

GCC Tokyo – Global Cybersecurity Camp v2.0

Advanced Binary Deobfuscation

NTT Secure Platform Laboratories

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- Yuma Kurogome
 - Security Researcher @ NTT Secure Platform Laboratories
 - Research Interests: Malware Detection, Analysis, and Anti-Analysis
 - Hobby: Climbing
- Recent Publication
 - Kurogome et al. EIGER: Automated IOC Generation for Accurate and Interpretable Malware Detection. ACSAC'19.
 - Fully-automated behavioral signature generation method
 - Based on combinatorial optimization



Function	Description		
$f_1(R) = S - size(R)$	Represent the entire dataset with a few rules.		
$f_2(R) = \sum_{r \in R} (\max_{r \in S \times C} width(r) - width(r))$	Highly evaluate a concise rule $i.e.$, rule with a few representations. We redefined $width(r)$ to the number of regular expression objects in r .		
$f_3(R) = \sum_{\substack{r_i, r_j \in R \\ i \leq j \\ c_i = c_j}} (N - overlap(r_i, r_j))$	Reduce the intra-class $overlap$ of rules. N is the number of points in the dataset.		

$f_5(R) = C - \sum_{c' \in C} \mathbb{1}(\exists r = (s, c) \in R \text{ such that } c = c')$	Have at least one rule for each class. We removed this function from our objective. The function 1 returns 1 whenever the condition it takes as an argument is true and 0 otherwise.
$f_6(R) = N \cdot S - \sum_{r \in R} incorrect \cdot cover(r) $	To encourage precision, reduce the size of incorrect-cover sets.
$f_7(R) = N - \sum_{(\mathbf{x},y) \in D} \mathbb{1}(\{r (\mathbf{x},y) \in correct\text{-}cover(r)\} \geq 1)$	To encourage recall, have at least one accurate rule describes each data points.



Introduction

Overview



Abstract

Reverse engineering is not easy, especially if a binary code is obfuscated. Once obfuscation performed, the binary would not be analyzed accurately with naive techniques alone. In this course, you will learn obfuscation principles (especially used by malware), theory and practice of obfuscated code analysis, and how to write your own tool for deobfuscation. In particular, we delve into data-flow analysis and SAT/SMT-based binary analysis (e.g., symbolic execution) to render obfuscation ineffective.

Objective

- Understand binary obfuscation techniques used in malware
- Acquire a skill of writing deobfuscation tools

Overview



- At the end of this course, you will be able to:
 - Have an in-depth understanding of theory, practice, and behind insights of obfuscation
 - Build a custom obfuscated payload with state-of-the-art packers
 - Apply compiler optimization techniques to binary analysis tasks
 - Design and implement automated binary analysis tools top on a symbolic execution engine
 - Even analyze obfuscated malware used in the APT campaign

Outline



- Introduction
- Obfuscation Techniques
 - Preliminaries
 - Garbage Code Insertion, Instruction Substitution, ...
 - Hands-On
- Deobfuscation Techniques
 - Preliminaries
 - Dataflow Analysis, Symbolic Execution, Equivalence Checking, ...
 - Hands-On
- Conclusion



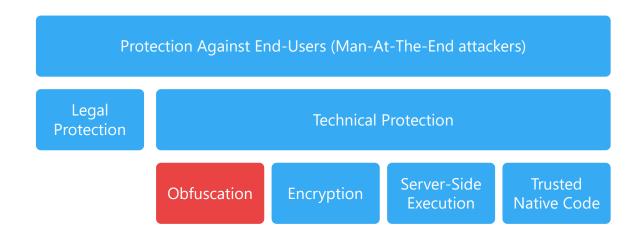
Obfuscation Techniques

Obfuscation



àbfəskéı[ən Obfuscation

Deobfuscation



- Definition (Informal)
 - Obfuscation is a transformation from program P to functionally equivalent program P' which is harder to extract information than from P.



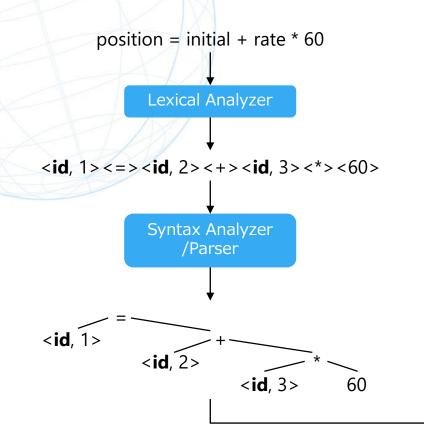
Compiler

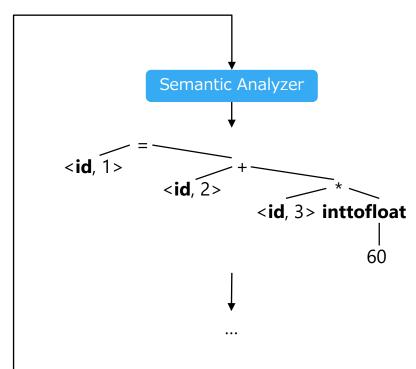


- To understand the obfuscation techniques, we delve into an architecture of a compiler e.g., LLVM:
 - Frontend
 - Backend

Compiler Frontend

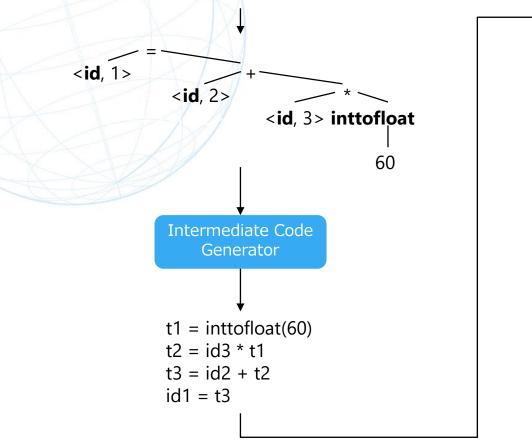


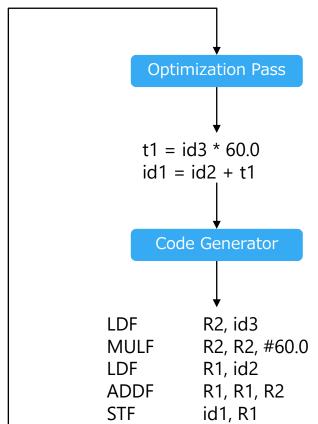




Compiler Backend



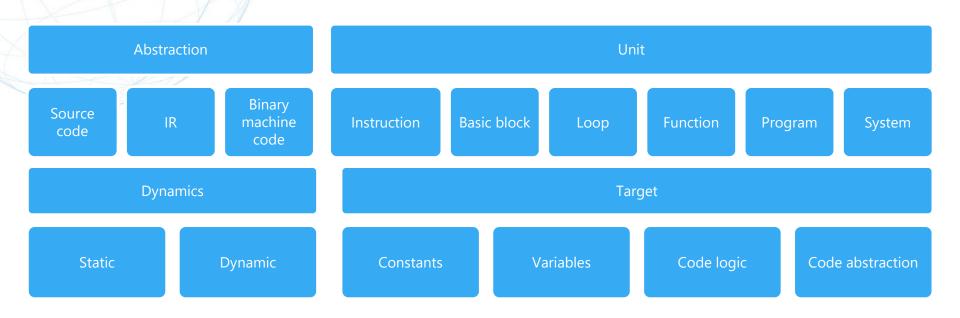




Taxonomy of Obfuscation

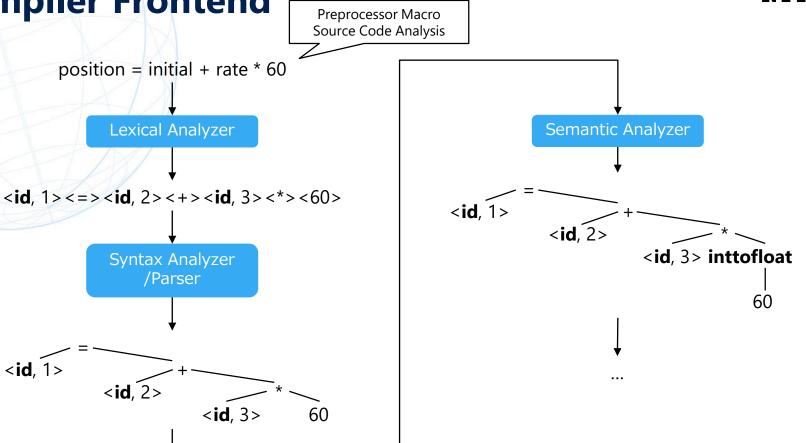


 When, where, and how to apply obfuscation is closely related to such a compiler architecture



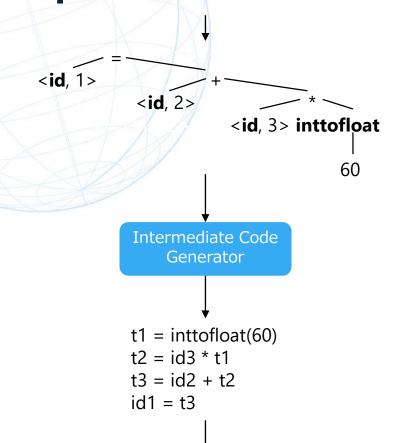
Compiler Frontend

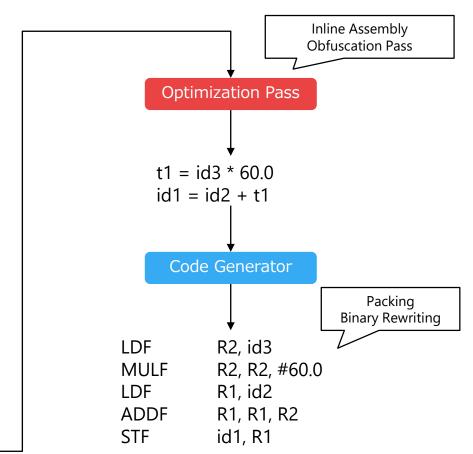




Compiler Backend







Obfuscation Techniques

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- There are 31 known obfuscation transformations
 - Most of them are applicable at the same time

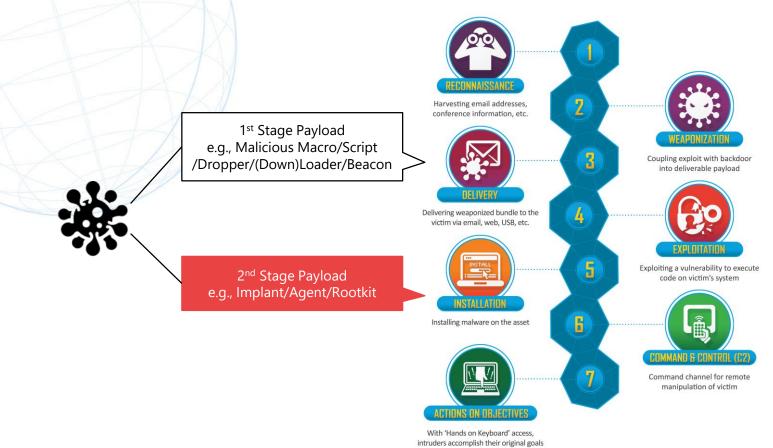
Obfuscation Transformation	Abstraction	Unit	Dynamics	Target
Opaque Predicates	All	Function	Static	Data constant
Convert static data to procedural data	All	Instruction	Static	Data constant
Mixed Boolean Arithmetic	All	Basic block	Static	Data constant
White-box cryptography	All	Function	Static	Data constant
One-way transformations	All	Instruction	Static	Data constant
Split variables	All	Function	Static	Data variable
Merge variables	All	Function	Static	Data variable
Restructure arrays	Source	Program	Static	Data variable
Reorder variables	All	Basic block	Static	Data variable
Dataflow flattening	Binary	Program	Static	Data variable
Randomized stack frames	Binary	System	Static	Data variable
Data space randomization	All	Program	Static	Data variable
Instruction reordering	All	Basic block	Static	Code logic
Instruction substitution	All	Instruction	Static	Code logic
Encode Arithmetic	All	Instruction	Static	Code logic
Garbage insertion	All	Basic block	Static	Code logic
Insert dead code	All	Function	Static	Code logic
Adding and removing calls	All	Program	Static	Code logic
Loop transformations	Source, IR	Loop	Static	Code logic
Adding and removing jumps	Binary	Function	Static	Code logic
Program encoding	All	All buy System	Dynamic	Code logic
Self-modifying code	All	Program	Dynamic	Code logic
Virtualization obfuscation	All	Function	Static	Code logic
Control flow flattening	All	Function	Static	Code logic
Branch functions	Binary	Instruction	Static	Code logic
Merging and splitting functions	All	Program	Static	Code abstraction
Remove comments and change formatting	Source	Program	Static	Code abstraction
Scrambling identifier names	Source	Program	Static	Code abstraction
Removing library calls and programming idioms	All	Function	Static	Code abstraction
Modify inheritance relations	Source, IR	Program	Static	Code abstraction
Function argument randomization	All	Function	Static	Code abstraction

Obfuscation Tools



- Commercial
 - Themida
 - Code Virtualizer
 - VMProtect
 - Enigma
 - Epona
 - **–** ...
- Academic
 - Tigress
 - Obfuscator-LLVM (O-LLVM)
 - **–** ...







