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Obfuscated Instructions for Software Protection

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Abstract

Many computer systems are designed to make it easy for end-users to install and update software. An undesirable side-effect, from the perspective of many software producers, is that hostile end-users may analyze or tamper with the software being installed or updated. This paper proposes a way to avoid the side-effect without affecting the ease of installation and update. We construct a computer system *M* with the following properties: 1) the end-user may install program *P* in any conveniently accessible area of *M*; 2) the program *P* contains obfuscated instructions whose semantics are obscure and difficult to understand; and 3) an internal interpreter *W*, embedded in a non-accessible area of *M*, interprets the obfuscated instructions without revealing their semantics. Our *W* is a finite state machine (FSM) which gives context-dependent semantics and operand syntax to the obfuscated instructions in *P*; thus, attempts to statically analyze the relation between instructions and their semantics will not succeed. We present a systematic method to construct a *P* whose instruction stream is always interpreted correctly regardless of its input, even though changes in input will (in general) affect the execution sequence of instructions in *P*. Our framework is easily applied to conventional computer systems by adding a FSM unit to a virtual machine or a reconfigurable processor.

1 Introduction

Security is an overarching problem for today's computer systems including personal computers, their peripherals, consumer electric devices, and any other machinery that contains software programs. Some systems administrators, and some software suppliers, require assurance that end-users will not analyze or tamper with protected programs or data. For example, a typical software digital rights management (DRM) system is designed to run in a "hostile" environment where the end-user is not fully trusted by the supplier of the content whose rights are being managed. Typically, these DRM systems contain cryptographic keys and algorithms that need to be kept secret [Chow, Johnson and Oorschot 2002]. There is, however, no known method for completely concealing these keys and algorithms from a determined attacker. For example, the keys for the CSS encryption standard for DVD media content were revealed by a "crack" in 1999. As a result, programs which subvert DVD copy protection are now widely distributed through the Internet [Patrizio 1999]. Embedded software in consumer electric devices, e.g. mobile phones and set-top boxes, also needs to be protected since these devices are also susceptible to attacks by hostile users [The U.K. Parliament 2002]. However, it seems impossible to completely prohibit end-user access to the software implementation, without also making it impossible to update this software to patch a "bug" or add a "feature".

In order to hide secrets in software implementation, software obfuscation techniques have been proposed [Cohen 1993, Collberg and Thomborson 2002, Kanzaki et al. 2003]. Software obfuscations transform a program so that it is more difficult to understand, yet is functionally equivalent to the original program. However, there is no evidence those techniques are powerful enough to hide secrets in a program [Barak et al. 2001]. Given enough time and effort, the obfuscated program can be understood by hostile users since it still contains all the necessary information to be thoroughly understood. Although software obfuscations are practically useful to some extent, a variety of complementary techniques are needed to dissuade the widest possible range of attackers.

Instead of obfuscating the program itself, this paper gives an idea for obfuscating the program interpretation. If the interpretation being taken is obscure and thus it can not be understood by a hostile user, the program being interpreted is also kept obscure since the user lacks the information about "how to read it." This idea is similar to the randomized instruction-set approach [Barrantes et al.

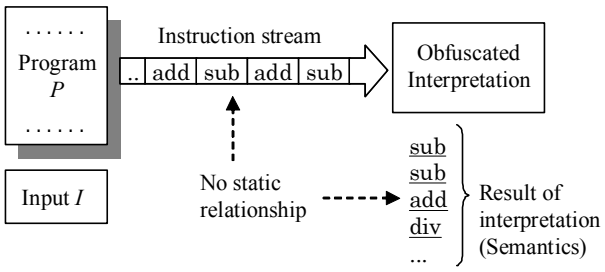

Figure 1. Concept of obfuscated interpretation

2003]; however, in the randomization approach, the interpretation itself is not obscure because randomized instructions still have one-to-one map to their semantics, although the map can be occasionally changed [Kc, Keromytis, and Prevelakis 2003]. On the other hand, our aim is to give a dynamic map between instructions and their semantics.

In this paper we describe enhancements to our recently-proposed framework for constructing an interpreter W, which carries out *obfuscated interpretations* for a given program P [Monden et al, 2003]. Here P is a translated version of an original program P_0 written in a common programming language (such as Java bytecode and x86 assembly.) The obfuscated interpretation means that an interpretation W for a given instruction c is not fixed; specifically, the interpretation $W(c)$ is determined not only by c itself but also by previous instructions input to W (Figure 1).

In order to realize an obfuscated interpretation in W, we employ a FSM that takes as input an instruction c where each state makes a different interpretation for c. Since transitions between states are made according to the input, the interpretation for a particular type of instruction varies with respect to previous inputs. Such W we call a FSM-based interpreter. In our framework, W is built independent of P_0; thus, many programs run on a single interpreter W, and any of the programs can be easily replaced to a new program for the sake of updating.

In our original proposal [Monden et al, 2003], we had required the obfuscating opcode translation to preserve the number and type of the operands. In this paper we demonstrate how to build a FSM without this restriction. This increases the range of possibilities from which the FSM W is chosen, which has an effect analogous to increasing the "key length" of a cryptographic cipher. That is, the proposal in this paper is more resilient to brute-force enumerative ("naïve key-search") attacks. This paper also extends its predecessor by demonstrating an example in x86 assembly code rather than in Java bytecode; this extension required us to add a dead-register analysis to our process for obfuscating code by interpretation.

In some sense, the mechanism of our obfuscated interpretation is a kind of stream cipher where a ciphered bit sequence is decoded one bit at a time dependent on its context [Robshaw 1995, Stinson 1995]; however, conventional stream ciphers can not be simply applied for encrypting the instructions in P since the instruction stream (execution sequence) of P varies according to conditional branches taken on its input. In our framework, through the process of translation $P_0 \rightarrow P$, we inject dummy instructions into P to force expedient state transitions in W so that P is always interpreted correctly regardless of its input.

Apart from obfuscation techniques, another possible way to hide secrets in software is program encryption [Albert and Morse 1984, Herzberg and Pinter 1987]. Encrypting P_0 by an encryption function E can make P_0 difficult to understand. However, decryption E^{-1} must take place before executing an encrypted program $E(P_0)$, and this decryption must reveal P_0 (or a part of P_0) to the execution unit or interpreter, thus, hostile users have a chance to intercept and read the decrypted program P_0. On the other hand, in our framework, although $W(P)$ may reveal an instruction stream of P_0 as it executes on a particular input I, it will not reveal P_0 itself. Anyway, obfuscation of code, obfuscation of interpretation, and encryption of code are not exclusive techniques, and should be used as complementary techniques to secure the software system.

