of the conditions and decide to jump or not. `call` instructions can be considered as a push instruction followed by a `jmp` instruction. The push instruction pushes the return address into the stack and the `jmp` instruction jumps to the address of the subroutine.

Indirect Branches. Since it is difficult to obtain the address of an indirect branch, we cannot decide whether the branch is an inner one or an outer one. One solution is to delay the decision until runtime. In such case, however, the implementation of

Table V. Examples of Native Instructions and Their Corresponding Virtual Instructions.

Native Instr.	VI
mov eax, ebx	load_r 3 store_r 0
mov eax, dword [esi+4]	load_r 6 load_i32 4 add32 load_ms store_r 0
add eax, edx	load_r 0 load_r 2 add32 store_r 0
jmp 4020a8h (direct inner jump)	load_i32 42a583h jmp_di

Note: 42a583h is the bytecode instruction address that corresponds to the native instruction at 4020a8h.

the handler is complex. Hence, for these instructions, instead of using a similar idea as that for *direct branches*, we use a special virtual instruction `undef`, which will be introduced later.

6.4. Other Instructions

The above three categories cover the commonly used instructions. Although the other native instructions are rarely used, such as `bts`, `enter`, `int n`, and `out`, our native IS should consider them too. For these instructions, we define a special virtual instruction - `undef`. At runtime, when encountering such an instruction, it first restores the native context and exits the VM. Then, it executes that native instruction in native context and finally re-enters the VM and continues to execute the left bytecode instructions. The *indirect branches* are also processed in this way.

7. NATIVE INSTRUCTIONS TO VIRTUAL INSTRUCTIONS

At obfuscation time, we first convert native instructions into virtual instructions. This process follows a three-phase fashion: first, loading the operands into stack with `load` virtual instructions; then, executing the aimed operation; and finally, storing the result into virtual context or a certain memory address with `store` virtual instructions. Table V gives some examples of native instructions and their corresponding virtual instructions.

Data transfer instructions are mainly mapped into `load` and `store` instructions. Typical examples of these instructions are `mov`, `push`, and `pop`. Arithmetical and logical instructions strictly follow the three-phase processing. Branch instructions are mapped into a `load` instruction followed by a branch virtual instruction. Native instructions with complex addressing modes are processed iteratively with the above virtual instructions, for example, the "`mov eax, dword[esi+4]`" instruction in Table V.

8. VIS TO BYTECODES

Virtual instructions will be encoded into bytecodes in the end. It is similar to that an assembler assembles assembly instructions into machine code and only can be interpreted by virtual interpreter of VM-based protection system. We adopt an encoding scheme less compacted than the x86 instruction architecture which uses separate bytes for the *opcode* and *operand* of a virtual instruction. In practice, we assign each

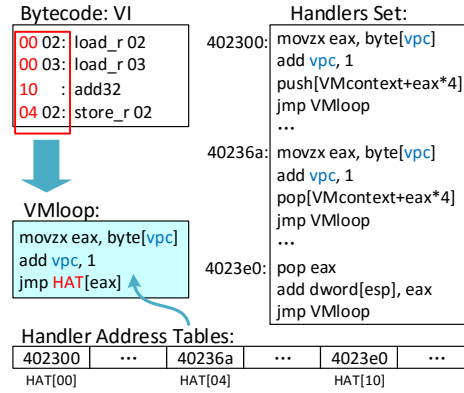


Fig. 4. Examples of some virtual instructions and their bytecode. Each virtual instruction is encoded into a bytecode instruction, which consists of an *opcode* and optionally an *operand*. The bytecode instructions feed into VMloop and the *opcode* of each bytecode instruction is used by VMloop as an index to find the address of the corresponding handler in the HAT (Handler Address Table).

virtual instruction a distinct ID as its *opcode*. The ID is used by VMloop as an index to find the address of the handler of the virtual instruction in the address table recording the addresses of each handler. Since the number of virtual instructions is less than 256, thus one byte is sufficient to encode their IDs. As for the *operands*, since they could be of different size⁴, we use one, two, or four bytes to encode them correspondingly. Figure 4 shows some examples of virtual instructions and their bytecode. The figure also demonstrates how VMloop fetches and interprets the bytecode instructions.

