

Software security, secure programming

Reverse-engineering from binary code

Master M2 Cybersecurity

Academic Year 2023 - 2024

Outline

Introduction

Low-level code representations

Disassembling

Application to BoF exploitation

Retrieving source-level information

Some Tools ...

Software = several knowledge/information levels

- ▶ (formal) models: overall architecture, component behaviors
- ▶ specifications, algorithms, abstract data structures
- ▶ source code
 - objects, variables, types, functions, control and data flows
- ▶ possible intermediate representations: Java bytecode, LLVM IR, etc.
- ▶ assembly
- ▶ binary code (relocatable / shared object / executable)

Some reverse-engineering settings:

- ▶ source level \rightarrow model level . . .
- ▶ de-compiling: binary \rightarrow source level
- ▶ disassembling: binary \rightarrow assembly level
- ▶ etc.

Why and when bothering with binary code ? (1)

→ when the source code is not/no longer **available**

- ▶ updating/maintaining legacy code
- ▶ “off-the-shell” components (COST), external libraries
- ▶ dynamically loaded code (applets, plugins, mobile apps)
- ▶ pieces of assembly code in the source
- ▶ suspicious files (malware, etc.)

Why and when bothering with binary code ? (2)

→ when the source code is not **sufficient**

“What You See Is Not What You Execute” [T. Reps]

- ▶ untrusted compilation chain
- ▶ low-level bugs, at the HW/SW interface
- ▶ **security analysis**
going beyond standard programming language semantics
(optimization, memory layout, undefined behavior, protections, etc.)

Beware ! Reverse-engineering is restricted by the law
(“Intellectual Property”, e.g. Art. L122-6-1 du Code de la Propriété Intellectuelle)

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Some Tools ...

Example 1: Java ByteCode (stack machine)¹

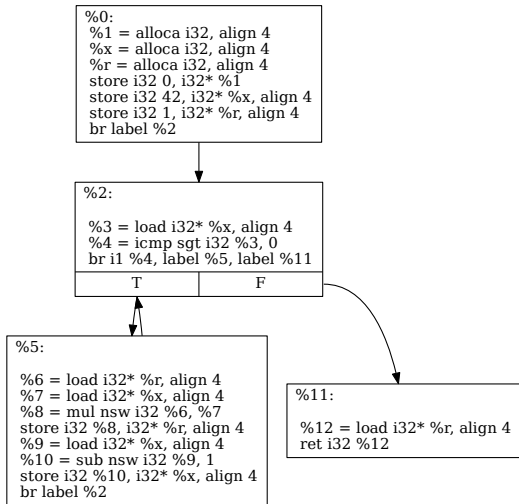
```
public static int main(java.lang.String[]);
Code:
    0: bipush          42
    2: istore_1
    3: iconst_1
    4: istore_2
    5: iload_1
    6: ifle           20
    9: iload_2
   10: iload_1
   11: imul
   12: istore_2
   13: iload_1
   14: iconst_1
   15: isub
   16: istore_1
   17: goto           5
   20: iload_2
   21: ireturn

public static int main() {
int x, r;
x=42 ; r=1 ;
while (x>0) {
    r = r*x;
    x = x-1;
} ;
return r ;
}
```

¹use `javap -c` to produce the bytecode

Example 2: LLVM IR (register based machine)

```
int main() {  
  int x, r;  
  x=42 ; r=1 ;  
  while (x>0) {  
    r = r*x;  
    x = x-1;  
  } ;  
  return r ;  
}
```



CFG for 'main' function

Example 3: assembly code (x86-64)²

```

                                main:
                                push   rbp
                                mov    rbp, rsp
                                mov    DWORD PTR [rbp-4], 42
                                mov    DWORD PTR [rbp-8], 1
                                jmp    .L2

int main() {
int x, r;
x=42 ; r=1 ;
while (x>0) {
    r = r*x;
    x = x-1;
} ;
return r ;
}

                                .L3:
                                mov    eax, DWORD PTR [rbp-8]
                                imul   eax, DWORD PTR [rbp-4]
                                mov    DWORD PTR [rbp-8], eax
                                sub    DWORD PTR [rbp-4], 1

                                .L2:
                                cmp    DWORD PTR [rbp-4], 0
                                jg     .L3
                                mov    eax, DWORD PTR [rbp-8]
                                pop    rbp
                                ret
```