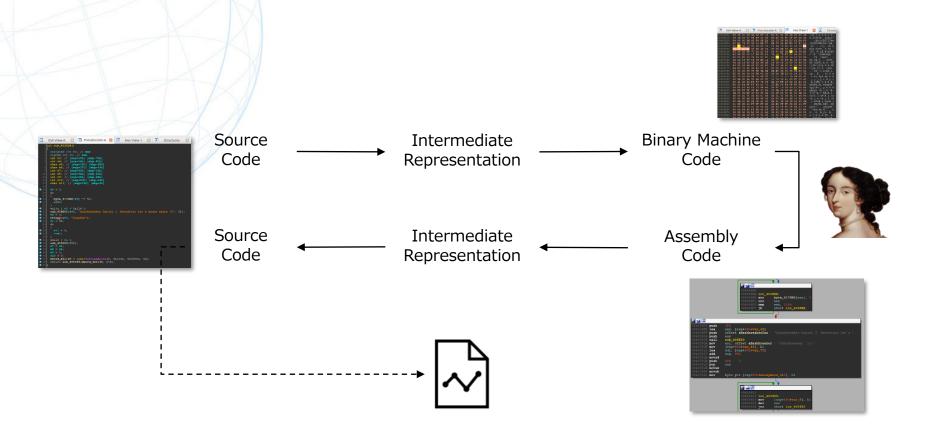




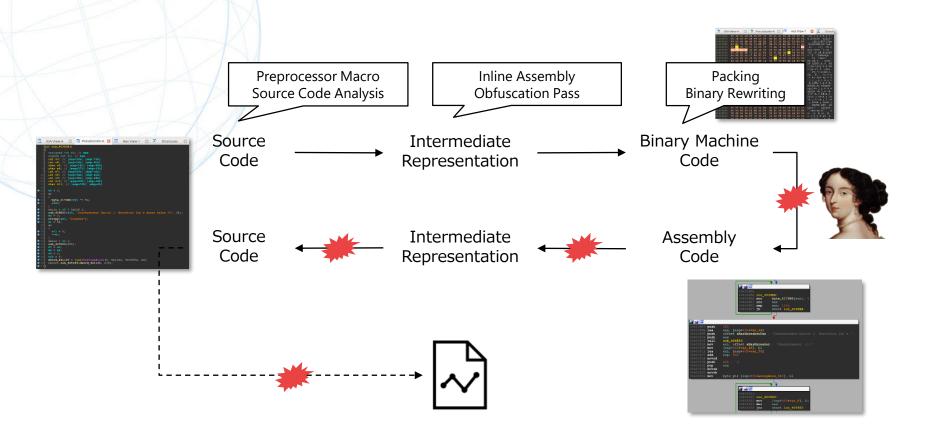


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```

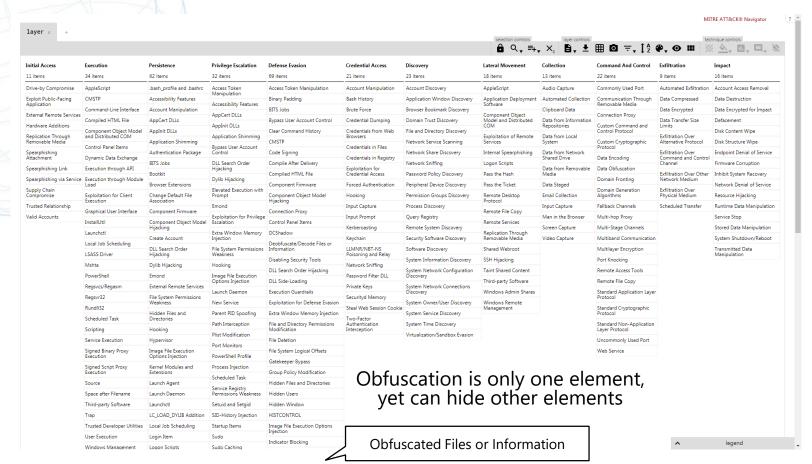












Obfuscation Techniques

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- Different techniques, common ideas:
 - Do useless things
 - Garbage/Dead Code Insertion
 - Change syntax
 - Instruction Substitution
 - Encode Literals
 - Encode Arithmetic
 - Change not only syntax but also semantics
 - Opaque Predicate
 - Control Flow Flattening
 - Virtualization Obfuscation

Garbage/Dead Code Insertion



- Insert code which runs but does not affect an intended result
- Often combined with other obfuscations

```
mov edx, 0xdeadc00d
                                                    mov eax, [ebp+arq 4]
mov eax, [ebp+arg_4]
                                                    mov ecx, [ebp+arg 0]
mov ecx, [ebp+arq 0]
                                                    mov edx. 5
mov edx. 5
                                                   mov [ebp+var_4], ecx
mov [ebp+var 4], ecx
                                                   mov [ebp+var_8], eax
mov [ebp+var_8], eax
mov eax, [ebp+var_4]
                                                   mov eax, [ebp+var_4]
                                                    add eax, [ebp+var_8]
add eax, [ebp+var_8]
                                                   mov ecx, [ebp+var 8]
mov ecx, 0
                                                    mov ecx, 0
mov [ebp+var_10], edx
                                                    mov [ebp+var 10], edx
mov edx, ecx
                                                    mov edx, ecx
mov ecx, [ebp+var_10]
                                                    mov ecx, [ebp+var 10]
div ecx
                                                    div ecx
mov [ebp+var C], eax
                                                    mov [ebp+var C], eax
```

^{*}An insertion of code which does not run is called junk code insertion

Instruction Substitution



Replace code with complex, yet equivalent code

mov eax, [ebp+arg_0]
mov [ebp+var_4], eax
mov [ebp+var_8], 0Ch
mov [ebp+var_C], 38h; '8'
mov [ebp+var_10], 7Fh
mov eax, [ebp+var_8]
add eax, [ebp+var_6]
add eax, [ebp+var_10]
add eax, [ebp+var_1]
mov [ebp+var_14], eax
mov eax, [ebp+var_14]

mov eax, [ebp+arg_0]
xor ecx, ecx
mov [ebp+var_8], eax
mov [ebp+var_C], 0Ch
mov [ebp+var_10], 38h; '8'
mov [ebp+var_14], 7Fh
mov eax, [ebp+var_C]
mov edx, [ebp+var_10]
sub eax, 2598A32Bh
add eax, edx
add eax, 2598A32Bh
mov edx, [ebp+var_14]

mov esi, ecx sub esi, eax mov eax, ecx sub eax, edx add esi, eax mov eax, ecx sub eax, esi mov edx, [ebp+var_8] sub ecx, edx sub eax, ecx mov [ebp+var_18], eax mov eax, [ebp+var_18]

• •

Encode Literals



- Replace literals (constants, strings) with more complex expressions
 - By dividing/encoding them

```
lea eax, format; "%s¥n"
lea ecx, aHelloWorld; "hello world"
mov [ebp+var_4], ecx
mov ecx, [ebp+var_4]
mov [esp], eax; format
mov [esp+4], ecx
call _printf
mov [ebp+var 8], eax
```

mov edx, [ebp+var 4] mov eax, [ebp+arq 4] add eax, edx mov byte ptr [eax], 68h; 'h' add [ebp+var 4], 1 mov edx, [ebp+var 4] mov eax, [ebp+arg_4] add eax, edx mov byte ptr [eax], 65h; 'e' add [ebp+var 4], 1 mov edx, [ebp+var_4] mov eax, [ebp+arg_4] add eax, edx mov byte ptr [eax], 6Ch; 'l' add [ebp+var 4], 1 mov edx, [ebp+var 4] mov eax, [ebp+arg_4] add eax, edx mov byte ptr [eax], 6Ch; 'l' add [ebp+var 4], 1 mov edx, [ebp+var 4] mov eax, [ebp+arg_4] add eax, edx mov byte ptr [eax], 6Fh; 'o'

add [ebp+var 4], 1 mov edx, [ebp+var 4] mov eax, [ebp+arg_4] add eax, edx mov byte ptr [eax], 20h; ' add [ebp+var 4], 1 mov edx, [ebp+var 4] mov eax, [ebp+arg 4] add eax, edx mov byte ptr [eax], 77h; 'w' add [ebp+var 4], 1 mov edx, [ebp+var 4] mov eax, [ebp+arq 4] add eax, edx mov byte ptr [eax], 6Fh; 'o' add [ebp+var 4], 1 mov edx, [ebp+var 4] mov eax, [ebp+arg_4] add eax, edx mov byte ptr [eax], 72h; 'r' add [ebp+var 4], 1 mov edx, [ebp+var 4] mov eax, [ebp+arg 4] add eax, edx mov byte ptr [eax], 6Ch; "

Encode Arithmetic/Mixed Boolean Arithmetic



Replace arithmetic/Boolean operations with more complex expressions

```
mov eax, [ebp+arg_0]
mov [ebp+var_4], eax
mov [ebp+var_8], 0Ch
mov [ebp+var_C], 38h; '8'
mov [ebp+var_10], 7Fh
mov eax, [ebp+var_8]
add eax, [ebp+var_C]
add eax, [ebp+var_10]
add eax, [ebp+var_14]
mov [ebp+var_14], eax
mov eax, [ebp+var_14]
```

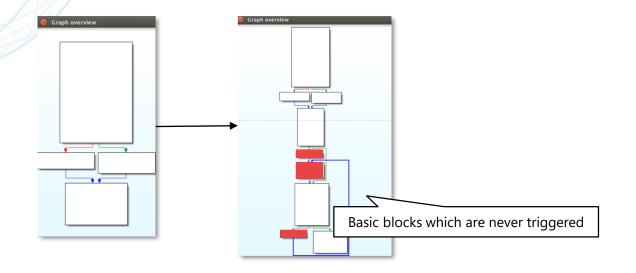
mov [ebp+var_10], 0Ch mov [ebp+var_C], 38h; '8' mov [ebp+var_8], 7Fh mov eax, [ebp+var_C] not eax mov edx, eax mov eax, [ebp+var_10] sub eax, edx lea edx, [eax-1] mov eax, [ebp+var_8] not eax sub edx, eax mov eax, edx sub eax, 1 or eax, [ebp+arq 0]

mov edx, eax mov eax, [ebp+var C] not eax mov ecx, eax mov eax, [ebp+var 10] sub eax, ecx lea ecx, [eax-1] mov eax, [ebp+var_8] not eax sub ecx, eax mov eax, ecx sub eax, 1 and eax, [ebp+arq 0] add eax. edx mov [ebp+var 4], eax mov eax, [ebp+var 4]

Opaque Predicate



- Insert a conditional branch (predicate) which is never or always be triggered
- Make an unconditional branch conditional

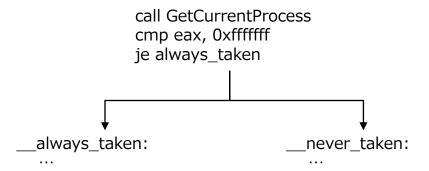


Opaque Predicate



Achieved by inserting deterministic operations:

$7y^2 - 1 \neq x^2$
2 x(x+1)
3 x(x+1)(x+2)
$x^2 > 0$
$7x^2 + 1 \not\equiv 0 \mod 7$
$x^2 + x + 7 \not\equiv 0 \mod 81$
$x > 0$ for $x \in I$ random where $I \subset X \setminus \{0\}$ a random interval