8.1. Randomize the Semantics of Bytecode Instructions

From the above demonstration, if an analyst gets known the semantics of a bytecode instruction, the next time she encounters it, she does not bother to analyze its handler once again to figure out what it does⁵. For example, in Figure 4, the bytecode instruction "10" means an addition operation through analyzing Handler_4023e0. The next time we encounter a bytecode instruction of "10", we could say that it does an addition operation immediately.

To mitigate the effect of reuse of previously obtained *analysis knowledge*, we randomize the semantics of virtual instructions. According to the encoding scheme we adopt, it is easy to achieve this goal. The idea is to change the relationship between the IDs (*opcodes*) and the virtual instructions, which is similar to [Kc et al. 2003]. Every time to encode the virtual instructions, the IDs are first shuffled once. Then the shuffled IDs are used to encode the virtual instructions. The addresses of handlers are also filled into the handler address table accordingly.

8.2. Partition Bytecode Program

With the randomization of the semantics of bytecode instructions, an analyst can not directly reuse her *analysis knowledge* to work out what a bytecode instruction actually does. However, the effect of the randomization could be easily bypassed. As shown in table V, the frequencies of virtual instructions are not uniform, where load_r and

⁴The *operand* of a virtual instruction could be an index for virtual register, an immediate value, or a memory address. They could be of different size: a virtual register index being 8 bits, an immediate value being 8/16/32 bits, and a memory address being 32 bits.

⁵Since handlers could be mutated to hinder analysis, it saves an analyst a lot of time and effort without bothering to analyze them once again.

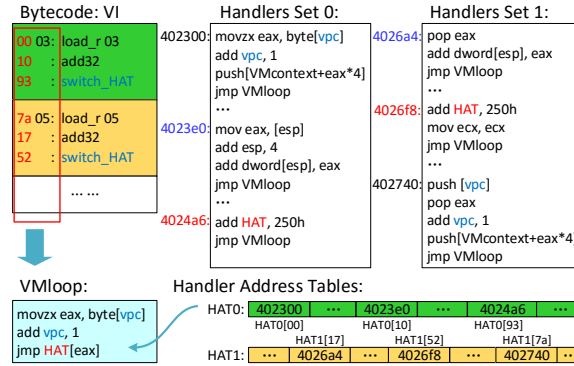


Fig. 5. Example of partitioning virtual instructions into several parts (two parts in this figure). Virtual instructions in different partitions are encoded differently and interpreted using different handlers set. The number of HAT increases accordingly. To switch the currently used (by VMloop) HAT to the next one, we add a new virtual instruction switch_HAT. The operand of switch_HAT is the size of a HAT.

store_r are two of the most frequently used virtual instructions. Thus, an analyst could infer the semantics of bytecode instructions based on the non-uniform frequencies of *opcodes*.

8.2.1. Bytecode Program Partition Design. To frustrate the inferences based on the frequencies of *opcodes*, we partition all the generated virtual instructions into several parts, each part been encoded differently. Specifically, during obfuscation, instead of encoding the generated virtual instructions all at a time, we encode those resulted parts separately. And prior to each encoding process, we first randomly shuffle the IDs of virtual instructions and then use the results for encoding. The effect of the shuffles is that an identical *opcode* in different parts of the bytecode program probably reveals different semantics, thus the frequencies of *opcodes* are obscured. Figure 5 shows an example of partitioning the virtual instructions into two parts. The opcode of a virtual instruction is probably encoded differently in different parts. For example, load_r is encoded into "00" in the first part, while "7a" in the other.

ALGORITHM 1: Partition Bytecode Program

Input: VIs of critical code segment, partition number N .

Output: Bytecode program with N partition.

- 1: Apply memory space M ;
 - 2: VIs randomly divided into N partitions;
 - 3: Generate N sets of handlers by using algorithm 2;
 - 4: **while** $N \neq 0$ **do**
 - 5: Take a partition;
 - 6: Randomly select a set of handlers and shuffle the IDs of virtual instructions;
 - 7: Build a corresponding HAT;
 - 8: Use the shuffle results to encode bytecode program P ;
 - 9: Store the P to M ;
 - 10: $N - -$;
 - 11: **end while**
-

Algorithm 1 demonstrated the implementation of the partition encoding. Partition the bytecode program, we will randomly divide virtual instructions into N partitions and obfuscate the original HAS (Handler Set) for N times to get N sets of handlers,