The rest of this paper is organized as follows. In Section 2, a framework for obfuscated interpretation is described which is less restrictive than our original proposal. Section 3 shows a case study of obfuscated interpretation. Section 4 discusses several attacks and defences. Finally, Section 5 concludes the paper with some suggestions for future work.

2 Framework for Obfuscated Interpretation

2.1 Overview

Before going into the mechanism of the FSM-based interpreter W, we describe the surroundings of W (Figure 2), then clarify the aim of our framework. The following are brief definitions of materials related to W.

P_0: is a target program intended to be hidden from hostile users. For simplicity, we assume P_0 is written in a low level programming language, such as bytecode or machine code, where each statement in P_0 consists of a single opcode and (occasionally) some operands.

W_0: is a common (conventional) interpreter for P_0, such as a Java Virtual Machine, a Common Language Runtime or an x86 processor.

P_x: is a program containing obfuscated instructions whose semantics are determined during execution according to their context. This P_x is an equivalently translated version of P_0, i.e. P_x has the same functionality as P_0.

I: is an input of P_0 and P_x. Note that P_0 and P_x take the same input.

x: is the specification of a FSM that defines a dynamic map between obfuscated instructions (inputs of the FSM) and their semantics (outputs of the FSM). This x is used both in a FSM-based interpreter W_x and a program translator T_x.

W_x: is a FSM-based interpreter that can evaluate obfuscated instructions of P_x according to the current state of the FSM built inside. This W_x is an extension of W_0 with a FSM unit of given specifications x.

T_x: is a program translator that automatically translates P_0 into P_x with respect to the specifications x.

M_x: is a computer system delivered to and/or owned by a program user.

In our framework, we assume W_x is hidden from the program user as much as possible, e.g. if M_x is an electronic device such as a mobile phone, then W_x should be built in a non-accessible part of M_x so as to prevent the user reading the implementation of W_x. However, P_x must be delivered to the user and put in an accessible area of M_x so as to enable its updating. There should be many functionally-different W_x, and ideally each machine M_x would be manufactured with a different W_x so that an adversary cannot easily guess one machine's interpreter after having "cracked" some other machine's interpreter.

Building an efficient T_x in a systematic manner is a fundamental part of this framework. Since P_x is quite different from ordinary programs, even though the program developer owns x, writing P_x from scratch is extremely difficult for the developer. In our framework, we provide a systematic method T_x to construct P_x from any given P_0 and x.

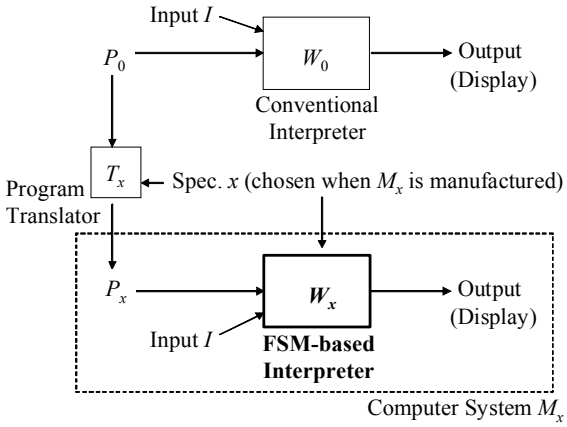

Figure 2. Framework for obfuscated interpretation

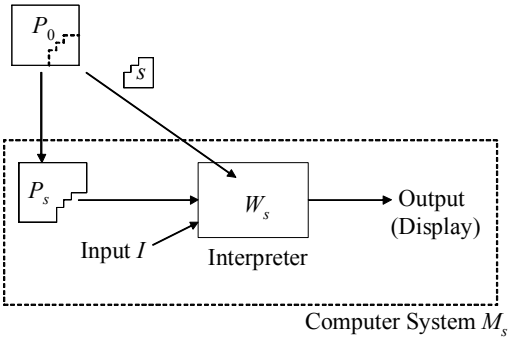

Figure 3. Alternative approach to hide program interpretation

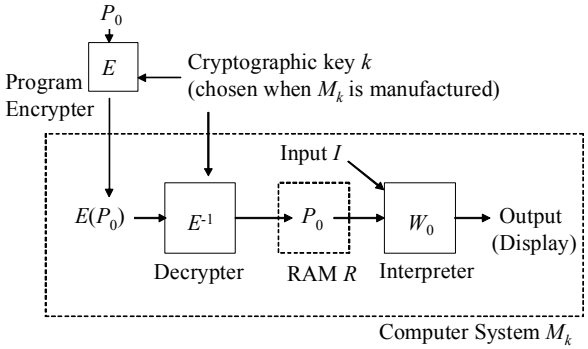

Figure 4. Basic approach for program encryption

In comparison to our framework, Figure 3 shows an alternative approach to hide the program interpretation from the user [T. Maude and D. Maude 1984, Zhang and Gupta 2003]. In this approach, an essential piece of code (denoted s) is cut off from P_0. This secret portion s is embedded in an interpreter W_s which is implemented in secure hardware, and attached to computer system M_s. The remaining part of the program (denoted P_s) is delivered to the user in

the usual way. This program is executed normally on the CPU in M_s, except for the secret portion which is executed by making calls to the interpreter W_s. For example, some of the arithmetic operations in P_s may be executed by W_s, possibly updating one or more state variables held in W_s. Since the return value from the calls to the interpreter W_s may be used to control branches and case statements in P_s, much of the control structure of P_0 can be obscured. One difficulty with this approach is that it does not allow multiprogramming: while W_s is holding state for P_s, no other program can be run on W_s. Another problem is that any adversary who examines P_s will soon discover how to call W_s. The adversary can then write a program which makes similar calls to W_s in various orders. An analysis of the variability in the output of W_s, when it is exercised in this systematic way, is likely to reveal secrets of W_s. A final problem is that updates to P_s will, in general, require updates to its secret portion s. Thus we must have a secure channel for the transmission of s in encrypted form, and this channel is another avenue for attack. On the other hand, in our framework, W_x is built independent of P_0; thus, many different programs run on a single interpreter W_x, and any of the programs can be easily updated without sending secret messages.