Arithmetic

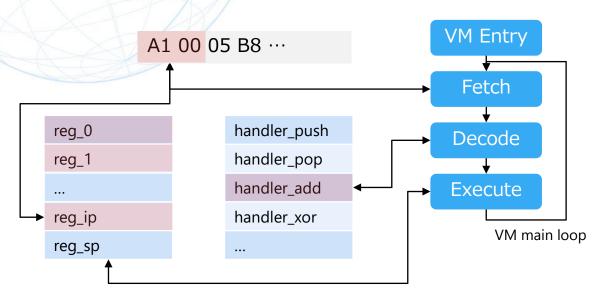
$$f(n) = \begin{cases} \frac{n}{2} & \text{if } n\%2 = 0\\ 3n+1 & \text{if } n\%2 = 1 \end{cases}$$

Collatz Conjecture

Virtualization Obfuscation



- Replace code with unique bytecode
 - Execute it on a virtual machine
- Bytecode format is independent to the host ISA



^{*}Obfuscated by Tigress -Virtualize option

```
unsigned int target_function(int n )
 char 1 target function $locals[8];
 union _1_target_function_$node _1_target_function_$stack[1][32];
 union _1_target_function_$node *_1_target_function_$sp[1];
 unsigned char *_1_target_function_$pc[1];
 _1_target_function_$sp[0] = _1_target_function_$stack[0];
 1 target function $pc[0] = 1 target function $array[0];
 while (1) {
  switch (*(_1_target_function_$pc[0])) {
  case _1_target_function_load_int$left_STA_0$result_STA_0:
  (_1_target_function_$pc[0]) ++;
  (_1_target_function_$sp[0] + 0)->_int
       = *((int *)(_1_target_function_$sp[0] + 0)->_void_star);
  break:
  case _1_target_function_branchIfTrue$expr_STA_0$label_LAB_0:
  (_1_target_function_$pc[0]) ++;
  if (( 1 target function sp[0] + 0)-> int) {
    _1_target_function_$pc[0] += *((int *)_1_target_function_$pc[0]);
  } else {
    _1target_function_pc[0] += 4;
```

Virtualization Obfuscation



- Handler Duplication
 - Generate diversified instruction handlers from a handler template



- Direct Threaded Code
 - Hide VM main loop by decentralize the dispatcher
 - Originally a performance optimization technique

```
case handler_push:
stack[reg_sp++] = reg_01;
break;

case handler_push:
stack[reg_sp++] = reg_01;
goto *bytecode[++reg_ip].insn.addr;
```

Return to the virtual CPU

Jump to the *next handler address*

Virtualization Obfuscation



- Limitations
 - Loop
 - Switch/Case statements
 - Exception handling

Control Flow Flattening



- Flatten each basic block as a case of the switch statement
 - Jump to the next block to be executed based on index in the switch statement
 - Update the index that points to the next block as each block executes

```
int main()
{
    int next = 0;

while(1){
    switch(next){
        case 0:
            printf("Hello, ");
        printf("world!\u00e4n");
        return 0;
}

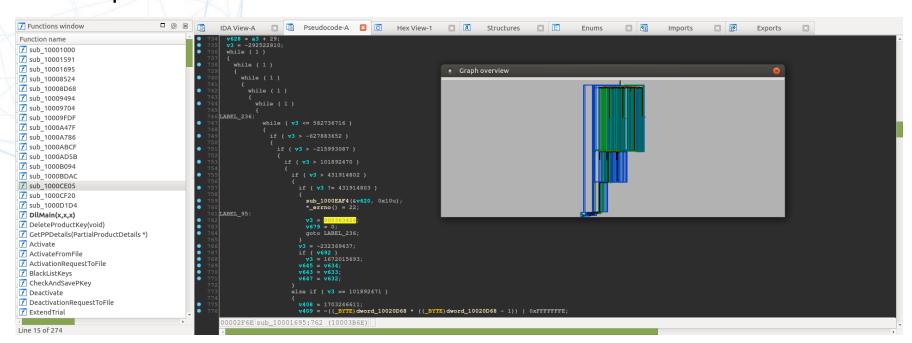
int main()
{
    int next = 0;

while(1){
        case 0:
            printf("Hello, ");
            next = 1;
            break;
        case 1:
            printf("world!\u00e4n");
            return 0;
        }
        }
    }
}
```

Control Flow Flattening



Example: ANEL



MD5: a79f59b1b17e8bfa3299e50a8af9cdaf ANEL is a RAT used by APT10 a.k.a. MenuPass, Stone Panda, or Red Apollo Haruyama. Defeating APT10 Compiler-Level Obfuscations. VB'19.

Hands-On 1: Obfuscation



- Duration: 20min
- Objective: Obfuscate sample code under the hands-on1 directory
- Step1: Prepare targets
 - test-add.c, test-mod2.c, test-hello.c, test-mod2-add.c
 - Write your own code
- Step2: Apply obfuscation transformations
 - O-LLVM: o-llvm.sh
 - ./o-llvm.sh ./src/ ../obfuscator/build/bin/clang
 - Tigress: tigress.sh
 - ./tigress.sh ./src/
 - Execute Tigress inside Docker container

Hands-On 1: Obfuscation



- Step3: Compare obfuscated binary files and un-obfuscated ones
 - How to build un-obfuscated binary files
 - make
 - Take a look at obfuscated source code generated by Tigress

Sample Code

```
NTT 😃
```

```
3 unsigned int target function(int n)
4 {
5
           int a, b, c, r;
                     //0x0C
           a = 12;
           b = 56; //0x38
8
9
           c = 127; //0x7F
10
11
           r = a + b + c + n;
12
13
           return r;
14 }
```

test-add.c

test-hello.c

```
3 unsigned int target_function(int n)
4 {
5          if(n % 2 == 0){
6               return 0;
7          }else{
8               return 1;
9          }
10 }
```

O-LLVM



- Obfuscates a given intermediate representation of LLVM (LLVM-IR)
 - Implemented as an optimization pass of the compiler toolchain
- Options
 - sub: Instruction Substitution
 - fla: Control Flow Flattening
 - bcf: Opaque Predicate (as it is also referred to as Bogus Control Flow)
- References
 - https://github.com/obfuscator-llvm/obfuscator/wiki
 - Junod et al. Obfuscator-LLVM Software Protection for the Masses. SPRO'15.
- Running Examples
 - \${OLLVM} -m32 -mllvm -sub \${FILE} -o "\${FILE_NO_EXT##*/}-sub.bin"
 - \${OLLVM} -m32 -mllvm -fla \${FILE} -o "\${FILE_NO_EXT##*/}-fla.bin"
 - \${OLLVM} -m32 -mllvm -bcf \${FILE} -o "\${FILE_NO_EXT##*/}-bcf.bin"

Tigress



- Obfuscates a given C source code
- Maintained by research group at University of Arizona, lead by Christian Collberg
- Advanced obfuscation transformations for which an analysis method has not yet been established is also applicable

Challen	ge Description	Number of binaries	Difficulty (1-10)	Script Prize	Status
0000	One level of virtualization, random dispatch.	5	1	script Certificate issued by DAPA	Solved
0001	One level of virtualization, superoperators, split instruction handlers.	5	2	Signed copy of script Surreptitious Software.	Solved
0002	One level of virtualization, bogus functions, implicit flow.	5	3	Signed copy of script Surreptitious Software.	Solved
0003	One level of virtualization, instruction handlers obfuscated with arithmetic encoding, virtualized function is split and the split parts merged.	5	2	Signed copy of script Surreptitious Software.	Solved
0004	Two levels of virtualization, implicit flow.	5	4	script USD 100.00	Solved
0005	One level of virtualization, one level of jitting, implicit flow.	f 5	4	script USD 100.00	Solved
0006	Two levels of jitting, implicit flow.	5	4	script USD 100.00	Open

Tigress



- Options (tigress --options)
 - Transform: Specify obfuscation transformation
 - Sub-Options of AddOpaque
 - AddOpaqueCount: A number of opaque predicates to be added
 - AddOpaqueKinds: Kinds of opaque predicates to be added
 - Functions: Specify function to be obfuscated
 - Environment: Specify architecture, OS, and compiler
 - out: Specify output source code name
 - o: Specify output binary name
- References
 - http://tigress.cs.arizona.edu/index.html

Tigress



- Running Examples
 - Encode Literals
 - tigress --Transform=EncodeLiterals --Functions=target_function --Environment=x86_64:Darwin:Clang:5.1 -m32 --out=\${FILE_NO_EXT##*/}-encodeliteral.c \${FILE} -o \${FILE_NO_EXT##*/}-encodeliteral.bin
 - Encode Arithmetic
 - tigress --Transform=EncodeArithmetic --Functions=target_function --Environment=x86_64:Darwin:Clang:5.1 m32 --out=\${FILE_NO_EXT##*/}-encodearith.c \${FILE} -o \${FILE_NO_EXT##*/}-encodearith.bin
 - Opaque Predicate
 - tigress --Transform=InitOpaque --Functions=main --Transform=AddOpaque --Function=target_function -- AddOpaqueCount=\${NUM} -AddOpaqueKinds=true --Environment=x86_64:Darwin:Clang:5.1 -m32 -- out=\${FILE_NO_EXT##*/}-opaque.c \${FILE} -o \${FILE_NO_EXT##*/}-opaque.bin
 - Control Flow Flattening
 - tigress --Transform=Flatten --Functions=target_function --Environment=x86_64:Darwin:Clang:5.1 -m32 -- out=\${FILE_NO_EXT##*/}-flatten.c \${FILE} -o \${FILE_NO_EXT##*/}-flatten.bin
 - Virtualization Obfuscation
 - tigress --Transform=Virtualize --Functions=target_function --Environment=x86_64:Darwin:Clang:5.1 -m32 -- out=\${FILE_NO_EXT##*/}-virtualized.c \${FILE} -o \${FILE_NO_EXT##*/}-virtualized.bin
- Notes
 - Transform and Functions are stackable:
 - tigress --Transform=Flatten --Functions=target_function --Transform=Virtualize --Functions= ...

IDA Pro





Interactive disassembler



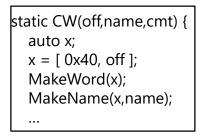
Hexdump



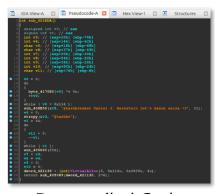
Debugging



Disassembly



IDC Scripting



Decompiled Code (Unavailable on Freeware version)

```
from idc import *
from idaapi import *

def main():
    ea = ScreenEA()
    ...
```

IDAPython Scripting (Unavailable on Freeware version)

IDA Pro

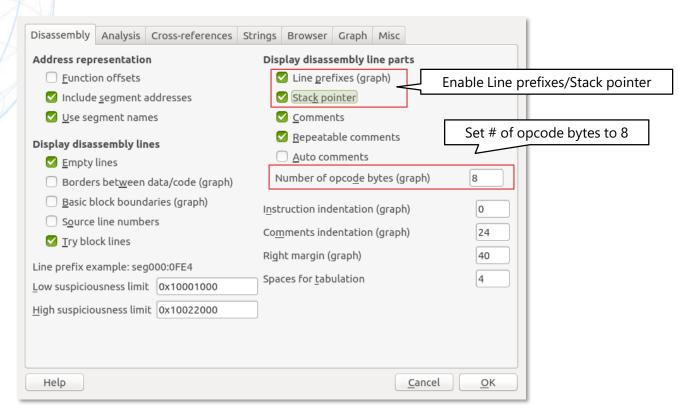


- IDB Database
 - Store byte sequence, modified labels, comments, etc.
- Subviews (View → Open subviews)
 - Imports
 - Exports
 - Strings
 - Hex
 - Functions
 - Structures

IDA Pro Tips



Options → General



IDA Pro Cheat Sheet



Shortcut Key	Description
Χ	Cross Reference (xref)
Enter	Jump to address
Esc	Jump to previous position
Space	Switch views
U	Un-define selected region
С	Interpret selected region as code
D	Interpret selected region as data
Р	Interpret selected region as function
Α	Interpret selected region as string
N	Rename function or variable
i	Add repeatable (xref-able) comment

Reference

https://www.hex-rays.com/products/ida/support/freefiles/IDA_Pro_Shortcuts.pdf

Applicability of Obfuscation Techniques



- Not all functions can be obfuscated properly
 - The applicability depends on a program structure and a transformation

√ - Success

	0	-LLV	M	Tigress							
	sub	bcf	fla	AddOpaque (w/ -q option)	EncodeLiterals	EncodeArithmetic	Virtualize	Flatten			
test-add.c	V	V	*1	V (V)	*3	V	V	V			
test-hello.c	*2	V	*1	V (V)	V	*2	V	V			
test-mod2.c	*2	V	V	√ (*4)	*3	V	V	V			

^{*1 - #} of Basic Blocks is not enough

^{*2 -} No substitutable operations

^{*3 -} No literals

^{*4 -} No room for inserting opaque predicate as it only contains conditional branch

Deobfuscation Techniques



- Approach
 - Simplify: Transform code into readable form
 - Elimination: Remove redundant code
 - Dynamic Analysis: Avoid reading obfuscated code
- Technology Stack
 - Dataflow Analysis
 - Symbolic Execution
 - Equivalence Checking
 - Abstract Interpretation
 - Program Synthesis
 - Taint Analysis
 - **—** ...