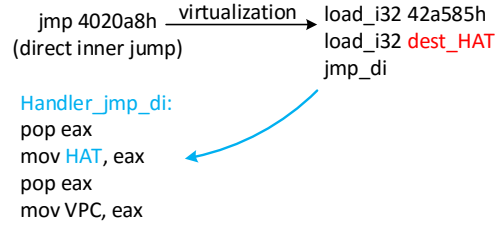


Fig. 6. The virtualization of a *direct inner* transfer instruction with HAT switching. The address of the destination HAT is pushed into stack by `load_i`, and is assigned to the HAT pointer used by VMloop at runtime.

and the detailed HAS obfuscation approach are demonstrated in section 8.3. For each partition, we will randomly select one set of handlers and shuffle the IDs of virtual IS, and then use the results to encode the VIs into a specific bytecode program. In the end, a complete bytecode program is generated, which has multiple partitions and the same bytecode has different semantics in different partitions. These specific bytecodes only can be interpreted by system's virtual interpreter.

As the *opcodes* of bytecode instructions are used by VMloop as the indexes for the addresses of their corresponding handlers, and different partitions are encoded differently, each partition needs their own HAT. At the end of a partition, the HAT used by VMloop should be switched to the HAT of the next partition. This is done by a new virtual instruction - `switch_HAT`. Since `switch_HAT` is always added to the end of a partition and the orders of HATs are in accordance with that of the partitions, `switch_HAT` needs to add the size of a HAT to the HAT pointer used by VMloop (as `Handler_4024a6` does in figure 5). In our prototype, the number of Handlers is 148 and the address of a Handler is 4 bytes, thus the size of a HAT is 592 (250h in hexadecimal) bytes.

The switchings of HATs is not limited to the end of partitions. A branch instruction also causes the switching when its destination resides in a different partition. Branch instructions change the control flow of a program through changing the VPC. When encounter such an instruction, we cannot simply append a `switch_HAT` to it, since the `switch_HAT` may not get interpreted by VMloop if the VPC is changed to a location in another partition. Hence, we put the code for switching inside the Handlers of the branch instructions. Here, the branch instructions indicate the *direct inner* ones, as *direct outer* branches and *indirect* branches all leave the virtual context and need not to worry about the switching of HATs. During protection, for each *direct inner* branch instruction, we first calculate its destination, and then figure out which partition the destination resides. The address of the HAT of that partition is pushed into stack by `load_i` and will be used by the Handler of the branch instruction to set the value of the HAT pointer used by VMloop. Figure 6 shows the virtualization of a *direct inner* branch instruction, compared to that in table IV.

8.2.2. Security Analysis of Partition Design. Assume there is an attacker now, which uses the attack method based on virtual execution that introduced in section 4 to reverse the partition bytecode program. First, the attacker needs to perform dynamic debugging the target program, and then spend some time to locate the address of VMloop from the obfuscated virtual interpreter. Next he needs to collect the bytecode program by analyzing the parameters of VMloop.

To restore the logical function of the original code, the attacker needs to analyze the semantics of these extracted bytecodes. But for the target program, which generated by using a special encoding schemes and its bytecode program is divided into multiple partitions. So the attacker must first obtain the partition informations of critical code

to further reverse analysis, but it is difficult for him. After the NIs is converted to a VIs, there is a HAT switching operation by using VI - switch_HAT at the end of each partition. However, virtual instruction is just an intermediate language in the process of protection, and it does not appear in the final program. All of the instructions will eventually be in the form of bytecodes, and the bytecode semantics of each partition is randomly changed (such as bytecode “93” and “52” in figure 5). So the attacker cannot use this feature to delineate the partition. He can only spend a lot of time through continuous tracking and debugging to predict the partition of the transformation.

Assume that the attacker gets the partition information after a lot of analysis. Next the attacker need to analyze the bytecode of each partition and extract the semantic information implied by the handlers. Because the bytecode of each partition has a different semantics, and their mapping handlers are also with different forms. Therefore, the attacker cannot reuse the previous *analysis knowledge* to attack the next partition, and for different target program that protected by DCVP is more like this. Unique partition configuration and different handler sets, so that the attacker cannot achieve the batch automatic attack by building attack knowledge base. The attacker has to spend a lot of time to analyze every detail for each program.

8.3. Obfuscate the Handler Sets

To further impede automated reverse analysis, we can obfuscate the handlers, and use different obfuscation strategies for handlers in different partitions. As a result, a handler in different partitions will looks different. An analyst cannot immediately recognize them as the the same one and needs to analyze each of them, which increases the workload of the analyst. At the same time also can prevent the attacker use attack knowledge base to match these handlers to achieve automated reverse analysis.