The most commonly-proposed method for hiding interpretation is program encryption [Albert and Morse 1984, Herzberg and Pinter 1987]. Figure 4 illustrates a typical scheme in which an encrypted program $E(P_0)$ is delivered to the user, and a decrypter E^{-1} including a decryption key k is put in a non-accessible area of a computer system M_k. This E^{-1} decrypts $E(P_0)$, and puts the resultant P_0 in a random-access memory R. Then, this P_0 is passed to the interpreter W_0 for execution. In this approach, $E(P_0)$ itself is not understandable to the user. Also, many different programs can run on a single system M_k, and they are easily updatable. However, the problem of this approach is that it is not easy to completely hide the decrypted P_0 from the user. One method for hiding the decrypted P_0 is to decrypt only a small piece of $E(P_0)$ at a time, and our approach takes this method to its logical extreme – we "decrypt" (translate) only one instruction at a time. Our approach minimises the size of RAM R, and building W_x in a non-accessible area of M_x's hardware is easily realized by adding a small FSM unit to current hardware-based virtual machines [such as picoJava, TinyJ, and Xpresso], modern implementations of the x86 instruction set (which translate it into a simpler microcode before execution), and reconfigurable processors. A final point of distinction, as noted in Section 1 above, is that our interpreter translates the dynamic program stream, whereas decryption operates on the static representation of the program.

2.2 FSM-based interpreter

2.2.1 Design types

There are five types of design choices for the FSM-based interpreter, which are dependent upon the instruction set used for P_x. Let Ins_{P0} and Ins_{Px} be the instruction sets for P_0 and P_x, and let L_{P0} and L_{px} be the programming language for P_0 and P_x respectively. We define five types of designs. Note: in our original proposal we had not defined "Type 2.5".

(Type 1) Ins_{Px} is the same as Ins_{P0} and all P_x have correct static semantics in L_{P0} (e.g. P_x would pass Java's bytecode verifier if P_0 were valid Java bytecode) although the dynamic semantics are determined during execution. Thus P_x is executable in the original interpreter W_0 although its outputs would be incorrect.

(Type 2) L_{Px} has the same syntax as L_{P0}, but the static semantics of P_x may be incorrect (e.g. if L_{P0} is Java bytecode, the stack signature of some opcodes in P_x may be incorrect). The number of different FSMs that could be used to interpret P_x is larger than in Type 1.

(Type 2.5) L_{Px} has different operand syntax to L_{P0}; individual opcodes in P_0 are translated into opcodes in P_x with the same number of bytes; and the opcode sets and encodings in Ins_{P0} and Ins_{Px} are identical. Because the type and number of operands (and their specifiers) associated with each opcode may differ from L_{P0}, P_x is generally not a valid program in L_{P0}. The number of different FSMs that could be used to interpret P_x is larger than in Type 2.

(Type 3) Ins_{Px} includes Ins_{P0} with some extra ("Type-3") instructions. These may be used to control the FSM. The number of different FSMs is larger than in Type 2.5.

(Type 4) Ins_{Px} differs completely from Ins_{P0}, however there exists some (secret) many-to-one mapping which transforms Ins_{Px} into a Type-3 instruction set. That is, P_x appears to be written in a totally different language than P_0. The number of different FSMs is larger than in Type 3.

In the rest of this paper, we focus on Type 2.5 designs.

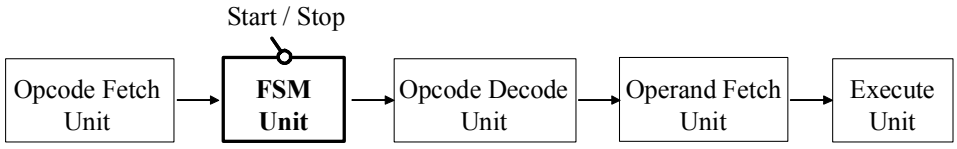

Figure 5. Pipelined stages of FSM-based interpreter

2.2.2 Architecture

Figure 5 shows a suitable architecture for FSM-based interpreter, characterized by pipelined stages of interpretation. In this paper we focus on opcodes to be translated in the FSM. In Type 2.5 design, the FSM-based interpreter is augmented by an additional pipeline stage, called a FSM unit, which translates a "Type-2.5" obfuscated opcode into an unobfuscated opcode, passing it to a conventional opcode decode unit. Then, the translated opcode is decoded, and the number of operands to be fetched is determined. After required operands are fetched in an operand fetch unit, the instruction is executed in an execute unit. This architecture is applicable to many present Java Virtual Machines (JVMs) and reconfigurable processors.

The FSM unit has a switch to start/stop the obfuscated interpretation to enable us running both an ordinary program and an obfuscated program on the same interpreter. If the FSM unit is stopped, then the interpreter works as an ordinary one, and if it is started, then the interpreter works as a FSM-based interpreter. The start/stop signal could be invoked by a system call, or a by a special Type-3 instruction.

2.2.3 FSM unit

The FSM unit (denoted as w_x) is a DFA (Deterministic Finite Automaton) defined by 6-tuple $(Q, \sum, \Psi, \Delta, \Lambda, q_0)$ where

$Q = \{q_0, q_1, \ldots, q_{n-1}\}$ is the states in the FSM.

$\sum = \{c_0, c_1, \ldots, c_{n-1}\}$ is the input alphabet.

$\Psi = \{\underline{c_0}, \underline{c_1}, \ldots, \underline{c_{n-1}}\}$ is the output alphabet (interpretations for inputs).

$\delta_i : \sum \rightarrow Q$ is the next-state function for state q_i.

$\Delta = (\delta_0, \delta_1, \ldots, \delta_{n-1})$ is the n-tuple of all next-state functions.

$\lambda_i : \sum \rightarrow \Psi$ is the output function for state q_i.

$\Lambda = (\lambda_0, \lambda_1, \ldots, \lambda_{n-1})$ is the n-tuple of all output functions.

$q_0 \in Q$ is the starting state of the FSM.

In Type 2.5 design, the instruction set for P_x is the same as that for P_0, so $Ins_{Px} = Ins_{P0}$. We assume $Ins_{Px} = \sum \cup O$ where elements $c_i \in \sum$ are obfuscated instructions, and $o_i \in O$ are non-obfuscated instructions. This means, P_x contains both c_i and o_i, and, if the FSM unit recognizes $c_i \in \sum$ as input then its semantics is determined by the FSM and it is passed to the execute unit, otherwise an input $o_i \in O$ is directly passed to the execute unit.

In our Type-2.5 design, each underlined symbol $\underline{c_i}$ in Ψ denotes the normal (untranslated) semantics for the correspondingly-indexed opcode c_i in $\sum$.