Deobfuscation Techniques

(De-)Obfuscation Techniques



- Different techniques, common ideas:
 - Do useless things
 - Garbage/Dead Code Insertion

dage/Dead Code Insertio

Dataflow Analysis (Liveness Analysis)

Dataflow Analysis

(Reachable Definition Analysis)

- Change syntax
 - Instruction Substitution
 - Encode Literals
 - Encode Arithmetic
- Change not only syntax but also semantics
 - Opaque Predicate
 - Virtualization Obfuscation
 - Control Flow Flattening

Dynamic Symbolic Execution Graph Pattern Matching

Symbolic Execution Equivalence Checking

VMHunt Program Synthesis

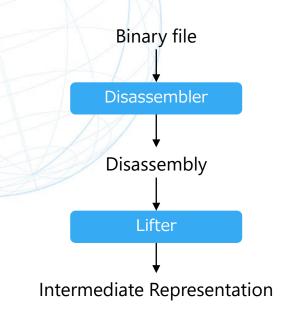
Binary Analysis Tools



- These techniques cannot be established without a modern binary analysis tools
 - IDA, radare2, Binary Ninja, angr, BINSEC, Triton, Miasm, McSema, etc.
- As well as a compiler, binary analysis tools typically consist of two major components:
 - Frontend
 - Backend

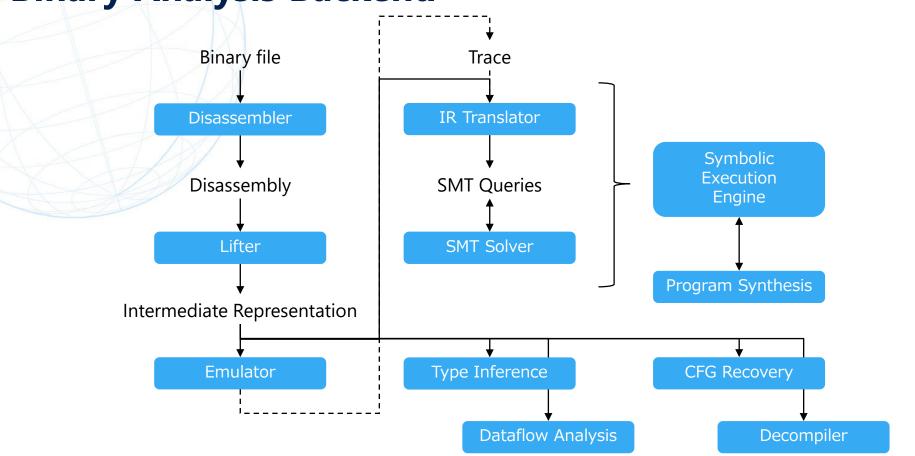
Binary Analysis Frontend





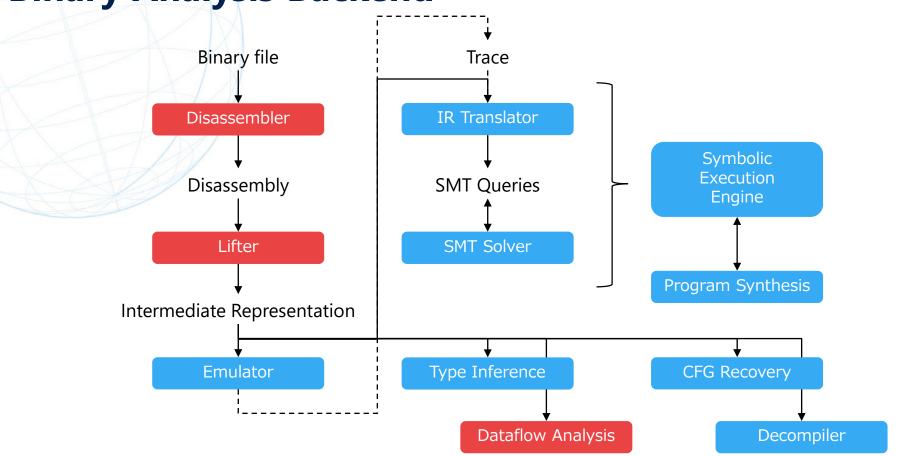
Binary Analysis Backend





Binary Analysis Backend







- A glue between binary code and analysis methods
 - Compiler optimization, symbolic execution, program synthesis, etc.
- IR enables us to handle code from different architectures in a single interface
 - x86, x64, ARM, etc.
- Regardless of a compiler or a binary analysis tool, IR is typically a Static Single Assignment (SSA) form
 - Each variable is assigned exactly once; it is defined before it is used
 - This property facilitates optimization or transformation

$$reg_01 = 5$$
 $reg_01_1 = 5$ $reg_02_1 = reg_01_1 - 3$ $reg_01_2 = reg_01_1 * 3$



- As with other languages, IR consists of:
 - Syntax: Which opcodes and operands can be combined
 - Operational Semantics: How operands are updated by each opcode

```
program
                 stmt*
                 var := exp \mid store(exp, exp)
stmt s
                                                                   Context
                                                                              Meaning
                   goto exp | assert exp
                                                                   \Sigma
                                                                              Maps a statement number to a statement
                   if exp then goto exp
                                                                              Maps a memory address to the current value
                                                                   \mu
                   else goto exp
                                                                              at that address
                 load(exp) \mid exp \lozenge_b exp \mid \lozenge_u exp
exp e
                                                                              Maps a variable name to its value
                   var \mid get input(src) \mid v
                                                                              The program counter
                 typical binary operators
                                                                   pc
                                                                              The next instruction
                 typical unary operators
                 32-bit unsigned integer
value v
```

 $\frac{\text{computation}}{\langle \text{current state} \rangle, \text{ stmt} \leadsto \langle \text{end state} \rangle, \text{ stmt'}} \qquad \frac{\mu, \Delta \vdash e \Downarrow v \quad v' = \lozenge_u v}{\mu, \Delta \vdash \lozenge_u e \Downarrow v'} \text{ UNOP} \qquad \frac{\mu, \Delta \vdash e_1 \Downarrow v_1 \quad \mu, \Delta \vdash e_2 \Downarrow v_2 \quad v' = v_1 \lozenge_b v_2}{\mu, \Delta \vdash e_1 \lozenge_b e_2 \Downarrow v'} \text{ BINO}$



- Limitations
 - Flag registers, floating points, SIMD, etc. are difficult to model;
 - Thus IR in binary analysis tool would not be equivalent to the semantics of the original code, but only approximates it



TABLE I: Existing open-source tools¹ for binary analysis.

Lifter Design						IR Characteristics					Architecture Support							
Tool	IR Name	Programming Language	Pure Parallelism	IR Optimization	AST Construction	Metadata Embedding	Explicit ⁵	Self- Contained ⁵	Hash-consed IR Support	x86 SIMD Support	Big Integer Splitting	98x	x86-64	ARMv7	ARMv8	Thumb	MIPS32	MIPS64
angr [40]	VEX ²	C & Python	Х	✓	✓	✓	Х	×	Х	✓	Х	✓	✓	✓	✓	/	/	✓
BAP [13]	BIL	OCaml ⁴	X	✓	✓	X	✓	✓	X	✓	X	✓	✓	/	/	✓	/	✓
BINSEC [18]	DBA	OCaml	X	X	✓	X	✓	✓	X	✓	×	✓	X	/	X	X	X	X
BinNavi [19]	REIL	Java	✓	X	✓	X	✓	✓	X	X	X	✓	X	X	X	X	X	X
BitBlaze [41]	Vine	C & OCaml	X	✓	✓	X	✓	✓	X	✓	×	✓	X	/	X	X	X	X
Insight [21]	Microcode ³	C++	✓	X	✓	X	/	✓	X	X	X	✓	/	/	X	X	X	X
Jakstab [30]	SSL	Java	✓	X	✓	X	/	✓	X	/	X	/	X	X	X	X	X	X
Miasm [15]	Miasm IR	C & Python	X	X	✓	X	X	X	X	✓	X	✓	/	/	/	/	/	X
radare2 [4]	ESIL [1]	Č	✓	X	X	X	✓	/	X	✓	X	✓	✓	/	/	✓	/	1
rev.ng [17]	LLVM	C++	✓	X	✓	X	X	✓	X	✓	X	✓	✓	✓	✓	✓	/	✓
B2R2*	LowUIR	F#	/	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

¹ We intentionally omit MCSema [45] as it relies on IDA Pro for disassembling binaries.

² angr internally uses VEX IR, and it lifts binaries using a module called PyVEX [3], which is a Python wrapper of the VEX lifter [34] originally written in C.

³ This should not be confused with IDA Pro's IR, which is also referred to as Microcode.

⁴ The ocaml-multicore project [28] aims to support multicore parallelism, but it is not yet integrated into the upstream.

⁵ We follow the definition of explicitness and self-containment in [29].

^{*} This is our work.



- Binary analysis tool
 - Provides Python interface; much easier than OCaml
 - Supports multiple file formats and architectures
- User can lift binary code to Miasm IR and apply various analysis
 - Symbolic Execution
 - Concolic Execution
 - Program Slicing
 - Emulation (JIT)
 - Simplification



- Strengths
 - More backward compatibility than Angr
 - Rich functionalities than Triton
- Weaknesses
 - The simplification for the value in the memory is poor
 - Once lifted to Miasm IR, it is difficult to back it to the x86 code
 - x86 → Miasm IR → LLVM IR → x86
 - Automatic analysis would not be scale to the entire binary



- Our aim is not about mastering Miasm itself
 - Other tools may be appropriate for some tasks
 - The point is to understand the principle of binary analysis explained so far
- Interface differences are not the essence
 - Binary analysis tools are basically designed to create instances of a target binary and analysis methods, and then perform analysis via the instance methods
 - Triton: Initialize TritonContext, allocate Instruction to it, and communicate with the solver from it
 - Angr: Initialize Project, generate CFG from it, and manage the symbolic state with SimulationManager
 - Miasm: Generate AsmCFG, convert it to IRCFG, and symbolically execute it via SymbolicExecutionEngine



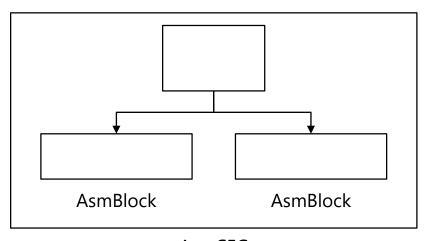
from miasm.analysis.binary import Container from miasm.analysis.machine import Machine from miasm.ir.symbexec import SymbolicExecutionEngine

```
# Get architecture
with open('target.bin', 'rb') as fstream:
  cont = Container.from stream(fstream)
machine = Machine(cont.arch)
# Get a "factory" for the detected architecture
mdis = machine.dis_engine(cont.bin_stream, loc_db=cont.loc_db)
# Get AsmCFG at the entry point
asmcfg = mdis.dis_multiblock(cont.entry_point)
# Get IRCFG from the AsmCFG
ir = machine.ir(cont.loc_db)
ircfq = ir.new_ircfg_from_asmcfg(asmcfg)
# Add name to the offset
cont.loc_db.add_location(offset=cont.entry_point, name='entrypoint')
# Initialize symbolic execution engine
sb = SymbolicExecutionEngine(ir ...)
```

Miasm Disassembly

NTT 🔘

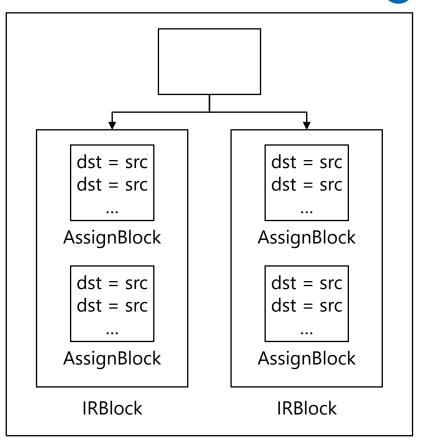
- AsmCFG
 - Control Flow Graph contains AsmBlocks
- AsmBlock
 - Basic Block