²see <https://godbolt.org/>

Memory layout at runtime (simplified)

Executable code = (binary) file produced by the compiler

→ need to be **loaded** in memory to be executed (using a loader)

However:

- ▶ no absolute addresses are stored in the executable code
→ decided at “load time”
- ▶ not all the executable code is stored in the executable file
(e.g., dynamic libraries)
→ lazy binding using relocation tables (e.g., GOT and PLT)
- ▶ data memory can be dynamically allocated
- ▶ data can become code (and conversely ...)
- ▶ etc.

→ the executable file should contain all the information required ...

∃ standards executable formats: ELF (Linux), PE (Windows), etc.

- ▶ header
- ▶ sections: text, initialized/uninitialized data, symbol tables, relocation tables, etc.

Rks: **stripped** (no symbol table) vs **verbose** (debug info) executables ...

Example 1: Linux Elf

ELF object file format

ELF header
Program header table
.text
.data
.rodata
.bss
.sym
.rel.text
.rel.data
.rel.rodata
.line
.debug
.strtab
Section header table

Demo: memory layout at runtime: `more /proc/xxxx/maps`

Example 2: Windows PE

PE File Format



PE File Format



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x86_64 assembly language in one slide

Registers:

- ▶ stack pointer (RSP), frame pointer (RBP), program counter (RIP)
- ▶ general purpose: RAX, RBX, RCX, RDX, RSI, RDI
- ▶ flags

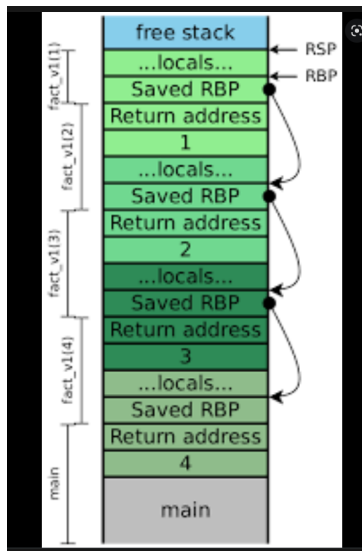
Instructions:

- ▶ data transfer (MOV), arithmetic (ADD, etc.)
- ▶ logic (AND, TEST, etc.)
- ▶ control transfer (JUMP, CALL, RET, etc)

Addressing modes (AT&T syntax):

- ▶ register: `movl %rax, %rbx` // $rbx \leftarrow rax$
- ▶ immediate: `movl $1, %rax` // $rax \leftarrow 1$
- ▶ direct memory: `movl %rax, -0x10(%rbp)` // $Mem[rbp-16] \leftarrow rax$

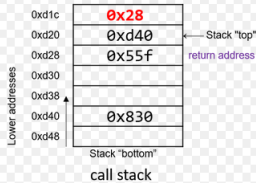
Stack layout for the x86 64-bits architecture (1)



Stack layout for the x86 64-bits architecture (2)

```
0x526 <assign>:  
0x526 push %rbp  
0x527 mov %rsp, %rbp  
→ 0x52a mov $0x28, -0x4(%rbp)  
0x531 mov -0x4(%rbp), %eax  
0x534 pop %rbp  
0x535 retq  
0x542 <main>:  
0x542 push %rbp  
0x543 mov %rsp, %rbp  
0x546 sub $0x10, %rsp  
0x54a callq 0x526 <assign>  
0x55f callq 0x536 <adder>  
0x554 mov %eax, -0x4(%rbp)  
0x557 mov -0x4(%rbp), %eax  
0x55a mov %eax, %esi
```

Registers	
%eax	0x0
%edi	1
%rsp	0xd20
%rbp	0xd20
%rip	0x531



Terminal:

```
$ ./prog
```

ABI (Application Binary Interface)

to “standardize” how processor resources should be used
⇒ required to ensure compatibilities at binary level

- ▶ sizes, layouts, and alignments of basic data types
- ▶ **calling conventions**
argument & return value passing, saved registers, etc.
- ▶ system calls to the operating system
- ▶ the binary format of object files, program libraries, etc.