ALGORITHM 2: Virtual Interpreter Obfuscation

Input: The original HAS, partition number N .

Output: N equivalent HASs with different forms.

```

1: while  $N \neq 0$  do
2:   Apply memory space M1;
3:   Take the first handler from HAS;
4:   while There are still untreated handler do
5:     Randomly select multiple obfuscation methods and using order of them;
6:     Obfuscate handler and store the results to M1;
7:     Take the next handler from HAS;
8:   end while
9:   Apply memory space M2;
10:  Using the anti-taint analysis technique to protect the code in M1;
11:  Store the results to M2, and release the memory space of M1;
12:   $N - -$ ;
13: end while
```

The obfuscation approach we take is shown in Algorithm 2. The number of HAS obfuscated is determined by the number of partitions. Our system will randomly select several methods from the obfuscation method library which contains the junk instructions injection, equivalent instruction substitution [Nicolaou George 2009], code out-of-order [Birrner et al. 2007] and control flow flattening [Wang et al. 2001]. Then the system will use the selected method in a random order to obfuscate the handler. Finally we have multiple equivalent but different forms of HASs. We will also adopt some anti-taint analysis techniques (some details are presented in section 8.4) to protect the

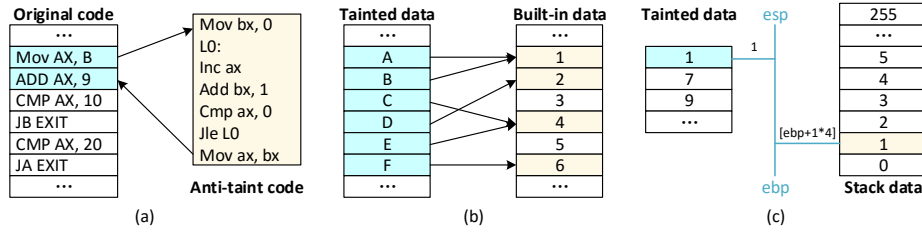


Fig. 7. Examples of three anti-taint analysis techniques. Respectively as, (a) the transfer of naive model, (b) the transfer of control dependencies and (c) the indirect transfer of stack pointer.

HASs that after obfuscated. This can effectively prevent the virtual interpreter from being attacked by some de-obfuscation methods.

For example, HAS (Handler Set) as an original handler set that consists of m handler. We use a HAT to store the address of these handlers, and their index corresponds to the *opcode* of virtual instruction. HAS will be obfuscated for n times with different strategies, n is dependent on the number of partitions. Then we get multiple HASs and which are semantic equivalence but have different forms. At this time, all of the equivalent handlers still have the same index. This is a type of insecure and direct mapping relationship. Therefore, according to the method that partition bytecode program and randomized the semantics of bytecode instructions in the upper section 8.2, we first randomly shuffle the IDs of virtual instructions and then use these results to generate a new HAT for each partition (as shown in figure 5). The effect of shuffles is that an identical *opcode* in different parts of the bytecode program probably reveals different semantics. The relationship of these equivalent handlers in different HASs should be:

$$HAS_1(i) \Leftrightarrow HAS_2(j) \Leftrightarrow \dots \Leftrightarrow HAS_n(k), 1 \leq i, j, k \leq m.$$

This various semantics of bytecode instructions and different forms of handlers can effectively prevent the attacker from using the attack knowledge base matching to realize the automated reverse analysis. The attacker has to spend a lot of time to analyze every detail.

8.4. Anti-Taint Analysis

Simply obfuscating the handlers, however, cannot prevent an attacker from reverse engineering completely. There are several existing de-obfuscating techniques that can be used to counter the traditional virtualization protection. Such as, Coogan et al. [Coogan et al. 2011], who use equational reasoning about assembly-level instruction semantics to simplify away obfuscation code from execution traces of emulation-obfuscated programs. Yadegari et al. [Yadegari et al. 2015], which use taint propagation to track the flow of values from the programs inputs to its outputs, and semantics-preserving code transformations to simplify the logic of the instructions that operate on and transform values through this flow.