Miasm IR

NTT (O)

- IRCFG
 - Control flow graph contains IRBlocks
- IRBlock
 - Contains AssignBlocks
- AssignBlock
 - Consists of assignments: dst = src
 - SSA from



Miasm IR



Element	Human Form
ExperInt	0x18
ExperId	EAX
ExprLoc	loc_17
ExprCond	A? B : C
ExprMem	@16[ESI]
ExprOp	A + B
ExprSlice	AH = EAX[8:16]
ExprCompose	AX = AH.AL
ExprAff	A = B

mov eax, ebx

ExprAff(ExprId("EAX", 32), ExprId("EBX", 32))

push eax

$$esp = esp - 0x4$$

@32[esp - 0x4] = eax

cmp eax, ebx

(De-)Obfuscation Techniques



- Different techniques, common ideas:
 - Do useless things
 - Garbage/Dead Code Insertion

Dataflow Analysis (Liveness Analysis)

- Change syntax
 - Instruction Substitution
 - Encode Literals
 - Encode Arithmetic

Dataflow Analysis (Reachable Definition Analysis)

- Change not only syntax but also semantics
 - Opaque Predicate
 - Virtualization Obfuscation
 - Control Flow Flattening

Symbolic Execution Equivalence Checking

VMHunt Program Synthesis

Dynamic Symbolic Execution Graph Pattern Matching

Dataflow Analysis



- Reachable Definition Analysis
 - Forward dataflow analysis
 - Analyze where the value of each variable x was defined when a certain point p in the program was reached
 - Application:
 - Constant propagation/folding
 - Transform expressions
- Liveness Analysis
 - Backward dataflow analysis
 - Analyze whether the value x in the program point p may be used when following the edge starting from p in the flow graph with respect to x
 - Application:
 - Dead code elimination

Dataflow Analysis



- Both reachable definition analysis and liveness analysis are IR optimization techniques used by a compiler backend, and are also useful for binary analysis
- Behind Insights
 - Obfuscation
 - Opposite of Optimization
 - Compiler
 - Generate, analyze, and optimize IR
 - Binary Analysis Tool
 - Generate, analyze, and optimize IR

Reachable Definition Analysis



Original code (Obfuscated by InstructionSubstitution)

01. mov eax, [ebp+arg_0]
02. xor ecx, ecx
03. mov [ebp+var_8], eax
04. mov [ebp+var_C], 0Ch
05. mov [ebp+var_10], 38h
06. mov [ebp+var_14], 7Fh
07. mov eax, [ebp+var_C]
08. mov edx, [ebp+var_10]

10. add eax, edx 11. add eax, 2598A32Bh

09. sub eax, 2598A32Bh

12. mov edx, [ebp+var_14]

...

reach={01}
reach={01, 02}
reach={01, 02, 03}
reach={01, 02, 03, 04}
reach={01, 02, 03, 04, 05}
reach={01, 02, 03, 04, 05, 06}
reach={02, 03, 04, 05, 06, 07}
reach={02, 03, 04, 05, 06, 07, 08}
reach={02, 03, 04, 05, 06, 08, 09}
reach={02, 03, 04, 05, 06, 08, 10}
reach={02, 03, 04, 05, 06, 08, 11}
reach={02, 03, 04, 05, 06, 11, 12}

Code after constant propagation (Partially constant folding applied)

•••

01. mov eax, [ebp+arg_0]

02. xor ecx, ecx

03. mov [ebp+var_8], eax

04. mov [ebp+var_C], 0Ch

05. mov [ebp+var_10], 38h

06. mov [ebp+var_14], 7Fh

07. mov eax, 0Ch

08. mov edx, 38h

09. eax = 0Ch - 2598A32Bh

10. eax = 0Ch - 2598A32Bh + 38h

11. eax = 0Ch - 2598A32Bh + 38h + 2598A32Bh

12. mov edx, 7Fh

38h+0Ch

^{*}Analysis is performed after IR lifting

Reachable Definition Analysis



Original code (Obfuscated by InstructionSubstitution)

13. mov esi, ecx

14. sub esi, eax

15. mov eax, ecx

16. sub eax, edx

17. add esi, eax

18. mov eax, ecx

19. sub eax, esi

20. mov edx, [ebp+var_8]

21. sub ecx, edx

22. sub eax, ecx

23. mov [ebp+var_18], eax

24. mov eax, [ebp+var_18]

reach={02, 03, 04, 05,06, 11, 12, 13} reach={02, 03, 04, 05,06, 11, 12, 14} reach={02, 03, 04, 05,06, 12, 14, 15} reach={02, 03, 04, 05,06, 12, 14, 16} reach={02, 03, 04, 05,06, 12, 16, 17} reach={02, 03, 04, 05,06, 12, 17, 18} reach={02, 03, 04, 05,06, 12, 17, 19} reach={02, 03, 04, 05,06, 17, 19, 20} reach={03, 04, 05,06, 17, 19, 20, 21} reach={03, 04, 05,06, 17, 20, 21, 22}

Code after constant propagation (Partially constant folding applied)

13. mov esi, 0h

14. esi = 0h - (38h + 0Ch)

15. mov eax, 0h

16. eax = 0h - 7Fh

17. esi = 0h - (38h + 0Ch) + 0h - 7F

/F |-(38h+0Ch+7Fh)

18. mov eax, 0h

19. eax = 0h - (-(38h+0Ch+7Fh))

20. mov edx, arg 0

38h+0Ch+7Fh

 $21. \text{ ecx} = 0\text{h} - \text{arg}_0$

22. $eax = 38h+0Ch+7Fh-(-arg_0)$

23. mov [ebp+var_18], eax

24. mov eax, [ebp+var_18]

38h+0Ch+7Fh+arg0

•••

^{*}Analysis is performed after IR lifting

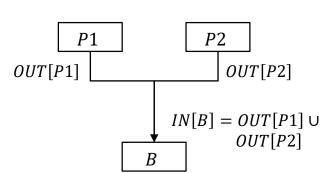
Reachable Definition Analysis



Notation	Description
В	Basic Block
gen[B]	Set of definitions generated in B and arriving at the end of B
kill[B]	Set of definitions killed by B
IN[B]	Set of definitions arriving at the start of B
OUT[B]	Set of definitions arriving at the end of B

Dataflow Equations:

$$IN[B] = \bigcup_{P \in Predecessors(B)} OUT[P]$$
 $OUT[B] = gen[B] \cup (IN[B] - kill[B])$



Liveness Analysis



```
•••
```

```
mov edx, 0xdeadc00d
mov eax, [ebp+arg_4]
mov ecx, [ebp+arq 0]
mov edx, 5
mov [ebp+var 4], ecx
mov [ebp+var_8], eax
mov eax, [ebp+var 4]
add eax, [ebp+var_8]
mov ecx, [ebp+var_8]
mov ecx, 0
mov [ebp+var_10], edx
mov edx, ecx
mov ecx, [ebp+var_10]
div ecx
mov [ebp+var C], eax
```

```
def=\{edx\}
def=\{eax\}, use=\{[ebp+arq 4]\}
def={ecx}, use={[ebp+arq 0]}
def=\{edx\}
def=\{[ebp+var 4]\}, use=\{ecx\}\}
def={[ebp+var_8]}, use={eax}
def={eax}, use={[ebp+var 4]}
def={eax}, use={eax, [ebp+var_8]}
def={ecx} use={[ebp+var_8]}
def={ecx}
def=\{[ebp+var_10]\}, use = \{edx\}
def={edx} use={ecx}
def={ecx}, use={[ebp+var_10]}
def={edx, eax}, use={edx, eax, ecx}
def={[ebp+var C]} use={eax}
```

live= $\{[ebp+arq_0], [ebp+arq_4]\}$ live= $\{[ebp+arq_0], [ebp+arq_4]\}$ live={eax, [ebp+arg_0]} live={eax, ecx} live={edx, eax, ecx} live={edx, [ebp+var_4], eax} live={edx, [ebp+var_8], [ebp+var_4]} live={edx, [ebp+var_8], eax} live={eax, edx, [ebp+var_8]} live={eax, edx} live={eax, ecx, edx} live={eax, [ebp+var 10], ecx} live={edx, eax, [ebp+var_10]} live={edx, eax, ecx} live={eax}

live = A variable used before being redefined liven = usen + liven+1 - defn

^{*}Analysis is performed after IR lifting

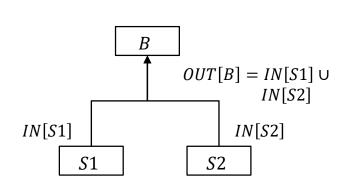
Liveness Analysis



Notation	Description
В	Basic Block
def[B]	Set of variables defined in B
use[B]	Set of variables used in B
IN[B]	Set of variables arriving at the start of B
OUT[B]	Set of variables arriving at the end of B

Dataflow Equations:

$$OUT[B] = \bigcup_{S \in Successors(B)} IN[S]$$
$$IN[B] = use[B] \cup (OUT[B] - def[B])$$



Hands-On 2: Deobfuscation via Optimization



- Duration: 30min
- Objective: Deobfuscate code via Miasm's dataflow analysis
- Step 1: Launch Jupyter Notebook
 - jupyter notebook
- Step 2: hands-on2/deadcode_removal.ipynb
 - Which line is the dead code within the code shown on the right?
 - Execute cells and confirm its effect
 - What's the method performs the removal?
- Step3: hands-on2/optimizer.ipynb
 - Optimize a binary obfuscated by O-LLVM –sub option
 - Using test-*-sub.bin generated at Hands-On 1
 - What's the method performs the constant propagation/folding?

0 main: 1 PUSH EBP 2 MOV EBP, ESP 3 MOV ECX, 0x23 4 MOV ECX, 0x4 5 MOV EAX, ECX 6 POP EBP 7 RET

Hands-On 2: Deobfuscation via Optimization



- Step 4: hands-on2/deadcode_unremoval.ipynb
 - Tweak the code shown on the right to prevent dead code removal
 - Constraint:
 - Do not change the output
 - Discussion
 - Discuss with your neighbors how to do it

0 main: 1 PUSH EBP 2 MOV EBP, ESP 3 MOV ECX, 0x23 4 MOV ECX, 0x4 5 MOV EAX, ECX 6 POP EBP 7 RET

Dataflow Analysis



- Limitations
 - Reachable definition analysis/liveness analysis are conservative methods
 - Preserve program semantics
 - Assume passing the entire path of a program
 - Flow-sensitive, path-insensitive
 - Take care of the order of instructions.
 - Do not take care of the conditional branches
 - How to interfere dataflow analysis?
 - Insert an opaque predicate and then create a dependency from it
 - Dataflow analysis does not take care of whether the path is actually executed
 - Junk code insertion would also work

Dataflow Analysis



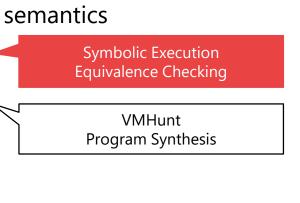
- Notes
 - We used the methods of Miasm this time
 - Another possible approach is to convert IR to LLVM IR and apply LLVM's optimization

(De-)Obfuscation Techniques



- Different techniques, common ideas:
 - Do useless things
 - Garbage/Dead Code Insertion
 - Change syntax
 - Instruction Substitution
 - Encode Literals
 - Encode Arithmetic
 - Change not only syntax but also semantics
 - Opaque Predicate
 - Virtualization Obfuscation
 - Control Flow Flattening

Dynamic Symbolic Execution Graph Pattern Matching



Dataflow Analysis

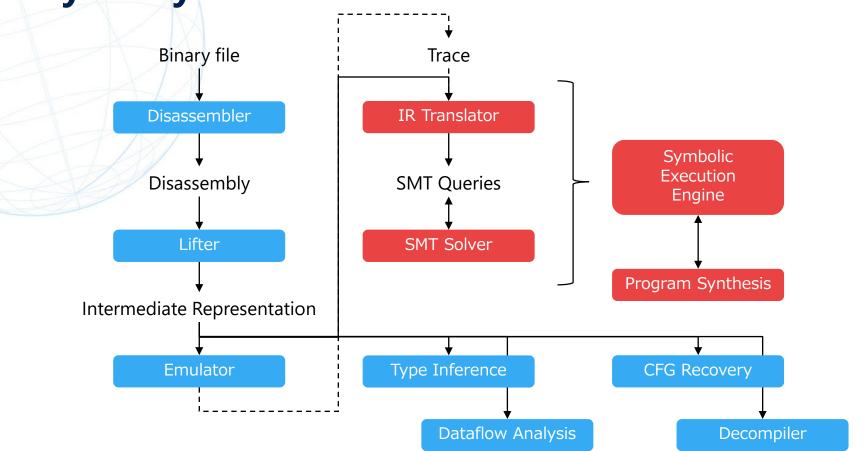
(Liveness Analysis)