	Cleans Stack	Arguments	Arg Ordering
cdecl	Caller	On the Stack	Right-to-left
fastcall	Callee	ECX,EDX, then stack	Left-to-Right
stdcall	Callee	On the Stack	Left-to-Right
VC++ thiscall	Callee	EDX (this), then stack	Right-to-left
GCC thiscall	Caller	On the Stack (this pointer first)	Right-to-left

Figure: some calling conventions

System V AMD64 calling convention (Linux) :

Integer/Pointer Arguments 1-6 transmitted on RDI, RSI, RDX, RCX, R8, R9

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Some Tools ...

Understanding and analysing binary code ?

```
01010100 01101000
01101001 01101110
01101011 00100000
01100100 01101001
01100110 01100110
01100101 01110010
01100101 01101110
01110100 00101110
```

```
00000000
00000001
00000003
00000007
00000008
0000000C
0000000F
00000011
00000014
00000016
00000019
0000001B
0000001D
0000001F
00000022
00000025
```

```
push    ebp
mov     ebp, esp
movzx   ecx, [ebp+arg_0]
pop     ebp
movzx   dx, cl
lea     eax, [edx+edx]
add     eax, edx
shl     eax, 2
add     eax, edx
shr     eax, 8
sub     cl, al
shr     cl, 1
add     al, cl
shr     al, 5
movzx   eax, al
retn
```

Disassembling !

statically:

disassemble the **whole** file content **without executing it** ...

dynamically: disassemble the **current** instruction path **during execution/emulation** ...

Static Disassembling (1)

Assume “reasonable” (stripped) code only

→ no obfuscation, no packing, no auto-modification, ...

Enough pitfalls to make it undecidable ...

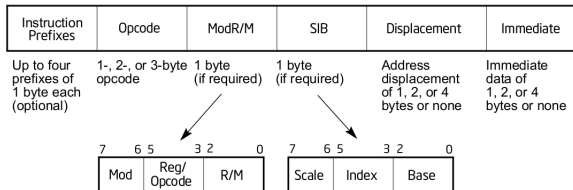
main issue: distinguishing **code** vs **data** ...

- ▶ interleavings between code and data segments
- ▶ dynamic jumps (`jmp <register>`)
- ▶ possible variable-length instruction encoding, # addressing modes, ...
e.g. > 1000 distinct x86 instructions

1.5 year to fix the semantics of x86 shift instruction at CMU

→ much worse when considering **self-modifying code**, **packers**, etc.

Example: x86 instruction format



Static Disassembling (2)

Classical static disassembling techniques

- ▶ linear sweep: follows increasing addresses (ex: `objdump`)
↔ pb with interleaved code/data ?
- ▶ recursive disassembly: control-flow driven (ex: `IDAPro`)
↔ pb with dynamic jumps ?
- ▶ hybrid: combines both to better detect errors ...

Some existing tools

- ▶ Disassemblers/Decompilers:
 - ▶ IDA Pro [HexRays]
 - ▶ Ghidra [NSA, open-source]
- ▶ On Linux platforms (for ELF formats):
 - ▶ `objdump` (-S for code disassembling)
 - ▶ `readelf`
- ▶ and many others (Capstone, Miasm, Radare2, Triton, etc.)
- ▶ ... + a huge number of **utility tools**
(hexadecimal operations, executable dissectors, etc.)

Static disassembly (cont'd)

See some Emmanuel Fleury slides ...

Indirect Jumps

BRANCH R_i

(branch address computed at runtime and stored inside register R_i)

⇒ A critical issue for **static** disassemblers/analysers . . .

Occurs when compiling:

- ▶ some `switch` statements
- ▶ high-order functions (with function as parameters and/or return values)
- ▶ pointers to functions
- ▶ dynamic method binding in OO-languages, virtual calls
- ▶ etc.