However, the work of Coogan et al. is based on equational reasoning about assembly level instruction semantics, and such a approach has some drawbacks that is difficult to simplify the complex equation, making it hard to separate out the different components of nested loops or complex control flow. So it is difficult to extract the implicit logic from the high level structures, such as control flow graphs or syntax trees. Besides, this is a kind of behavior based analysis method, which has good applicability to the analysis of malicious code, but the result of the analysis of the benign program is not good. The results can not fully reflect the function of the protected code.

Work of Yadegari et al. can be effective even when applied to previously unseen obfuscations, but there are still some shortcomings that code simplification should be first to identify input-to-output flows by using taint analysis. They rely on the taint propagation and forward/backward taint analysis to identify the explicit flow of values from inputs to outputs, then use control dependence analysis to identify implicit flows. Further on this basis to do trace simplification. Therefore, we can strengthen the handlers obfuscation approach with the anti-taint analysis to impede this kind of de-obfuscate approach.

In order to protect the obfuscated virtual interpretation procedure, we will adopt the anti-taint analysis techniques to protect the data flow of the handlers from taint analysis. Specific ways are as follows:

The transfer of naive model. A simple case is given in Figure 7-(a), assuming that there is a variable B that has been marked by taint, we need to transfer the value of B to AX . If we use the MOV instruction, AX will also be tainted. The transfer of naive model is that to do subtraction operation for B , at the same time to do addition operation for AX . When the value of B is reduced to "0", the value of AX increased from "0" to B , and AX will not be marked as a tainted data.

The transfer of control dependencies. Control dependence analysis is an important step towards the process of taint analysis. For a set of tainted data, to carry out anti-taint analysis processing. As shown in Figure 7-(b), we can launder tainted data by assigning the data that non tainted directly to the tainted data. This process needs to match the tainted data and not tainted data, in order to ensure the correctness of the data will not be affected.

The indirect transfer of stack pointer. As we can see from Figure 7-(c). The indirect transfer of stack pointer took advantage of the working principle of the stack to implement the anti-taint analysis. The principle of this method is to first put a set of non tainted data into the stack, and then through the address pointer of stack data to access the stack data, and finally use the stack data to replace the tainted data to implement the anti-taint analysis.

The above three methods can effectively prevent the spread of tainted data by laundering tainted data, and then can effectively resist the taint analysis.

9. EVALUATION

In this section, we will evaluate the effectiveness of our method for mitigating the effect of reuse of *analysis knowledge* and the spatial and temporal overhead of our method.

9.1. Effectiveness Evaluation

DCVP is effective for impeding reverse analysis by invalidating existing *analysis knowledge*. From Section 2, we learned that understanding the semantics of bytecode instructions is essential for reverse engineering a VM-obfuscated program. Semantics are encapsulated in handlers, and the work of extracting them from handlers is tedious and error-prone. Therefore, it will save analysts lots of time and energy if the semantics of bytecode instructions are accessible, without bothering to trace and analyze the handlers once again. DCVP's aim is to frustrate this attempt and force analysts to analyze the handlers every time. Through randomizing the semantics of bytecode instructions, the same bytecode instruction probably means different obfuscated instances, and even different in the same obfuscated program by adopting different encoding schemes for different partitions of the bytecode program, which can largely confuse analysts and increase their workload.

Table VI. Statistics of the Target Programs.

Target Program	Version	Size(KB)	Critical Code	N1	N2	Ratio	N3
md5.exe	2.3	11	Transform()	1327	563	42.36%	85013
gzip.exe	1.2.4	56	deflate()	10181	153	1.50%	539082
bcrypt.exe	1.1.2	68	Blowfish_Encrypt()	2997	54	1.80%	1735710
mat_mul.exe	-	184	ijkalgorithm()	49327	60	0.12%	84325

Note: The 5th and 6th column gives the number of instructions in the entire program and these critical functions respectively, The 7th column gives the proportion of critical code. We use Pin¹⁰ to count the number of the dynamically executed instructions in the critical functions and the results are shown in the last column. We chose only 60 instructions of mat_mul is special to verify the impact of DCVP on the program overhead when protecting a small amount of code. The results are shown in figure 9 and the impact is not obvious.

Assuming that the number of virtual instructions, or the number of handlers in other words, is H , then the probability of two identical bytecode instructions in two obfuscated programs having the same semantics is $\frac{1}{H}$. The total number of distinct shuffle of the *opcodes* is $H!$. In an obfuscated program, supposing the bytecode program is partitioned into N parts, then the probability that a bytecode instruction in different partitions having the same semantics is $(\frac{1}{H})^{N-1}$. Therefore, we believe DCVP can effectively remove the *analysis knowledge* about the semantics of bytecode instructions.