Dataflow Analysis

(Reachable Definition Analysis)

Binary Analysis Backend





SMT Solver = SAT Solver + Theories



- SAT: Satisfiability Problem
 - Propositional logic

 $(malicous \lor benign) \land (\neg malicous \lor benign) \land (\neg malicous \lor \neg benign)$



- SMT: Satisfiability Modulo Theories
 - First-order predicate logic

```
(malicous \lor benign) \land (\neg malicous \lor benign)
\land (\neg malicous \lor \neg benign)
\land x * x - x = 2 
Theories
\bullet EUF
\bullet Arithmetic
\bullet Array
```

BitVector, etc.

```
from z3 import *
malicious, benign = Bools('malicious
benign')
s = Solver()
s.add(Or(malicious, benign),
Or(Not(malicious), benign),
Or(Not(malicious), Not(benign)))
print(s.check())
print(s.model())
```

```
from z3 import *
malicious, benign = Bools('malicious
benign')

x, y = Int('x ')
s = Solver()
s.add(Or(malicious, benign),
Or(Not(malicious), benign),
Or(Not(malicious), Not(benign)),
And((x * 4) - x == 2))

print(s.check())
print(s.model())
print(s.sexpr())
```

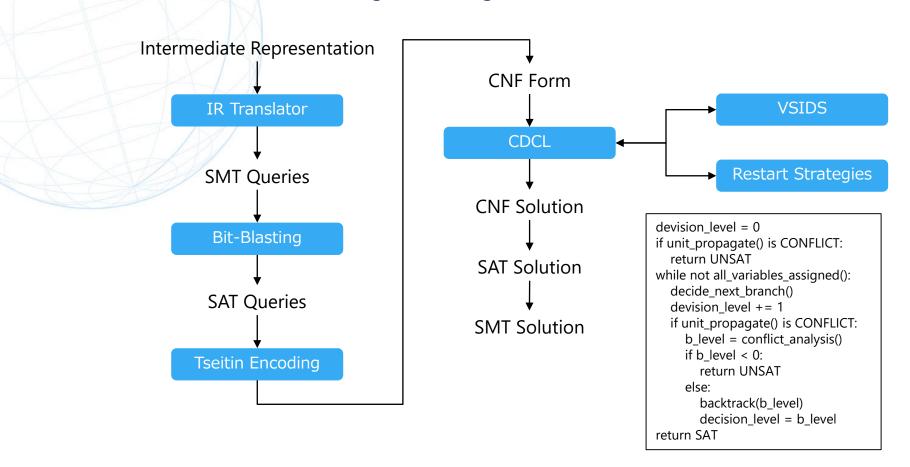
SMT Solver



- Can handle various types and operators in addition to propositional logic (SAT)
- Treat variables as BitVectors in binary analysis

SMT Solver in Binary Analysis





SMT Solver in Binary Analysis



- Applications
 - Symbolic Execution
 - Equivalence Checking
 - Program Synthesis

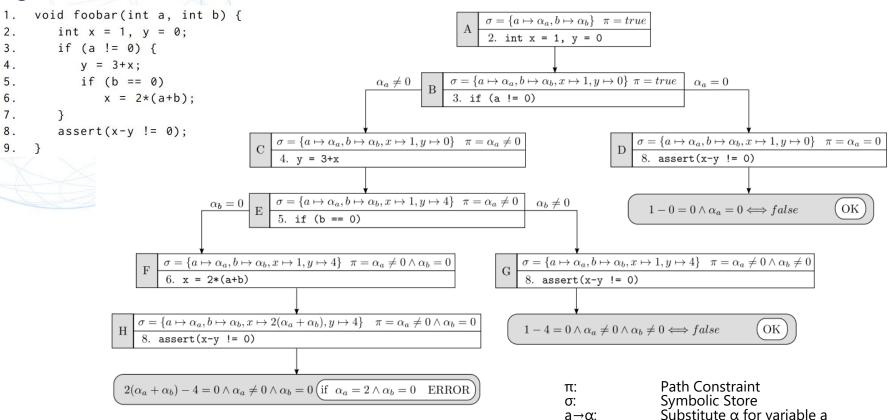


- A method for test case generation, proposed by J. C. King in 1976
 - What input values are needed to satisfy the conditions s at a program point p?
- How it works
 - Execute a program sequentially while treating input values as symbols that represent all possible values
 - Add constraints on symbols
 - Path Constraint: Constraints to execute a path
 - Symbolic Store: Updated symbol information
 - When the point is reached, solve the constraints with SMT solver and get a concrete input value
 - Need to convert IR to SMT solver-acceptable expressions



Fig. 1. Warm-up example: which values of a and b make the assert fail?







- Use case
 - Extract conditions when a malware would be activated
 - Extract conditions when a vulnerability would be triggered (Automatic Exploit Generation)
 - _>.

Symbolic Execution with Miasm



- Path explorer
 - hands-on3/simple_explore.ipynb
 - Traverses multiple paths with symbolic execution and returns the final state

```
# Generate IRCFG from the AsmCFG
ircfg = ir arch.new ircfg from asmcfg(asmcfg)
# Initialize symbolic variables
symbols init = {
  ExprMem(ExprId('ESP init', 32), 32): ExprInt(0xdeadbeef, 32)
for i, r in enumerate(all regs ids):
  symbols init[r] = all regs ids init[i]
final states = []
# Explore symbolic states
explore(ir arch,
        symbols init,
        ircfq,
        lbl stop=0xdeadbeef,
        final states=final states)
```

```
class FinalState:
  def init (self, result, sym, path conds, path history):
    self.result = result
     self.sb = sym
    self.path_conds = path conds
     self.path history = path history
def explore(ir, start addr, start symbols,
     ircfg, cond limit=30, uncond limit=100,
     lbl stop=None, final states=[]):
  def codepath walk(addr, symbols, conds, depth, final states, path):
     sb = SymbolicExecutionEngine(ir, symbols)
   return codepath walk(start addr, start symbols, [], 0, final states, [])
```

Symbolic Execution with Miasm



Path explorer

```
def codepath walk(addr, symbols, conds, depth, final states, path):
  sb = SymbolicExecutionEngine(ir, symbols)
  for in range(uncond limit):
     if isinstance(addr, ExprInt):
       if addr. get int() == lbl stop:
          final states.append(FinalState(True, sb, conds, path))
          return
     path.append(addr)
     pc = sb.run block at(ircfg, addr)
     if isinstance(pc, ExprCond): # If conditional branch
       # Calculate the condition to take true or false paths
       cond true = {pc.cond: ExprInt(1, 32)}
       cond false = {pc.cond: ExprInt(0, 32)}
       # The destination addr of the true or false paths
       addr_true = expr_simp(
            sb.eval_expr(pc.replace_expr(cond_true), {}))
       addr_false = expr_simp(
            sb.eval_expr(pc.replace_expr(cond_false), {}))
```

```
# Add the path conditions to reach this point
  conds true = list(conds) + list(cond true.items())
  conds false = list(conds) + list(cond false.items())
  # Recursive call for the true or false path
  codepath walk(
       addr true, sb.symbols.copy(),
       conds true, depth + 1, final states, list(path))
  codepath walk(
       addr false, sb.symbols.copy(),
       conds false, depth + 1, final states, list(path))
  return
else:
  addr = expr simp(sb.eval expr(pc))
final_states.append(FinalState(True, sb, conds, path))
return
```

Symbolic Execution with Miasm



- Path explorer
 - How the function codepath_walk() works
 - Execute a block
 - Calculate constraints for True/False paths
 - Duplicate the symbolic state for each path
 - Invoke codepath_walk()
 - This means the script forks the state each time a branch is taken
 - Make sense? Let's move on to the opaque predicate detection with this

Opaque Predicate Detection



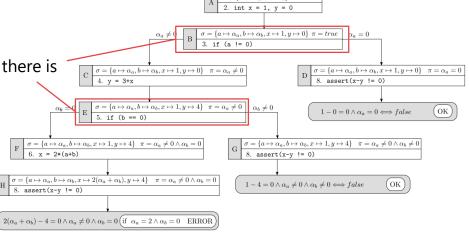
- How to detect opaque predicate with path exploration?
- Opaque predicate returns deterministic value regardless of an input value

Thus what we need do is to find the branch that determines True or False regardless of the input value

Implementation Plan:

Invoke the SMT solver at every branch and verify whether there is an input value that can take True Path or False Path; if exists, the path is a normal; if does not exist, the path should be opaque predicate

Q: Is it appropriate to do a feasibility check in the final state?



Hands-On 3: Opaque Predicate Detection



- Duration: 30min
- Objective: Let's implement the detection method described above
- Step 1: hands-on3/simple_explore_smt.ipynb
 - Implement the method
- Step 2: hands-on3/opfind.ipynb
 - Import the explorer from the simple_explore_smt.ipynb and complete the opfind.ipynb
 - Detect opaque predicate within O-LLVM-obfuscated code
 - Using test-*-bcf.bin generated at Hands-On 1
 - Open the binary with IDA and execute IDC file generated by opfind
 - It colors opaque predicates

Hands-On 3: Opaque Predicate Detection



- Step 3: APT malware analysis
 - Detect opaque predicate within X-Tunnel*1 malware via opfind.ipynb
 - Zip password: infected
 - Target function: 0x406da0
 - Generate IDC and colorize IDA view
 - Detect opaque predicates in other functions
- Step 4 (Optional): More APT malware analysis
 - Detect opaque predicate within ANEL*2 malware via opfind.ipynb
 - Zip password: infected

– ...

^{*1} MD5: ac3e087e43be67bdc674747c665b46c2 X-Tunnel is a malicious implant used by APT28 a.k.a. Fancy Bear or Sofacy Bardin et al. Backward-Bounded DSE: Targeting Infeasibility Questions on Obfuscated Codes. Oakland'17. *2 MD5: a79f59b1b17e8bfa3299e50a8af9cdaf ANEL is a RAT used by APT10 a.k.a. MenuPass, Stone Panda, or Red Apollo Haruyama. Defeating APT10 Compiler-Level Obfuscations. VB'19.



- Limitations
 - A search algorithm is up to its use case
 - DFS, random path selection, coverage-guided search, etc.
 - A room for optimization
 - State memorization, function summary
 - Accurate implementation of memory model and instruction semantics is difficult



- Limitations
 - Attacks generate constraints difficult to solve for SMT solver
 - Hash/Crypto functions
 - Nonlinear functions
 - Collatz conjecture
 - Path explosion
 - Loop/recursion

 - When to or how much use the concrete value obtained by actual execution?
 - Attacks aimed at path explosion
 - Range Divider
 - Input-dependent loop/recursion

Banescu et al. Code Obfuscation Against Symbolic Execution Attacks. ACSAC'16. Olivier et al. How to Kill Symbolic Deobfuscation for Free. ACSAC'19. Wang et al. Linear Obfuscation to Combat Symbolic Execution. ESORICS'11. Sharif et al. Impeding Malware Analysis Using Conditional Code Obfuscation. NDSS'08. *Symbolic execution with a concrete execution/values together is called Dynamic Symbolic Execution (DSE) or Concolic Execution



- Another approach that allows us to detect opaque predicate
 - Originally a software verification technique
 - Analyze an abstracted program rather than a concrete program itself
 - Track only specified properties of variables used in the program
- How it works
 - Convert each instruction to an abstract semantics.
 - Map variables to an abstract state according to the semantics
 - Simulate abstract semantics and update abstract state
 - Check abstract state at the desired time



- Example: Sign Analysis
 - Define the following abstract domain:
 - Neg: $\widehat{-} := \{x \in \mathbb{Z} | x < 0\}$
 - Zero: $\hat{0} := \{0\} \subset \mathbb{Z}$
 - Pos: $\widehat{+} := \{x \in \mathbb{Z} | x > 0\}$
 - Top (don't know): $T := \mathbb{Z}$
 - Bottom (empty): ⊥ := Ø
 - Define the abstract semantics:

•
$$\hat{+} + \hat{+} = \hat{+}$$

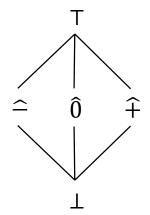
•
$$\hat{+} + \hat{0} = \hat{+}$$

•
$$\hat{+} + \hat{-} = T$$

• ...