Source code example:

```
enum {DIGIT, AT, BANG, MINUS}
f (char c) {
switch(c) {
case '0': case '1': case '2': case '3': case '4':
case '5': case '6': case '7': case '8': case '9': return DIGIT ;
case '@': return AT ;
case '!': return BANG ;
case '-': return MINUS ;
}
}
```

Code produced with x86-64 gcc8.2³

```
f:
    push    rbp
    mov     rbp, rsp
    mov     eax, edi
    mov     BYTE PTR [rbp-4], al
    movsx   eax, BYTE PTR [rbp-4]
    sub     eax, 33                ; Ascii for '!'
    cmp     eax, 31                ; 64 is Ascii for '@'
    ja     .L2                    ; out of bounds ...
    mov     eax, eax
    mov     rax, QWORD PTR .L4[0+rax*8] ; offset in a jump table
    jmp     rax
```

³See <https://godbolt.org/>

Dynamic disassembly

Main advantage: disassembling process **guided by** the execution

- ▶ ensures that **instructions only** are disassembled
- ▶ the whole execution context is available (registers, flags, addresses, etc.)
- ▶ dynamic jump destinations are resolved
- ▶ dynamic libraries are handled
- ▶ etc.

However:

- ▶ only a **(small) part** of the executable is disassembled
- ▶ need some suitable **execution platform**, e.g.:
 - ▶ emulation environment
 - ▶ binary level code instrumentation
 - ▶ (scriptable) debugger
 - ▶ etc.

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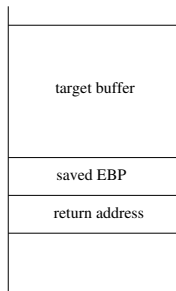
Retrieving source-level information

Some Tools ...

Reminder

A classical buffer overflow situation . . .

- ▶ the content of the target buffer is **attacker controlled**
- ▶ the return address can be overwritten (no protections)
- ▶ the control-flow can be re-directed to a **shell code**

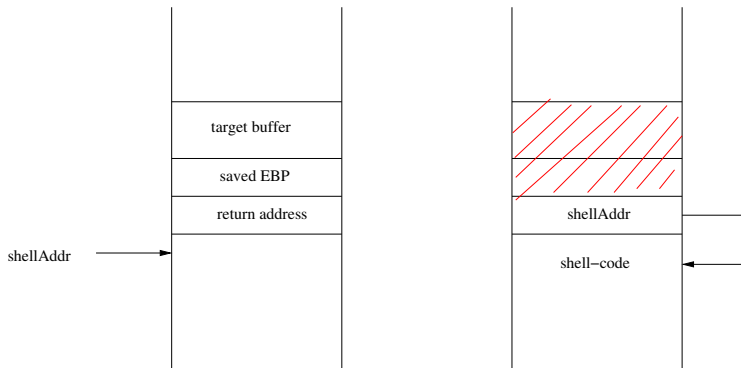


Remaining questions:

- ▶ where to put the shell-code ?
- ▶ which “input value” should be provided by the attacker ?

Writing the shell-code in the stack (1)

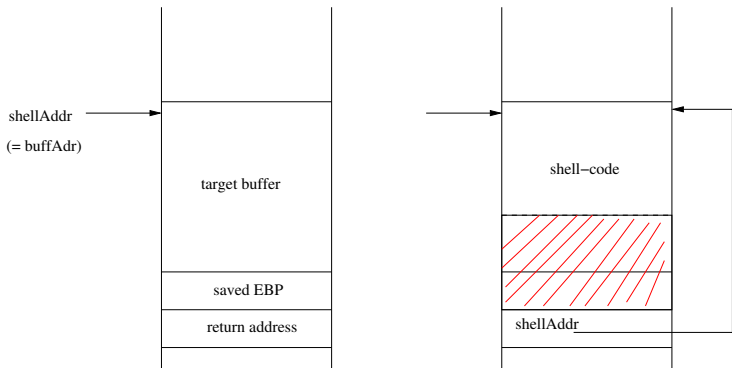
Solution 1: put the shell-code **below** the return address (i.e., in the caller's stack frame)



attacker input = padding + shellAddr + shell-code

Writing the shell-code in the stack (2)

Solution 2: put the shell-code inside the **target buffer**
(i.e., in the current stack frame)

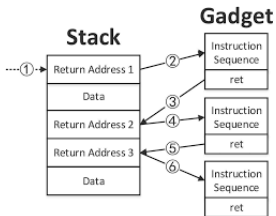


attacker input = **shell-code** + padding + shellAddr

When the stack segment is not executable ?