9.2. Overhead Evaluation

To evaluate the spatial and temporal overhead of our method, we implemented a prototype, namely DCVP, for obfuscating x86 PE executables on the Windows platform. In the implementation, we devised 148 virtual instructions and their corresponding handlers. We conducted all the experiments on a Dell Optiplex 960h with an Intel®Core™ 2 Duo Processor E8400 at 3.00GHz with 4.00GB of RAM. The operating system environment is Windows 7 Enterprise.

We use DCVP to protect four x86 PE executables, namely md5.exe⁶, gzip.exe⁷, bcrypt.exe⁸, mat_mul.exe⁹. The first three are used to process a text file (test.txt) of 10KB and mat_mul is used to calculate the product of two 5×5 matrices. Table VI shows the statistics of these executables. For each program, we choose a piece of critical code to protect, as shown in table VI. The programs are protected 10 times, each time with a parameter that specifies a different number (1~10) of partitions.

Figure 8 shows the size of the obfuscated programs. The horizontal axis specifies the number of partitions in the obfuscated programs and “0” means the original program. As the partitions increase, the increased bytes mostly come from the added HATs and HAS. Since the size of a HAT is only 592 bytes, the sizes of the HATs increase slowly. Besides, the sections in PE executables are aligned to a value (4096 or 512 usually)[Pietrek 1994], the increase of sizes may not reveal immediately as the partitions increase. The filesize of the program is mainly affected by the number of HAS, and it increases with the increase of HAS regularity.

To evaluate the runtime overhead that DCVP introduces, we run the obfuscated programs for several times and calculate the average execution time of them: md5, gzip, and bcrypt are used to process a text file (test.txt) of 10KB; matrix_mul is used to calculate the product of two 5×5 matrices. The average execution time is shown in

⁶MD5: Command Line Message Digest Utility. <http://www.fourmilab.ch/md5/>.

⁷gzip. <http://www.gzip.org/#sources>.

⁸Bcrypt - Blowfish file encryption. <http://sourceforge.net/projects/bcrypt/>.

⁹Matrix multiplication. <https://github.com/MartinThoma/matrix-multiplication>.

¹⁰Pin - A Dynamic Binary Instrumentation Tool. <https://software.intel.com/en-us/articles/pin-a-dynamic-binary-instrumentation-tool>.

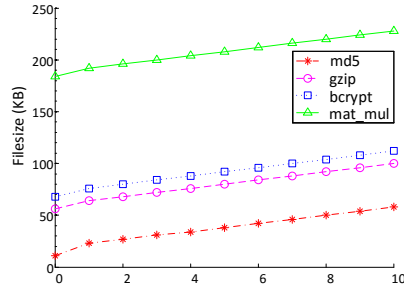


Fig. 8. The impact on file size (KB) of DCVP. The file size slightly increased with the increase of number of partitions

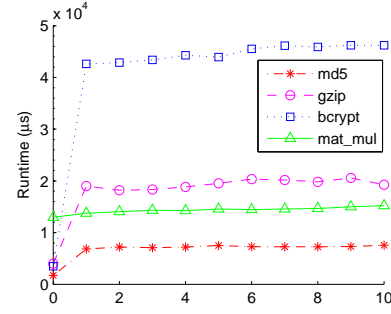


Fig. 9. The impact on runtime performance (μs) of DCVP with different partitions.

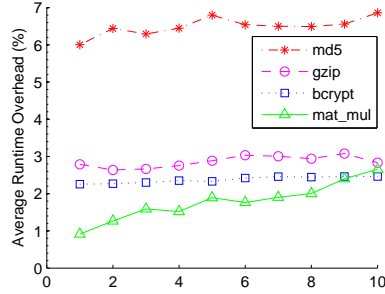


Fig. 10. The average runtime overhead per dynamically executed critical instruction.