- Abstract function α : maps sets of concrete variables to the most precise value in the abstract domain
- Concretization function γ : maps each abstract value to sets of concrete elements



A power set of the sets (More precisely, a complete lattice)





• Example: Sign Analysis

Concrete		Abstract		
Semantics	State	Semantics	State	
$x_1 = 1$	$\langle 1, ?, ?, ? \rangle$	$x_1 = \widehat{+}$	$\langle \widehat{+}, \bot, \bot, \bot \rangle$	
$x_2 = -1$	⟨1, −1,?,?⟩	$x_2 = \widehat{}$	$\langle \widehat{+}, \widehat{-}, \bot, \bot \rangle$	
$x_3 = x_1 * x_2$	⟨1, −1, −1,?⟩	$x_3 = \widehat{-} * \widehat{+}$	$\langle \widehat{+}, \widehat{-}, \widehat{-}, \perp \rangle$	
$x_4 = x_1 + x_2$	$\langle 1, -1, -1, 0 \rangle$	$x_4 = \hat{+} + \hat{-}$	⟨̂ +̂ , ^ , ^ , T⟩	



- Galois Connection
 - Once abstracted by the function α , you cannot retrieve the concrete value;
 - Yet, you can analyze exact properties of variables on the abstract domain (Soundness)
- The abstract domain can be any form as long as the inclusion relation can be described as a power set
 - Sign
 - Type information
 - **—** ...



The theory is profound; the paper seems to be obfuscated ...

For orders and posets, $\mathbb{O}[\![o]\!] \triangleq o, o \in \{\Rightarrow, \Leftrightarrow, \leq, \subseteq, =\},\$ $\mathbb{O}[\![\subseteq]\!] \triangleq \subseteq, \ldots, \mathbb{O}[\![\ddot{o}]\!] \triangleq ((\mathbb{O}[\![o]\!])), \text{ and } \mathcal{P}[\![\langle s, o \rangle]\!] \triangleq \mathbb{S}[\![s]\!] \otimes \mathbb{O}[\![o]\!].$ For GCs, $\mathcal{T}[1[p]] \triangleq \mathcal{P}[p] \hookrightarrow \mathcal{P}[p]$, $\mathcal{T}[\sim[s_{\mathbb{L}}, s_{\mathcal{M}}]] \triangleq \mathbf{P}(\mathcal{S}[s_{\mathbb{L}}] *$ $\mathcal{S}[\![s_{\mathcal{M}}]\!]) \circledast \subseteq \ \, \Longrightarrow \mathcal{S}[\![s_{\mathbb{L}}]\!] \ \, \Longrightarrow \ \, \mathbf{P} \, \mathcal{S}[\![s_{\mathcal{M}}]\!] \circledast \subseteq \ \, , \mathcal{T}[\![\cup[s]]\!] \triangleq \mathbf{P} \, (\mathbf{P} \, \mathcal{S}[\![s]\!]) \otimes$ $\subseteq \ \leftrightharpoons \ \mathbf{P} \ \mathcal{S}[\![s]\!] \ \circledast \subseteq \ \mathcal{T}[\![\neg[s]\!]\!] \ \triangleq \ \mathbf{P} \ \mathcal{S}[\![s]\!] \ \circledast \subseteq \ \leftrightharpoons \ \mathbf{P} \ \mathcal{S}[\![s]\!] \ \circledast \subseteq^{-1},$ $\mathcal{T}[\![\infty[s]\!]] \triangleq \mathbf{P} (\operatorname{seq} \mathcal{S}[\![s]\!]) \circledast \subseteq \Longrightarrow \mathbf{P} \mathcal{S}[\![s]\!] \circledast \subseteq, \mathcal{T}[\![\leadsto[s_1, s_2]\!]] \triangleq$ $\mathbf{P} \left(\mathbb{S} \llbracket s_1 \rrbracket * \mathbb{S} \llbracket s_2 \rrbracket \right) \circledast \subseteq \ \, \Longrightarrow \mathbf{P} \, \mathbb{S} \llbracket s_1 \rrbracket \ \, \Longrightarrow \mathbf{P} \, \mathbb{S} \llbracket s_2 \rrbracket \circledast \dot{\subseteq}, \mathcal{T} \llbracket \mapsto [s_1, s_2] \rrbracket \triangleq$ $\mathbf{P}\left(\mathcal{S}\llbracket s_1\rrbracket *\rightarrow \mathcal{S}\llbracket s_2\rrbracket\right) \circledast \subseteq \Longrightarrow \mathbf{P} \mathcal{S}\llbracket s_1\rrbracket *\rightarrow \mathbf{P} \mathcal{S}\llbracket s_2\rrbracket \circledast \dot{\subseteq}, \mathcal{T}\llbracket \times [s_1, s_2]\rrbracket$ $\triangleq \mathbf{P}\left(\mathcal{S}\llbracket s_1 \rrbracket *\rightarrow \mathcal{S}\llbracket s_2 \rrbracket\right) \circledast \subseteq \leftrightarrows \mathcal{S}\llbracket s_1 \rrbracket *\rightarrow \mathbf{P} \mathcal{S}\llbracket s_2 \rrbracket \circledast \dot{\subseteq}, \mathcal{T}\llbracket \mathsf{R}[g] \rrbracket \triangleq$ $\mathcal{T}[g], \mathcal{T}[s \rightarrow g] \triangleq \mathcal{S}[s] * \mathcal{T}[g], \dots$



- Applications
 - Opaque Predicate Detection
 - How it works
 - For each block, find the branch where the condition is true for any value;
 - Find when the variable which triggers the *conditional* jump is T it's *unconditional!*
 - The plugin for a Ghidra disassembler/decompiler by Rolf Rolles is publicly available:
 - https://www.msreverseengineering.com/blog/2019/4/17/an-abstract-interpretationbased-deobfuscation-plugin-for-ghidra
 - Value-Set Analysis (VSA)
 - A binary analysis method which uses type information as an abstract domain
 - Uses pointer analysis together
 - Can be used to buffer overflow detection
 - The tool with the most advanced VSA interface is angr

NTT 😃

- Abstract Interpretation vs Symbolic Execution
 - Both approximate states

Nature of Program Analysis for Testing and Verification

,	Sound	Complete	
Under-approximate Testing, Dynamic Symbolic Execution, Dynamic Software Model Checking	All programs reported unsafe are actually unsafe Only real bugs	Successfully reports all unsafe programs Finds all bugs	
Over-approximate Abstract Interpretation, Software Model Checking with Predicate Abstraction	All programs proven safe are actually safe Only real proofs	Successfully proves safety of all safe programs Finds all proofs	

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- Limitations
 - Accurate implementation of memory model and instruction semantics is difficult – same as symbolic execution
 - Range Divider same as symbolic execution-based opaque predicate detection

Range Divider



- A method to cause path explosion in symbolic execution by adding extra branches
 - # of branches: $k \rightarrow \#$ of states: 2^k
- Path constraint would not be UNSAT like opaque predicate
 - Execute a branch depends on an input value
 - Whichever a branch executed, the result is the same

Listing 2: Range divider with 2 branches

Both paths would be executed!

Table 3: Impact of obfuscations on DSE

Table 3: Impact of obfuscations on DSE							
Transformation	Dataset #1		Dataset #2				
	Goal 1	Goal 2	Goal 1	Goal 2	Goal 2		
(#TO/#Samples)	3h TO	1h TO	24h TO	3h TO	8h TO		
Virt	0/46	0/15	0/7	0/7	0/7		
Virt ×2	1/46	0/15	0/7	0/7	0/7		
Virt ×3	5/46	2/15	1/7	0/7	0/7		
SPLIT $(k = 10)$	1/46	0/15	0/7	0/7	0/7		
SPLIT $(k = 13)$	4/46	0/15	1/7	1/7	0/7		
SPLIT $(k = 17)$	18/46	2/15	3/7	2/7	1/7		
FOR $(k=1)$	2/46	0/15	0/7	0/7	0/7		
FOR $(k = 3)$	30/46	8/15	3/7	2/7	1/7		
FOR $(k=5)$	46/46	15/15	7/7	7/7	7/7		

Timeout
3h for Dataset #1, 24h for Dataset 32

Banescu et al. Code Obfuscation Against Symbolic Execution Attacks. ACSAC'16. Olivier et al. How to Kill Symbolic Deobfuscation for Free. ACSAC'19.

Range Divider



- Robust to symbolic execution/abstract interpretation
- a.k.a. 2-way Opaque Predicates, Code Clone
- Tigress can apply Range Divider via OpaqueKinds=question option

SMT Solver in Binary Analysis

NTT 😃

- Applications
 - Symbolic Execution
 - Equivalence Checking
 - Program Synthesis

Equivalence Checking



- A method to determine if two given codes have the same behavior
 - Same code: Syntactically-equivalent
 - Different code, but same behavior: Semantically-equivalent
- How it works
 - Perform symbolic execution per basic block
 - All inputs (register, memory) are symbolized
 - Compare outputs
 - With SMT solver by generating a *counterexample*
 - If no counterexample, the blocks are equivalent

Implementation Plan:

Verify if there is a solution that negates "the two basic blocks are not equivalent". If exists, the assumption is correct, i.e. not equivalent; Otherwise, the assumption is incorrect, i.e. equivalent.

Gao et al. BinHunt: Automatically Finding Semantic Differences in Binary Programs. ICICS'08. Shirazi et al. DoSE: Deobfuscation based on Semantic Equivalence. SSPREW'18.

```
# Convert miasm IR to Z3 expression
cond 1 = Translator.to language('z3')
                            .from expr(v1)
cond_2 = Translator.to_language('z3')
                            .from_expr(v2)
solver = z3.Solver()
solver.add(???)
if solver.check() == sat:
              # not equivalent
else: # UNSAT
              # equivalent!
```

Equivalence Checking

NTT 😃

- a.k.a. (Semantic) Binary Diffing, Code Clone Detection
- Applications
 - Opaque Predicate Detection
 - N-days Vulnerability Detection

Hands-On 4: Range Divider Detection



- Duration: 30min
- Objective: Let's implement the equivalence checking method
- Step 1: hands-on4/eqcheck.ipynb
 - Implement the method
- Step 2: Malware analysis
 - Detect range-divided functions within Vipasana*1 and Asprox*2 malware
 - Zip password: infected
 - Vipassana target function: 0x434DF0
 - Asprox target function: 0x100091AC
 - Detect other equivalent functions (including Range Divider and syntacticallyequivalent functions)

^{*1} MD5: 2aea3b217e6a3d08ef684594192cafc8

^{*2} MD5: 0d655ecb0b27564685114e1d2e598627 Vipasana is a ransomware; Asprox is a trojan

Hands-On 4: Range Divider Detection



- Step 4: Tigress Range Divider
 - Test the script for Tigress-obfuscated code
 - Use OpaqueKinds=question option
 - The range divider detection method would not work, why?
 - Discussion
 - How can we improve the method?