The input (and output) alphabet is partitioned into two classes by an integer b, such that symbols $c_0, c_1, \ldots, c_{b-1}$ are in the first class C_1 (of branching opcodes including non-conditional jump) and the remaining symbols $c_b, c_{b+1}, \ldots, c_{n-1}$ are in the second class C_2 (of non-branching opcodes).

The FSM design has the following constraints.

1. Each $\delta_i : \sum \rightarrow Q$ is a bijection; we will use its inverse $\delta_i^{-1} : Q \rightarrow \sum$.
2. Each $\lambda_i : \sum \rightarrow \Psi$ is a bijection, defining $\lambda_i^{-1} : \Psi \rightarrow \sum$.
3. For all i and j, the length of the translated opcode $\lambda_i(c_j)$ is the same as the obfuscated opcode c_j so that the opcode fetch unit can correctly fetch obfuscated opcodes. For example, in the instruction set of Intel x86 CPU family, the length of MOV opcode is the same as SUB but it differs from MOVZX [Intel 1999]. Thus the MOV opcode may be obfuscated as "sub" but not as "movzx".
4. For all pairs of states q_i, q_k there exists a "dummy instruction sequence" $\underline{d_j}$ with the following three properties. First, $\underline{d_j}$ is a short sequence of (translated) instructions containing exactly one obfuscated instruction. Second, an FSM initially in state q_i will be in state q_k after it produces $\underline{d_j}$ as output. Third, $\underline{d_j}$ has no effective functionality.

Thus $\underline{d_j}$ is an efficiently executed no-op that forces the FSM to make any desired transition. Note that for any pair of states q_i, q_k there exists c_z such that $\delta_i(c_z) = q_k$, because the next-state function δ_i is a bijection. The obfuscated instruction in $\underline{d_j}$ is $\lambda_i(c_z)$.

5. For all states q_k and branching instructions $c_j \in C_1$, there exists a state q_i with the property $\delta_i(c_j) = q_k$. That is, if we have a branching instruction c_j and a desired state q_k to be reached, we can find some initial state q_i that reaches q_k via the input c_j. (When we translate a branch instruction c_j, we apply the previous constraint to force the FSM into state q_i if the instruction at the target of the branch must be interpreted in state q_k.)

Figure 6 shows a simple example of w_x where

$Q = \{q_0, q_1\}$

$\sum = \{\text{add, sub}\}$

$\Psi = \{\underline{\text{add}}, \underline{\text{sub}}\}$

$\Delta : \delta_0(\text{add}) = q_1, \delta_0(\text{sub}) = q_0, \delta_1(\text{add}) = q_0, \delta_1(\text{sub}) = q_1$

$\Lambda : \lambda_0(\text{add}) = \underline{\text{sub}}, \lambda_0(\text{sub}) = \underline{\text{add}}, \lambda_1(\text{add}) = \underline{\text{add}}, \lambda_1(\text{add}) = \underline{\text{sub}}$

This w_x takes an opcode $c_i \in \{\text{add, sub}\}$ as an input, translates it into its semantics $\underline{c_i} \in \{\underline{\text{add}}, \underline{\text{sub}}\}$, and outputs $\underline{c_i}$. Figure 7 shows an example of interpretation for an instruction stream done by this w_x. Obviously, even this simple FSM has the ability to conduct the obfuscated interpretation. As shown in Figure 7, the opcode "add" is interpreted as either $\underline{\text{add}}$ or $\underline{\text{sub}}$ according to its context.

2.2.4 Program translator

In order to utilize the FSM-based interpreter W_x, a program translator $T_x : P_0 \rightarrow P_x$ is indispensable. However, building T_x is much more than building an inverse interpreter of w_x. Let us assume we have w_x of Figure 6, and P_0 of Figure 8 that computes a summation $p := 1+2+3+\ldots+n$. The loop in P_0 must be taken into account. We need a consistency of interpretation: the instructions in each execution of the loop in P_x must always be translated into the same instruction stream (in this case, "add p, x" and "sub x, 1"). In other words, w_x must always be in the same state every time the execution reaches the control-flow junction at the top of the loop body. Taking advantage of constraints 4 and 5 above, we inject a sequence of dummy instructions into the tail of the loop, so that the FSM will reach the desired

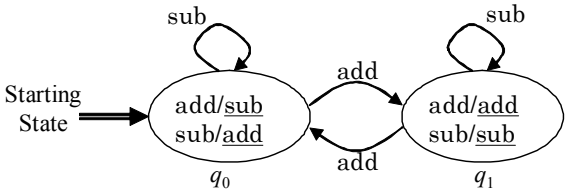

Figure 6. Example of FSM w_x

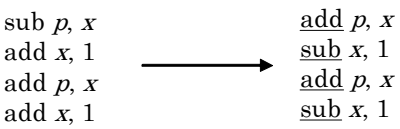

Figure 7. Example of instruction stream interpretation

```
        let x = n
        let p = 1
loop:   if x == 0 exit
        add p, x
        sub x, 1
        goto loop:
```

Figure 8. Example of P_0

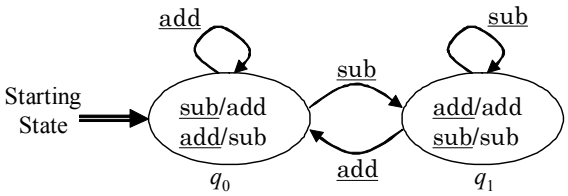

Figure 9. Example of w_x^{-1}

state at the top of the loop without changing program semantics.

Anyway, we first build an inverse interpreter of w_x (denoted as w_x^{-1}), then we use this inverse interpreter to translate P_0 into P_x. Our w_x^{-1} is the DFA defined by 6-tuples $(Q', \sum', \Psi', \Delta', \Lambda^{-1}, q_0)$ where

$Q' = Q = \{q_0, q_1, \ldots, q_{n-1}\}$ is the states in the FSM.

$\sum' = \Psi = \{\underline{c_0}, \underline{c_1}, \ldots, \underline{c_{n-1}}\}$ is the input alphabet.

$\Psi' = \sum = \{c_0, c_1, \ldots, c_{n-1}\}$ is the output alphabet.

$\delta_i' : \sum' \rightarrow Q'$ is the next-state function for state q_i, where $\delta_i'(\underline{c_j})$ has the value $\delta_i(\lambda_i^{-1}(\underline{c_j}))$ for all i, j.