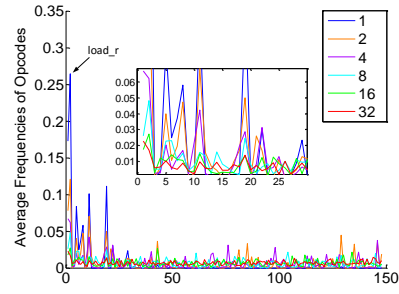


Fig. 11. The average frequencies of *opcodes*. The horizontal axis specifies the *opcodes*.

figure 9. Among them, bcrypt has the largest increase of execution time from original program¹¹ to the obfuscated program with one partition. This resulted from that the critical instructions in bcrypt is executed much more times than others (as shown in the last column in table VI). Besides, the execution time changes little as the number of partitions increases. From section 8.2 we can learn that if the number of partitions increases by one, the program only needs to execute an extra handler to interpret the switch_HAT instruction. The introduced runtime overhead is negligible. In some situations, the execution time of an obfuscated program with more partitions may have a slightly lower runtime overhead. This probably results from the locality of reference¹².

We evaluate the average runtime overhead per dynamically executed instruction. We use T_{ob} to denote the execution time of a obfuscated program, T_o for that of the original program, and C_e for the count of the critical instructions been dynamically executed. The average runtime overhead per dynamically executed instruction is calculated by

$$(T_{ob} - T_o)/C_e.$$

The results are shown in figure 10. From figure 10, we can learn that md5 has the largest average runtime overhead per dynamically executed instruction. The reason is that the critical code of md5 is full of arithmetical and logical instructions, which takes a longer time to interpret.

¹¹The execution time of the original program is specified by “0” on the horizontal axis.

¹²Locality of reference. https://en.wikipedia.org/wiki/Locality_of_reference

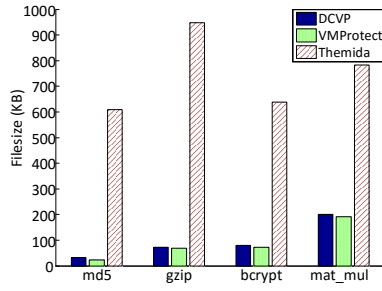


Fig. 12. The comparison of impact on file size (KB) with VMProtect and Themida.

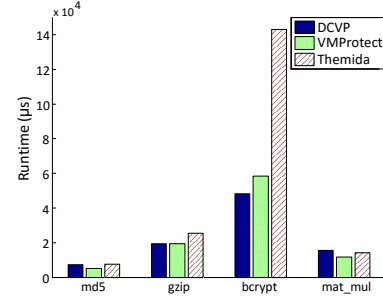


Fig. 13. The comparison of runtime performance (μ s) with VMProtect and Themida.

We also put the four target programs together and count the average frequencies of *opcodes*. We take the obfuscated programs with 1, 2, 4, 8, 16, and 32 partitions for comparison. The results are presented in figure 11. As we can see, as the number of partitions increases, the frequencies of *opcodes* tend to be closer. When the partition number is 1, we can easily get the instruction that has the highest frequency is “load_r”, since it is the most commonly used instruction.

Finally, we use two commercial code virtualization protection system for comparison, VMProtect [VMProtect-Software 2016] and Themida [Oreans-Technologies 2016b]. Figure 12 shows the impact of the three virtualization protection system on the file size of the four target programs. The cost of Themida is much greater than the other two system, and the impact of DCVP and VMProtect is similar. This result should be related to the design of virtual instructions and handlers. Runtime overhead as shown in Figure 13. In general, the effects of the three protection systems are similar. Special, the runtime overhead of bcrypt that protected by Themida is far greater than the other target programs.

10. RELATED WORK

Software protection is used to protect the intellectual property encapsulated within software programs from been understood and modified, by transforming target program into a more obscure and hard-understanding one. The earliest published works in software protection can be traced back to 1980, Kent [Kent 1981] addressed the security requirements of software vendors: protection from software copying and modification. During the past decades, numerous approaches of software protection have been proposed, e.g. junk instructions, equivalent instructions [Nicolaou George 2009], packer (such as, “ASProtect”¹³, “UPX”¹⁴), code encryption, control flow and data flow obfuscation [Collberg and Thomborson 2002; Liem et al. 2008; Ge et al. 2005], etc. These conventional approaches alone provide only limited obscurity, and one protection system usually integrates several of these and makes them work together to provide a certain level of obscurity.

In recent years, there have been many different code protection technology. Such as, control flow integrity [Zhang et al. 2013; Zhang and Sekar 2013] provide a strong protection against modern control flow hijacking attacks, including those based on Return-Oriented Programming (ROP). Code Randomization, Stephen Crane et al. [Crane et al. 2015] presents a practical, fine-grained code randomization defense, called Readactor, resilient to both static and dynamic ROP attacks. At the same time, the code reverse

¹³Application Protection Tools for Software Developers, <http://www.aspack.com/asprotect32.html>.