Do not store shellcode in the stack ... use **existing code instructions** instead !

- ▶ return-to-libc: redirect the control-flow towards library code
- ▶ return oriented programming (ROP)
payload = sequence of return-terminated instructions (gadgets)



- ▶ gadget programming is “turing complete”
- ▶ ∃ tools for gadget extraction (ROPgadget, Ropper, ROPium, etc.)
- ▶ ∃ ROP variants:
COP (call-oriented programming), JOP (jump-oriented programming)

Rks: may also ∃ library calls allowing to **make the stack executable** ...

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Objectives

When the code has been (partially !) disassembled ...

... how to retrieve useful **source-level** information ?
(e.g.: variables, types, functions, control and data-flow relations, etc.)

Challenges

Still a **gap** between assembly and source-level code ...

- ▶ basic source elements lost in translation:
functions, variables, types, (conditionnal) expressions, ...
- ▶ pervasive address computations (addresses = values)
- ▶ etc.

Rk: \neq between code produced by a compiler and written by hand
(structural patterns, calling conventions, ...)

Again, \exists static and dynamic approaches ...

Function identification

Retrieve functions boundaries in a stripped binary code ?

Why is it difficult ?

- ▶ not always clean `call/ret` patterns: optimizations, multiple entry points, inlining, etc.
- ▶ not always clean code segment layout: extra bytes (\neq any function), non-contiguous functions, etc.

Possible solution ...

- ▶ from pattern-matching on (manually generated) binary signatures
 - ▶ simple ones (`push [ebp]`) or advanced heuristics as in [IDAPro]
 - ▶ standart library function signature database (FLIRT)
- ▶ ...
- ▶ to supervised machine learning classification ...

→ no “sound and complete” solutions ...

Variable and type recovery

2 main issues

- ▶ retrieve the memory layout (stack frames, heap structure, etc.)
- ▶ infer size and (basic) type of each accessed memory location

Memory Layout

“addresses” of global/local variables, parameters, allocated chunks

- ▶ static basic access patterns (`epb+offset`) [IDAPro]
- ▶ Value-Set-Analysis (VSA)

Types

- ▶ dynamic analysis:
type chunks (library calls) + loop pattern analysis (arrays)
- ▶ static analysis: VSA + Abstract Structure Identification
- ▶ Proof-based decompilation relation inference
type system + program witness [POPL 2016]

Static variable recovery

Retrieve the **address** (and size) of each program “variable” ?

Difficult because:

- ▶ addresses and other values are not distinguishable
- ▶ address \leftrightarrow variable is not one-to-one
- ▶ address arithmetic is pervasive
- ▶ both direct and indirect memory addressing

Memory regions + abstract locations

A memory model with 3 distinct regions:

- ▶ Global: global variables
- ▶ Local: local variables + parameters (1 per proc.)
- ▶ Dynamic: dynamically allocated chunks
- ▶ Registers

\leftrightarrow associates a relative address to each variable (**a-loc**)

The so-called “naive” approach (IDAPro)

Heuristic

Addresses used for **direct** variable accesses are:

- ▶ **absolute** (for globals + dynamic)
- ▶ relative w.r.t **frame/stack pointer** (for globals)

→ can be statically retrieved with simple patterns ...

Limitations

- ▶ variables indirectly accessed (e.g., `[eax]`) are not retrieved (e.g., structure fields)
- ▶ array = (large) contiguous block of data

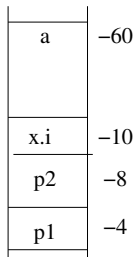
⇒ Fast recovery technique, can be used as a bootstrap

But coarse-grained information, may hamper further analyses ...

Example

```
typedef struct  
    {int i ; char c ;} S ;
```

```
int main() {  
    S x, a[10] ;  
    char *p1 ; int *p2 ;  
    p1 = &(a[9].c) ;  
    p2 = &(x.i) ;  
    return 0 ;  
}
```



```
var_60= byte ptr -60h  
var_10= byte ptr -10h  
var_8= dword ptr -8  
var_4= dword ptr -4
```

```
push    ebp  
mov     ebp, esp  
sub     esp, 60h  
lea    eax, [ebp+var_60]  
add    eax, 4Ch  
mov    [ebp+var_4], eax  
lea    eax, [ebp+var_10]  
mov    [ebp+var_8], eax  
mov    eax, 0  
leave  
retn  
main endp
```

Going beyond: Value Set Analysis (VSA)

Compute the contents of each a-loc at each program location ...