Δ' = (δ_0', δ_1',…, δ_{n-1}') is the n-tuple of all next-state functions.

λ_i': $\sum$' $\rightarrow$ Ψ' is the output function for state q_i, where each λ_i' : $\sum$' $\rightarrow$ Ψ' has the value $\lambda_i^{-1}(\underline{c_i})$ for all i, j.

Λ' = (λ_0', λ_1', …, λ_{n-1}') is the n-tuple of all output functions.

$q_0 \in Q$' is the starting state of the FSM.

Figure 9 shows an example of w_x^{-1} corresponding to w_x of Figure 6. As shown in Figure 9, w_x^{-1} has the same number of states and transitions as w_x.

Next, we give a procedure for the translation T_x: $P_0 \rightarrow P_x$. Figure 10 shows this procedure where:

PC is a program counter (we assume PC is a line number of P_0).

$code_{P0}(PC)$ is an instruction in P_0 at PC.

$code_{Px}(PC)$ is an instruction in P_x at PC.

$q_s \in Q$ is a state of w_x^{-1}.

$state(PC)$ is a state in which $code_{P0}(PC)$ was interpreted.

We also assume this procedure T_x uses a stack (denoted as *Stack*), and its operation *push* and *pop*, to accumulate values of PC.

Figure 11 shows an example of P_x translated from P_0 of Figure 8. In this example, a dummy instruction "add *p*, 0" is inserted into P_x to force the state transition $q_1 \rightarrow q_0$ so that w comes to q_0 every time the execution reaches the entry point of loop.

3 Case Study

3.1 Program translation

In this section we explain a more complex example, in which we execute the procedure T_x:$P_0 \rightarrow P_x$ of Figure 10 using the inverse interpreter w_x^{-1} given in Table 1. This w_x^{-1} is designed for programs written in an Intel x86 instruction set. We use the AT&T syntax (GNU assembler format) to write assembly codes in L_{P0} and L_{Px}. Our sample w_x^{-1} has eight states Q' = {q_0, q_1, …q_7} with q_0 a starting state, and has eight types of instructions $\sum$' = {jmp, jne, pushl, decl, movl_{89}, subl, movl_{8B}, leal}. Here, "movl_{89}" indicates MOV instructions whose opcode byte are "89", and "movl_{8B}" indicates "8B" opcode as well. Two instructions (jmp and jne) are branching instructions. The other six are non-branching instructions. For each instruction in Table 2, a binary

```
Let state(k) := NULL for all k of P0
Let qs := q0
 Set PC to the entry point of P0
loop:
 If PC = exit of P0 then goto resume
 If state(PC) ≠ NULL && state(PC) ≠ qs then{
  Call choose&insert_dummy
  Goto resume
 }
 Let state(PC) := qs
 If codeP0(PC)∈∑' then { /* obfuscated instruction */
Interpret codeP0(PC) via wx^-1, i.e.
Let qs := δs'(codeP0(PC))
Let codePx(PC) := λs^-1(codeP0(PC))
 }else{ /* non-obfuscated instruction */
Let codePx(PC) := codeP0(PC)
 }
If codeP0(PC) = branching instruction then {
  If codeP0(PC) ≠ non-conditional jump then {
   Do push(PCfalse) where PCfalse is a line number of next
instruction in false branch
   Let state(PCfalse) = qs
  }
  Let PC := a line number of next instruction in true
branch
}else{
  PC := PC + 1
 }
Goto loop

resume:
 If Stack is empty then end
PC := pop()
qs := state(PC)
Goto loop

choose&insert_dummy:
 Let PCprev := previous value of PC
 If codeP0(PCprev) = non-branching instruction then{
  Choose ci∈∑' that satisfies δs'(ci) = state(PC)
  Let di := a sequence of dummy instructions for ci
  Let di := λs^-1(di)
  Insert di into Px right after the line number = PCprev
 }else{
Choose k that satisfies δk'(codeP0(PCprev)) = state(PC)
  Choose ci∈∑' that satisfies δstate(PCprev)'(ci) = qk
  Let di := a sequence of dummy instructions for ci
  Let di := λs^-1(di)
  Insert di into Px at the line number = PCprev
  state(PCprev) = qk
}
 return
```

Figure 10. Procedure for T_x: $P_0 \rightarrow P_x$

(hexadecimal) representation of the opcode is shown. Please see [Intel 1999] for detailed information on instruction semantics.

```
      let x = n
      let p = 1
loop: if x == 0 exit
      sub p, x
      add x, 1
      add p, 0          ; dummy instruction
      goto loop:
```

Figure 11. Example of translated P_x

```
int sumodd(int N){
        int i, p;
        p = 0;
        for(i = 1; i <= N; i++){
                if(i % 2 == 1) p = p + i;
        }
        return p;
}
```

Figure 12. Example of P_0 in C language

Table 2 shows sequences of dummy instructions $\underline{d_i}$ for each $\underline{c_i} \in \sum'$. The obfuscated (translated) dummy sequence $d_i = \lambda_j^{-1}(d_i)$ does not change the behaviour of P_x, yet it causes one state-transition in w_x. Some of these d_i modify registers, and these must be "dead registers" to define our desired no-op function. Dead registers can be detected easily by static analysis of P_0 [Irwin, Page and Smart 2002]. If there no dead register is available, one can be created by adding pushl and pop instructions to d_i to preserve the value of a live register.

The target P_0, which is to be translated, is shown in Figure 13. This P_0 is a x86 assembly program, compiled by gcc from the C source program shown in Figure 12. This P_0 computes a summation of odd numbers $p := 1+3+5+\ldots+n$. Figure 14 shows P_x corresponding to this P_0. In Figure 13, numbers described in leftmost column indicates line numbers, and their corresponding lines are described in Figure 14 as well. Second column in Figure 13 describes the state of w^{-1} in which each instruction is interpreted. Due to limited space, we have not included a detailed explanation of our translation process in this paper. However, a full explanation of a sample translation of a Java bytecode program for a Type-2 interpreter is shown in our previous paper [Monden et al, 2003].

3.2 Obscurity of translated program

The program P_x obtained by above translation has some fundamental characteristics to make itself obscure. Below we describe the characteristics of P_x in Figure 14 compared with P_0 in Figure 13.