¹⁴Ultimate Packer for eXecutables (UPX), <http://upx.sourceforge.net/>.

analysis technology is developing. Symbolic and concolic execution [Yadegari and Debray 2015] and Data flow tracking and taint analysis [Jee et al. 2012; Balliu et al. 2014; Yadegari et al. 2015] can find important applications in a number of security-related program analyses, including analysis of malicious code. This paper focuses on the code virtualization protection and its reverse analysis technology.

Code virtualized obfuscation, has recently been used to protect software from malicious reverse engineering [Oreans-Technologies 2016a; VMProtect-Software 2016; Fang et al. 2011; Wang et al. 2014; Wang et al. 2013]. In Section 2 and 4 we have already introduced the details of VM-based obfuscation and possible attacks. Existing researches on VM-based obfuscation focus on foiling reverse analysis. TDVMP [Wang et al. 2014] obfuscates handlers to generate multiple semantics-equivalent but appearance-different ones and embeds them into target program. At runtime, it will execute different instructions since the execution of each handler is chose from the several candidates randomly, i.e., the obfuscated program has a per-process execution diversity. This is especially useful for defeating dynamic analysis. Fang et al. [Fang et al. 2011] presented a multi-stage obfuscation method that iteratively transforms a program for many times in using different interpretations. DCVP focuses on invalidating the analysis knowledge about the semantics of bytecode instructions and preventing from quick and large scale reverse analyses, which is orthogonal to the above approaches and is complementary to them.

Has been also have some deobfuscation techniques of code virtualization was put forward. Representative like, Sharif et al. [Sharif et al. 2009] used dynamic data-flow and taint analysis to identify data buffers containing the bytecode program and extract the syntactic and semantic information about the bytecode instructions. Coogan et al. [Coogan et al. 2011] proposed an approach to identify instructions that related to system calls, and automatically extract an approximate dynamic trace of the original code. Yadegari et al. [Yadegari et al. 2015], proposed an approach to track the flow of inputs values, and then use semantics-preserving code transformations to simplify the logic of the instructions. These approach, however, or can only extract some execution characteristics of target program and can not restore the structure of the original code completely, or needed taint analysis to track and analyze the data flow, and this process may be impeded by enforcing dataflow obfuscation to the handling procedures [Liem et al. 2008]. These methods are limited more or less.

DCVP adopts ISR (Instruction Set Randomization) techniques while generating randomized and distinct virtual instruction sets. ISR has been used to prevent code injection attacks by randomizing the underlying system instructions [Barrantes et al. 2003; Kc et al. 2003; Portokalidis and Keromytis 2010]. In this approach, instructions are encrypted with a set of random keys and then decrypted before being fetched and executed by the CPU. ISR is effective for defeating code injection attacks but cannot prevent from reverse engineering attacks. As in our attack model, software programs are executed in a malicious host environment, where attackers are able to trace and log the decrypted instructions for later analysis. DCVP employs an approach similar to ISR while generating random virtual instruction sets, by changing the relationship between the opcodes and the virtual instructions [Kc et al. 2003], but it never “decrypts” the virtual instructions back into their original ones. Instead, DCVP uses handlers to interpret the virtual instructions, and the handlers of virtual instructions are more complex than their corresponding native instructions. Besides, DCVP uses the multiple partitions and has the different ISRs in a single program, making the reverse analyses even more difficult and tedious.

11. CONCLUSION

In this paper, we have introduced the internals of code virtualized obfuscation and the process of reverse analyzing a VM-obfuscated program. Although such obfuscation poses a great obstacle to an analyst, the presence of *analysis knowledge* can ease the work of the analyst. To mitigate the effect of reuse of *analysis knowledge*, we present DCVP, which disables the *analysis knowledge* by randomizing the semantics of bytecode instructions. Furthermore, DCVP partitions the generated virtual instructions into several parts, each been encoded differently. This defeats the attempts to infer the semantics of bytecode instructions based on the non-uniform frequencies of *opcodes*. Our evaluations show that DCVP is effective for mitigating the effect of reuse of *analysis knowledge*. As future work, we plan to: (1) use existing virtual instructions to switch the HAT instead of the specific `switch_HAT` for sake of the stealthiness of the switching; (2) work on data flow obfuscation to defeat semantics-based de-obfuscation.

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