... as an **over-approximation** of:

- ▶ the set of (integer) values of each data at each prog. loc.
- ▶ the addresses of “new” a-locs (indirectly accessed)

→ combines simultaneously numeric and pointer-analysis

Rk: should be also combined with CFG-recovery ...

⇒ Can be expressed as a forward data-flow analysis ...

A building block for many other static analysis ...

- ▶ function “signature” (size and number of parameters)
- ▶ data-flow dependencies, taint analysis
- ▶ alias analysis
- ▶ type recovery, abstract structure identification
- ▶ etc.

Example: data-flow analysis

Does the value of y depend from x ?

```
int x, *p, y;  
x = 3 ;  
p = &x ;  
...  
y = *p + 4 ; // data-flow from x to y ?
```

At assembly level:

1. needs to **retrieve** x address
2. needs to **follow** memory transfers from x address ...

```
mov [ebp-4], 3 /* x=3 ; */  
lea eax, [ebp-4]  
mov [ebp-8], eax /* p = &x ;*/  
mov eax, [ebp-8]  
  
... /* follow operations on eax ...  
  
mov eax, [eax] /* y = *p+4 ; ??? */  
add eax, 4  
mov [ebp-12], eax
```

CFG construction

Main issue

handling dynamic jumps (e.g., `jmp eax`) due to:

- ▶ `switch` statements (“jump table”)
- ▶ function pointers, trampoline, object-oriented source code, ...

Some existing solutions

- ▶ heuristic-based approach (“simple” switch statements) [IDA]
- ▶ abstract interpretation: interleaving between VSA and CFG expansion
 - ▶ use of dedicated abstract domains
 - ▶ use of under-approximations ...

Rk: may create many program “entry points” \Rightarrow many CFGs ...

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IDA Pro [HexRays]

- ▶ Commercial disassembler and debugger
- ▶ Supports 50+ processors (intel, ARM, .NET, PowerPC, MIPS, etc.)
- ▶ Recognizes **library functions** FLIRT (C/C++ only)
- ▶ Builds call graphs and CFGs
- ▶ Tags **arguments/local variables**
- ▶ Rename labels (variables names etc.)
- ▶ Provides **scripting environment** (IDC, Python) and debugging facilities

Script example

```
#include <idc.idc>
/* this IDA pro script enumerate all functions and prints info about them */
static main()
{
    auto addr, end, args, locals, frame, firstArg, name, ret;
    addr=0;
    for ( addr=NextFunction(addr); addr != BADADDR; addr=NextFunction(addr) )
    {
        name=Name(addr);
        end= GetFunctionAttr(addr,FUNCATTR_END);
        locals=GetFunctionAttr(addr,FUNCATTR_FRSIZE);
        frame=GetFunctionAttr(addr,FUNCATTR_FRAME);
        ret=GetMemberOffset(frame, " r");
        if (ret == -1) continue;
        firstArg=ret +4;
        args=GetStrucSize(frame) -firstArg;
        Message("function %s start at %x, end at %x\n",name, addr, end);
        Message("Local variables size is %d bytes\n",locals);
        Message("arguments size %d (%d arguments)\n",args, args/4);
    }
}
```

A dynamic code instrumentation framework

- ▶ run time instrumentation on the binary files
- ▶ provides APIs to define **insertion points** and **callbacks** (e.g., after specific inst., at each function entry point, etc.)
- ▶ Free for non-commercial use, works on Linux and windows

Example: instruction counting

```
#include "pin.h"
UINT64 icount = 0;
void docount() { icount++; }

void Instruction(INS ins, void *v)
{
  INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR)docount, IARG_END);
}

void Fini(INT32 code, void *v)
{ std::cerr << "Count " << icount << endl; }

int main(int argc, char * argv[])
{
  PIN_Init(argc, argv);
  INS_AddInstrumentFunction(Instruction, 0);
  PIN_AddFiniFunction(Fini, 0);
  PIN_StartProgram();
  return 0;
}
```