1. As described in 2.2.1, P_x uses the opcodes of an original x86 assembly language L_{P0}, but it is not itself a valid x86 program since the operand signatures in P_x are not all correct in L_{P0}. For example, in line 2 of Figure 14, the "pushl" opcode requires one operand in L_{P0}, however it has two operands in P_x. This indicates P_x cannot be parsed accurately by a disassembler for L_{Px} into instructions, since the correct number of operands required for each opcode L_{Px} differs from that in L_{P0}. (Indeed, L_{Px} might not even have a consistent syntax.)
2. Instructions in P_x do not have static binding to their semantics. For example, "pushl" in line 2 is interpreted as "movl$_{89}$" via w_x (see the same line in Figure 13), but in line 24, it is interpreted as "leal". Note that dummy instructions, for example the one between line 25 and 26, also have non-static semantics, so they are not statically recognizable as dummy instructions.
3. The control flow of P_0 is not apparently preserved in P_x, *i.e.* if P_x were executed without translation "just as it appears", it would take different branches than P_0. For example, the conditional jump "jne" in line 10 is actually an unconditional JMP. (In addition, if a translated program P_x contain a dummy instruction sequence for a branching instruction, then the apparent control flow of P_x is more complex than P_0.)

4 Security Analysis

In this section, we analyze the security of our scheme against adversaries of varying resources, knowledge, and persistence.

Generally speaking, our security objective is to prevent an adversary from understanding the protected software. The understanding of an adversary is not directly measurable, however, so we define our security metric by a series of restrictions on an adversary's future actions.

1. [Local tamper-proofing] The adversary should not understand the protected software well enough to make small alterations in program representation and behavior. An example of a small alteration is the replacement of an IFNE (jne) opcode with a GOTO (jmp) opcode, in order to defeat a license check [LaDue 1997].
2. [Global tamper-proofing] The adversary should not understand the protected software well

```
.globl sumodd
        .type   sumodd,@function
example:
 1    q0       pushl   %ebp
 2    q2       movl89  %esp, %ebp
 3    q4       subl    $8, %esp
 4    q4       movlC7  $0, -4(%ebp)
 5    q4       movlC7  $1, -8(%ebp)
 6          .L3:
 7    q4       movl8B  -8(%ebp), %eax
 8    q7       cmpl    8(%ebp), %eax
 9    q7       jle     .L6
10    q7       jmp     .L4
11    q7  .L6:
12    q7       movl8B  -8(%ebp), %edx
13    q7       movl89  %edx, %eax
14    q4       sarl    $31, %eax
15    q4       shrl    $31, %eax
16    q4       leal    (%eax,%edx), %eax
17    q4       sarl    $1, %eax
18    q4       sall    $1, %eax
19    q4       subl    %eax, %edx
20    q0       movl89  %edx, %eax
21    q1       cmpl    $1, %eax
22    q1       jne     .L5
23    q3       movl8B  -8(%ebp), %edx
24    q4       leal    -4(%ebp), %eax
25    q5       addl    %edx, (%eax)
      q5
26    q3  .L5:
27    q3       leal    -8(%ebp), %eax
28    q0       incl    (%eax)
29    q0       jmp     .L3
      q0
30    q0  .L4:
31    q0       movl8B  -4(%ebp), %eax
32    q3       leave
33    q3       ret
```

Figure 13. P_0 in AT&T syntax

```
.globl sumodd
        .type   sumodd,@function
example:
 1        decl    %ebp
 2        pushl   %esp, %ebp
 3        subl    $8, %esp
 4        movlC7  $0, -4(%ebp)
 5        movlC7  $1, -8(%ebp)
 6    .L3:
 7        leal    -8(%ebp), %eax
 8        cmpl    8(%ebp), %eax
 9        jle     .L6
10        jne     .L4
11    .L6:
12        leal    -8(%ebp), %edx
13        pushl   %edx, %eax
14        sarl    $31, %eax
15        shrl    $31, %eax
16        leal    (%eax,%edx), %eax
17        sarl    $1, %eax
18        sall    $1, %eax
19        movlC7  %eax, %edx
20        movl89  %edx, %eax
21        cmpl    $1, %eax
22        jmp     .L5
23        leal    -8(%ebp), %edx
24        pushl   -4(%ebp), %eax
25        addl    %edx, (%eax)
          subl    %eax ,%ebx        ; dummy q5→q3
26    .L5:
27        movlC7  -8(%ebp), %eax
28        incl    (%eax)
29        jne     .L3
30    .L4:
31        leal    -4(%ebp), %eax
32        leave
33        ret
```

Figure 14. P_x in AT&T syntax

enough to make large-scale alterations in representation and/or small alterations in behavior. An example of a large-scale alteration in representation is a de-compilation and re-compilation. Such an attack will obscure many static code watermarks [Collberg and Thomborson 2002], and it will defeat a copyright-violation test that is based on a code comparison.

3. [Reverse engineering; algorithmic understanding] The adversary should not understand the protected software well enough to make a large-scale alteration in its behavior, for example by identifying, copying, and re-using a substantial portion of its code (or its embedded "secrets" such as a decryption key) in another software product.

We have listed these restrictions in order of increasing understanding. Only an adversary with "level-3 understanding", in our metric, is able to reverse-engineer a program. Such an adversary would also possess level-2 and level-1 understanding. An adversary who has level-2 understanding can de-compile (or at least dis-assemble) the code, and then make wholesale changes in program representation and some changes in behavior. An adversary with level-1 understanding may discover, through a trial-and-error process, a conditional branch whose annulment will defeat a simple license-checking mechanism.

We do not expect to be able to prevent expert and well-resourced adversaries from gaining level-1 understanding of a program. However, as argued below, our protection scheme in conjunction with other obfuscations will prevent adversaries with considerable knowledge, resources and motivation from ever gaining level-3 understanding. Weaker adversaries will be unable to gain level-2 or even level-1 understanding, unless they are very persistent.

We characterize an adversary's knowledge and resources along several dimensions (labeled A, B, etc.), as listed below. To simplify our analyses, we consider only adversaries who are equal on all dimensions. An adversary that is at level-0 is a naïve end-user. Our level-1 adversary is an end-user with very limited technical skill and ability. Our level-2 adversary has a debugger and good technical skills. Our level-3 adversary is expert and extremely well-resourced, and our level-4 adversary is in possession of powerful custom software.