Equivalence Checking



- Limitations
 - Is Basic Blocks-oriented comparison appropriate?
 - Chunk with in a block, 1 block, 2 blocks, ... function, functions, ...?
 - Path explosion occurs when the # of unit becomes large
 - BinSim: Defines system call, its arguments, and parts that depend on those arguments as a unit
 - The essence is how to determine a unit: Point of interests and range of its dependency
 - Definition of equivalence
 - We should regard units as equivalent even when they have different outputs not used later
 - We need to concretize this idea to combat Tigress's Range Divider

(De-)Obfuscation Techniques



- Different techniques, common ideas:
 - Do useless things
 - Garbage/Dead Code Insertion
 - Change syntax
 - Instruction Substitution
 - Encode Literals
 - Encode Arithmetic
 - Change not only syntax but also semantics
 - Opaque Predicate
 - Virtualization Obfuscation
 - Control Flow Flattening

Dynamic Symbolic Execution Graph Pattern Matching

Symbolic Execution
Equivalence Checking

Dataflow Analysis

(Liveness Analysis)

Dataflow Analysis

(Reachable Definition Analysis)

VMHunt Program Synthesis

VM Deobfuscation



- VM analysis task consists of the three parts:
 - Locate:
 - Where is the VMEntry, handlers, and VMExit?
 - And how is the VM EIP updated?
 - Extract:
 - Dump the VM handlers
 - Simplify:
 - Recover the original semantics of each handler:
 - Arithmetic operations (add, sub, mul, div, ...) typically retrieve 2 values from a virtual register and write the result back to the register. Once you notice it's an arithmetic operator, all you need to do is analyze the differences
 - A conditional jump typically takes two values from a virtual register and writes the result back to the virtual instruction pointer

VM Deobfuscation



- Several techniques come to the rescue:
 - Locate:
 - Virtualized Snippet Boundary Detection (VMHunt)
 - Extract:
 - Virtualized Kernel Extraction (VMHunt)
 - Simplify:
 - Writing an IDA Processor Module on your own
 - Symbolic Execution
 - With expression simplification
 - Including DSE and Multiple Granularity Symbolic Execution (VMHunt)
 - Program Synthesis
 - CEGIS, Syntia
 - Compiler Optimization

```
reg_names = [
    # General purpose registers
    "reg_0",
    "reg_1",
    ...
]
instructions = [
    {'name': 'push', 'feature': CF_USE1}, # 0
    {'name': 'pop', 'feature': CF_CHG1}, # 1
    ...
]
```

VMHunt



- A method tailored for VM deobfuscation
- Based on dynamic analysis, some heuristics, and a variant of symbolic execution
- How it works
 - Locate context switch between the host and the VM
 - Extract the kernel from two operations:
 - The write to the VM context area
 - The write to the native stack area
 - Simplify the kernel code via symbolic execution

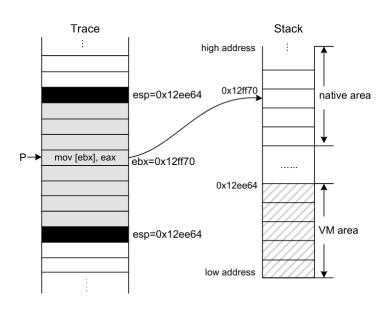
VMHunt



Intuition: Context Switch

```
// native program execution
 2 push edi
                  // context saving
 3 push
8 push eax
9 pushfd
10 imp
       0x1234
                  // virtualized snippet begin
12 mov
13 add
14 xor
                  // virtualized snippet end
16 popfd
                  // context restoring
17 pop
         eax
18 pop
         ecx
19 pop
        ebp
20 pop
        edx
21 pop
        ebx
22 pop
        esi
23 pop
        edi
24 jmp
        0x8048123
25 ...
                  // continue native program
26 . . .
                  // execution
```





... while avoiding extra bytecode analysis

VMHunt



- Can be combined with other methods:
 - Optimization
 - Program Synthesis



- A method for generating program snippet from a test case
 - Infer the transformation (program) between input and output
 - Transform new input with an inferred program
- Example: Excel Flash Fill

	Test case			
	Inputs		Outputs	
	Α	В	С	D
1	Baker	John	john.baker@company.com	
2	Cooper	Sandra	sandra.cooper@company.com	=
3	Jones	Miles	miles.jones@company.com	
4	Parker	Amy	amy.parker@company.com	
5	Smith	Peter	peter.smith@company.com	
6	Carter	Crissy	crissy.carter@company.com	
7				



- Formulated as a search problem
 - Input
 - Test case: Inputs, outputs
 - IR Fragments
 - Output
 - A combination of fragments which satisfies the test case
 - Algorithm
 - Enumerative Search (w/ Pruning)
 - SMT Solving; Counterexample-Guided Inductive Synthesis (CEGIS)
 - Metropolis-Hastings
 - Monte Carlo Tree Search (MCTS) Syntia
 - Bayesian Net
 - ..

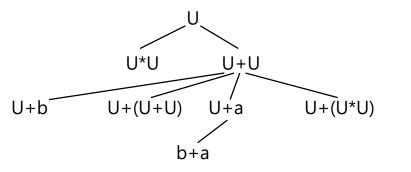


- CEGIS
 - Reduce search space by SMT solving

```
Symbolic Execution
IR fragments
                                  inputs ----
          Candidate program P
                                                            def synthesizer(inputs):
                                                               (i_1 \dots i_n) = inputs
                                                               query = (\exists P. \sigma(i_1, P) \land ... \land \sigma(i_N, P))
            Counterexample x
                                                               result, model = decide(query)
                                                               if result is SAT:
                                                                  return model
  def refinement_loop():
                                                               else:
     inputs = \Phi
                                                                  return UNSAT
     while True:
        candidate = synthesizer(inputs)
        if candidate is UNSAT:
                                                            def verifier(P):
           return UNSAT
                                                               query = \exists x. \neg \sigma(x, P)
        result = verifier(candidate)
                                                               result, model = decide(query)
        if result is valid:
                                                               if result is SAT:
           return candidate
                                                                  return model
        else:
                                                               else:
           inputs.append(res)
                                                                  return valid
```



- Syntia
 - Formulate the problem as a game tree search
 - Solve MCTS problem by UCT (Upper Confidence bounds applied to Trees) with simulated annealing
 - Calculate score for each node;
 - How to calculate it? Similar to equivalence checking
 - Backtrack
 - Open source: https://github.com/RUB-SysSec/syntia



U: Non-terminal symbol a, b, c, ...: Input variables



- Limitations
 - Program synthesis in general
 - Non-determinism
 - Point functions
 - CEGIS
 - Sometimes tries to synthesize a constant

Hands-On 5: VM Deobfuscation



- Duration: 30min
- Objective: Deobfuscate ZeusVM with a simple symbolic execution
- Step 1: hands-on5/vm_explore.ipynb
 - Analyze zeus.bin with IDA and locate VM handlers
 - Run vm_explore.ipynb
 - The method expr_simp allows you to name and reduce symbolic expressions with lambda expressions
 - What was needed in advance?
 - Locate handler addresses
 - Analyze some semantics (VM_PC_init and RET_ADDR in our hands-on)
 - How can we speed up the analysis?
 - Compare it with solved/zeus_get_ir.ipynb and implement your idea

VM Deobfuscation



- Limitations
 - Locate, Extract
 - In most cases, dynamic analysis is also required
 - Rarely as simple as ZeusVM
 - What if the assumption about VM context switch is broken?
 - Simplify
 - Our hands-on required manual semantic reasoning
 - Techniques described before are basically based on symbolic execution;
 - Limited by the limitations of symbolic execution
 - Which simplification method is better? Empirical analysis is required

(De-)Obfuscation Techniques



- Different techniques, common ideas:
 - Do useless things
 - Garbage/Dead Code Insertion
 - Change syntax
 - Instruction Substitution
 - Encode Literals
 - Encode Arithmetic
 - Change not only syntax but also semantics
 - Opaque Predicate
 - Virtualization Obfuscation
 - Control Flow Flattening

Symbolic Execution Equivalence Checking

VMHunt Program Synthesis

Dataflow Analysis

(Liveness Analysis)

Dataflow Analysis

(Reachable Definition Analysis)

Dynamic Symbolic Execution Graph Pattern Matching

Control Flow Unflattening



- Dynamic analysis is required
- Control Flow Flattening can be addressed by the following:
 - Dynamic symbolic execution
 - Symbolic execution + dynamic execution = dynamic symbolic execution
 - (w/ taint analysis)
 - Heuristics
 - · Graph pattern matching
- Spoiler: neither is a fundamental solution

Dynamic Symbolic Execution



- If the target is doing something with the input, skipping static analysis would be efficient
- In Miasm, DSE implementation would be: prepare a Sandbox instance and attach DSEPathConstraint to it
 - Still, this requires a manual analysis of the input size/type and termination conditions
- Example: hands-on6/cff_dse.ipynb

```
# Initialize a sandbox environment

sb = Sandbox_Linux_x86_64(options.filename, options, globals())

machine = Machine('x86_64')

ret_addr = 0x000000001337beef

sb.jitter.add_breakpoint(ret_addr, code_sentinelle)

sb.jitter.push_uint64_t(ret_addr)

sb.jitter.vm.add_memory_page(...
```

```
# Initialize a DSE instance with a given strategy
dse = DSEPathConstraint(machine, produce_solution=strategy)
dse.attach(sb.jitter) # Attach to the sandbox
dse.update_state_from_concrete()

# Symbolize the argument
```

•••

regs = sb.jitter.ir arch.arch.regs

Graph Pattern Matching



- How it works
 - Locate a flattened jump table
 - Find next block of every basic block
 - Generate a chain of blocks
 - Modify the control flow graph
- The plugin for IDA is publicly available: https://github.com/carbonblack/HexRaysDeob/
 - Performs analysis at Microcode (IR) level
 - Even works for ANEL malware sample
 - Unfortunately, IDA Freeware cannot process this plugin

Graph Pattern Matching



- Miasm provides interfaces for subgraph matching and block merging
- In Miasm, such a heuristics implementation would be:
 - Set a callback for disassemble;
 - Find blocks which match a specified pattern;
 - Apply a block merging pass of DiGraphSimplifier to the blocks
- Question: Is it robust?

Hands-On 6: Control Flow Unflattening



- Duration: 30min
- Objective: Unflatten the flattened binary files
- Step 1: hands-on6/cff_dse.pynb
 - Run cff_dse for the flattening-volatile.bin
 - Returns 0 only when given a specific string (flag)
- Step 2: hands-on6/cff_explore.ipynb
 - Customize cff_explore for simplifying the CFG of the test-mod2-fla.bin
 - Let's make a unflattened CFG and display it
 - No answer provided, try your idea

```
import pydotplus
from IPython.display import Image, display_png
# Visualize the CFG
with open('cfg.dot', 'w') as f:
    f.write(ircfg.dot())
graph = pydotplus.graphviz.graph_from_dot_file('cfg.dot')
graph.write_png('cfg.png')
display_png(Image(graph.create_png()))
```

Control Flow Unflattening

- Limitations
 - Hardening CFF is easy
 - Inter-procedural data flow
 - Adding opaque predicate
 - Encoding/hiding next block number



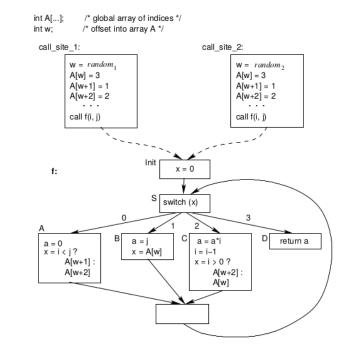


Figure 3: Enhancing flattening with Interprocedural Data Flow



Conclusion

Summary



- Obfuscation Techniques
 - Preliminaries
 - Garbage Code Insertion, Instruction Substitution, ...
 - Hands-On
- Deobfuscation Techniques
 - Preliminaries
 - Dataflow Analysis, Symbolic Execution, Equivalence Checking, ...
 - Hands-On
- Now you have a skill of implementing these techniques in practice
 - But all have their limitations

Takeaways

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- Learning curve
 - Easy:
 - Being used by tools/methods: "It doesn't work."
 - Medium:
 - Mastering tools/methods: "It doesn't work, because ..."
 - Hard:
 - Mastering tools/methods; push the envelope: "I got this to work!"

Takeaways



- Lets' look back:
 - What are the obfuscation techniques?
 - What are the obfuscation techniques?
 - What is the scope and limitations of deobfuscation methods?
- Imagine:
 - How to overcome the limitations of existing methods?
 - What if you face unknown obfuscation techniques?
- Let's see through the essence

Other Topics

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- Other dataflow analysis methods
- Taint analysis

Acknowledgement

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- Yuhei Kawakoya
 - Course material and sample code
- Makoto Iwamura
 - Sample code
- Ryo Ichikawa (icchy)
 - Environment setup

Recommended Readings



- Aho et al. Compilers: Principles, Techniques, and Tools. 1986.
- Collberg and Nagra. Surreptitious Software: Obfuscation, Watermarking, and Tamperproofing for Software Protection. 2009.
- Gazet et al. Practical Reverse Engineering: X86, X64, ARM, Windows Kernel, Reversing Tools, and Obfuscation. 2014.
- Andriesse. Practical Binary Analysis: Build Your Own Linux Tools for Binary Instrumentation, Analysis, and Disassembly. 2018.
- Banescu. Breaking Obfuscated Programs with Symbolic Execution. <u>https://www.slideshare.net/SebastianBanescu/breaking-obfuscated-programs-with-symbolic-execution</u>. 2017.
- Rolles. Möbius Strip Reverse Engineering. http://www.msreverseengineering.com/.
- Yurichev. SAT/SMT by Example. https://yurichev.com/writings/SAT_SMT_by_example.pdf.
- And research papers referenced in this material