A. FSM interpretation.

0. The level-0 adversary has a computer system M_x (containing interpreter W_x as shown in Figure 2) and a copy of the translated (protected) program P_x. Note that these resources are required to execute the protected program.
1. The adversary has an algorithmic understanding of the principles of FSM-based interpretation, as described in this article.
2. The adversary has a debugger with "breakpoint" functionality, attached to an obfuscated software implementation of W_x. Alternatively, the adversary has a logic state analyzer, attached to the inputs and outputs of a hardware implementation of W_x.
3. The adversary is able to reverse-engineer a software implementation of W_x, so that it is possible to collect output traces from W_x, and to inject arbitrary input for translation by W_x.
4. The adversary has source code for a generic interpreter *W(x)* which emulates W_x for any x, and a generic translator *T(x)* which implements T_x for any x.

B. Observation.

0. In a level-0 observation, the adversary observes the audio-visual outputs of the computer system M_x, as it executes a program.
1. The adversary determines, by inspection of audio-visual outputs, whether or not M_x is running a program that has the same behavior as the protected program.
2. The adversary records a snapshot (*i.e.* a small number of opcodes and operands, before and after FSM interpretation) of the input and output of W_x.
3. The adversary records a complete trace of the output of W_x, during a run of the protected program on computer system M_x.
4. The adversary has a generic interpreter *W(x)*, and knows how to use this to record a complete trace of the output of W_x for any x. The adversary also has a generic translator *T(x)* whose outputs can be recorded.

C. Control.

0. The adversary operates the keyboard and mouse inputs of the computer system M_x, as it executes the protected program.
1. The adversary can modify the statements in program P_x in any desired way, before running it on computer system M_x.
2. The adversary injects a small number of (arbitrary) inputs into W_x, after the unit has interpreted some (arbitrary) number of opcodes and operands. These injections are at low speed, and for this reason they will generally not produce the same audio-visual output from system M_x as if these inputs were normally presented to W_x.
3. The adversary injects arbitrary inputs into W_x, at full bandwidth.
4. The adversary injects arbitrary inputs, including the setting of parameter x, into *T(x)* and *W(x)*.

Under our definitions above, level-0 adversaries have very few avenues of attack. They might attempt a "black-box re-engineering" – inferring program code from program behavior. Such an attack is infeasible unless program behavior is trivial, and in any event it would not breach any of our security objectives.

The only other avenue of attack of a level-0 adversary is an inspection and cryptographic analysis of the translated program P_x. An early step in such an analysis would be a working knowledge of the principles of FSM interpretation, which would be much more effectively gained by reading this article (a level-1 attack) than by a naïve level-0 attack.

We turn to the level-1 attacks. A cryptographically-skilled adversary with knowledge of programming language semantics and our FSM algorithm would probably start by building a table of "dummy instruction sequences" $\underline{d_i}$ similar to Table 2. Note that the obfuscation on these sequences is weak. Each dummy sequence consists of a short (possibly empty) prefix of non-obfuscated instructions, a single

obfuscated instruction, and a short (possibly empty) suffix of non-obfuscated instructions. Algorithm T_x will place a dummy instruction sequence at the end of branch to a predecessor instruction, except in the (relatively rare) cases where the FSM is in the same state in both paths to the target instruction. So the suffixes will be recognizable as the commonly-repeated patterns before a backwards-branch or jump. Note that all control-flow opcodes are recognizable (either as class-C_1 opcodes, or as unobfuscated opcodes) in our Type 2.5 FSM design, although the adversary will certainly make some mistakes in recognition of branching opcodes wherever instruction boundaries are obscure in the obfuscated code due to the differing operand syntax in L_{P0} and L_{px} . For example a 0xEB byte in the obfuscated sequence is reasonably likely to be an obfuscated branch opcode but it may also be an operand.

The adversary might examine $O(n^2)$ loops to be reasonably certain of having discovered all suffixes, so hypothesizing $\underline{d_j}$ may take days but not months if n = 100. The prefixes can be recognized as the commonly-repeated short sequences that occur immediately before a single (variable) instruction that precedes a suffix. The attacker can prune the list of possible dummy sequences by discarding any prefix-suffix pair that is not a no-op for at least one choice of (variable) instruction semantics.

Our cryptographically-skilled level-1 attacker could then build up a (hypothesized) list d_{jk} of obfuscated dummy sequences by substituting all (hypothesised) c_k for the $\underline{c_j}$ in each (hypothesized) sequence $\underline{d_j}$. Using their level-1 control, they could insert an arbitrary instruction at the beginning of a (hypothesized) loop body; this will soon reveal the location of a sensitive loop, whose semantics visibly affects program operation (a level-1 observation). The attacker would then insert a short no-op sequence to confirm that program correctness is not hypersensitive to loop timing. Then the attacker would choose one pair d_{ij}, d_{kz} of the (hypothesized) obfuscated dummy sequences for insertion at this point in the program. A small fraction of these pairs (about 1/10000 if there are 100 obfuscated opcodes) will not affect program correctness. One such discovery constitutes a major "crack" because the attacker is almost certain that the FSM was in the same state at the beginning and the end of this sequence. After 10000 such discoveries, the attacker would have cracked a 100-state FSM W_x. We have not done a complete cryptographic analysis, however our preliminary analysis indicates that $O(n^4)$ observations and controls would suffice for an attack of the type described above, on an n-state Type 2.5 FSM by an extremely persistent level-1 attacker with cryptographic skill. This might take months or years, because each step requires our adversary to observe a run of a modified P_x' on their machine M_x. We could increase the difficulty of such attacks by increasing the search space, for example by using multiple "dummy sequences" for each instruction, by randomizing the locations in which we insert "dummy sequences" (our translation algorithm T_x could insert a dummy sequence at any point in the straight-line code leading up to a branchpoint in P_0), by using a Type-2 or Type-2.5 design without a partition between branching and non-branching opcodes, by using a Type-3 FSM to make it harder for the attacker to recognize no-op suffixes and prefixes, or by using a Type-4 FSM to increase n. We intend to explore these options in future work.

The "crack" described above for a level-1 attacker gives them level-2 understanding of a single machine M_x, for they can predict how a single FSM W_x will translate arbitrary inputs – including the obfuscated program P_x! (Note: the attacker must do some cut-and-paste work, and some exercising of program paths, perhaps by program modification, to transform their traces of P_x into a program listing. Alternatively, they might choose to write source code for a specialised de-obfuscator T_x: this may take months, but they have probably already spent months if not years to reach this level of understanding: they are now essentially a level-3 adversary.) The level-1 adversary in possession of this "crack" can also discover the FSM state at any point in the code where their code insertions can visibly affect program correctness. With this knowledge they can inject short code sequences, followed by an appropriate "dummy sequence" to preserve the correctness of translation of the subsequent code.

We now briefly consider level-2 and level-3 adversaries.

A level-2 adversary can correlate the outputs with the inputs of the FSM, where these inputs are the ones associated with any desired "breakpoint" in a (possibly modified) P_x. This ability will greatly speed the brute-force attack described above for our level-1 adversary, and it will allow new attack strategies such as directly observing the translation $\lambda_i(c_z)$ of an instruction c_z that occurs in (hypothesised) dummy sequences in P_x. Our preliminary analysis indicates that $O(n^3)$ observations and controls, each taking a few seconds or milliseconds (in an

automated attack), will suffice for a level-2 attacker to achieve level-2 understanding.

A level-3 adversary can collect an execution trace of P_0, and they can correlate all branch-points in this trace with the corresponding branch-points in P_x. If P_x is short, they can produce an accurate cleartext bytecode listing by hand. If P_x is long, they should try to obtain a copy of a "general-purpose" deobfuscating tool that some other level-3 adversary may have produced when cracking some other $M_{x'}$. If no such tool exists, our level-3 attacker may write and publish such a tool, so that subsequent level-3 attackers merely have to obtain the tool to get a program listing for any P_x. However we note that, if the value of x is embedded in secure hardware, and if the party in possession of T_x preserves the secrecy of x, level-3 adversaries will be rare – they must either have the ability to "crack" secure hardware or they must develop more powerful cryptanalytic attacks than we have outlined above for our hypothetical level-2 adversary.

We close our security analysis with a warning. Our translation system is essentially cryptographic in nature, so it should only be used to obfuscate long programs that have been "randomized" (*i.e.* obfuscated) before they are translated by our T_x. Otherwise the attacker will be able to make a likely guess to the cleartext, which may greatly speed their attack.

5 Conclusion

In this paper we proposed a framework for obfuscating the program interpretation. We defined a FSM-based interpreter w_x that gives context-dependent semantics to program instructions. We also defined a program translator T_x to systematically construct a program P_x, which is executable with w_x, from a given program P_0 written in a conventional programming language.

Our case study of a "Type 2.5" translation of an x86 assembly-language P_0 into an "x86-like" P_x showed that instructions in P_x have non-static semantics, i.e. functionality is hidden from program users, yet P_x is still functionally equivalent to P_0.

Our preliminary security analysis showed that our design is reasonably secure against adversaries of varying resources, knowledge, and persistence. Our analysis highlighted some areas where our design could be improved, and we conclude that our design should only be used to obfuscate long programs that have been "randomized" (*i.e.* obfuscated) before they are translated.

In the future, we will develop detailed designs for interpreters of Type 1, 3 and 4, and we intend to clarify their advantages and shortcomings.

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Table 1. Example of FSM w_x^{-1}

State	Input / Output	transition	State	Input / Output	transition
q_0	EB jmp / 75 jne 75 jne / EB jmp 55 pushl %ebp / 4D decl %ebp 4D decl %epb / 55 pushl %ebp 89 movl_{89} / 89 movl_{89} 29 subl / 29 subl 8B movl_{8B} / 8D leal 8D leal / 8B movl_{8B}	q_4 q_7 q_2 q_5 q_1 q_6 q_3 q_0	q_4	EB jmp / 75 jne 75 jne / EB jmp 55 pushl %ebp / 89 movl_{89} 48 decl %ebp / 48 decl %ebp 89 movl_{89} / 29 subl 29 subl / 8B movl_{8B} 8B movl_{8B} / 8D leal 8D leal / 55 pushl %ebp	q_6 q_4 q_2 q_1 q_3 q_0 q_7 q_5
q_1	EB jmp / 75 jne 75 jne / EB jmp 55 pushl %ebp / 8D leal 4D decl %ebp / 55 pushl %ebp 89 movl_{89} / 8B movl_{8B} 29 subl / 29 subl 8B movl_{8B} / 89 movl_{89} 8D leal / 4D decl %ebp	q_1 q_3 q_4 q_2 q_0 q_6 q_7 q_5	q_5	EB jmp / EB jmp 75 jne / 75 jne 55 pushl %ebp / 8B movl_{8B} 4D decl %ebp / 55 pushl %ebp 89 movl_{89} / 29 subl 29 subl / 89 movl_{89} 8B movl_{8B} / 4D decl %ebp 8D leal / 8D leal	q_2 q_1 q_4 q_0 q_3 q_6 q_5 q_7
q_2	EB jmp / 75 jne 75 jne / EB jmp 55 pushl %ebp / 29 subl 4D decl %ebp / 8D leal 89 movl_{89} / 55 pushl %ebp 29 subl / 8B movl_{8B} 8B movl_{8B} / 89 movl_{89} 8D leal / 4D decl %ebp	q_7 q_0 q_6 q_5 q_4 q_3 q_1 q_2	q_6	EB jmp / 75 jne 75 jne / EB jmp 55 pushl %ebp / 8D leal 4D decl %ebp / 89 movl_{89} 89 movl_{89} / 8B movl_{8B} 29 subl / 4D decl %ebp 8B movl_{8B} / 55 pushl %ebp 8D leal / 29 subl	q_5 q_2 q_4 q_1 q_6 q_7 q_0 q_3
q_3	EB jmp / EB jmp 75 jne / 75 jne 55 pushl %ebp / 4D decl %ebp 4D decl %ebp / 89 movl_{89} 89 movl_{89} / 29 subl 29 subl / 55 pushl %ebp 8B movl_{8B} / 8D leal 8D leal / 8B movl_{8B}	q_3 q_5 q_2 q_6 q_1 q_7 q_4 q_0	q_7	EB jmp / 75 jne 75 jne / EB jmp 55 pushl %ebp / 4D decl %ebp 4D decl %ebp / 89 movl_{89} 89 movl_{89} / 55 pushl %ebp 29 subl / 29 subl 8B movl_{8B} / 8D leal 8D leal / 8B movl_{8B}	q_0 q_6 q_5 q_3 q_4 q_1 q_7 q_2

Table 2. List of sequence of dummy instructions

Sequence of dummy instructions	#
jmp .Lx any instructions .Lx	0
jne .Lx addl $0,%eax .Lx	1
pushl %eax pop %eax	2
decl %eax incl %eax	3
mvl_{89} %eax,%ebx*	4
movl $0, %eax **subl** %ebx,%eax	5
mvl_{8B} -4(ebp),%eax*	6
leal -4(ebp),%eax*	7

* these registers must be dead