Dynamic Binary Analysis and Obfuscated Codes

How to don't kill yourself when you reverse obfuscated codes.

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Quarkslab

About us

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Roadmap of this talk

1. Obfuscation introduction
2. Dynamic Binary Analysis introduction
3. The Triton framework
4. Conclusion
5. Future works

Obfuscation Introduction

What is an obfuscation?

Wikipedia: *"Obfuscation is the obscuring of intended meaning in communication, making the message confusing, willfully ambiguous, or harder to understand."* [1]

[1] https://en.wikipedia.org/wiki/Obfuscation

Why softwares may contain obfuscated codes?

- Intellectual property
- DRM
- Hiding secrets

What kind of obfuscations may we find in modern softwares?

- Opaque predicates
- Control-flow flattening
- Virtualization
- MBA and bitwise operations
- Use of uncommon instructions.

Example: Opaque predicates

- Objective: Create unreachable basic blocks
- The constraint $\neg\pi_1$ is always `UNSAT`
- The basic block φ_3 is never executed

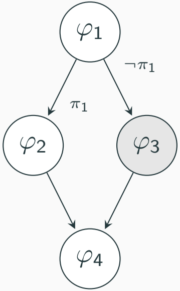

Figure 1: Control Flow Graph

Example: CFG flattened

- Objective: Remove structured control flows
- The basic block φ_2 is now used as dispatcher
- The dispatcher manages the control flow
  - Static analysis: hard to predict which basic block will be called next

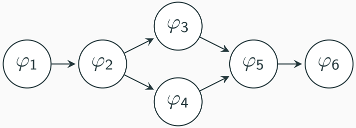

Figure 2: Original CFG

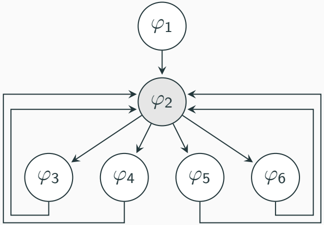

Figure 3: Flattened CFG

Example: Virtualization

- Objective: Emulate the original code via a custom ISA (Instruction Set Architecture)
- Example:

```
xor R1, R2
```

```
push R1
push R2
mov eax, [esp]
mov ebx, [esp - 0x4]
xor eax, ebx
push eax
```

Example: Virtualization

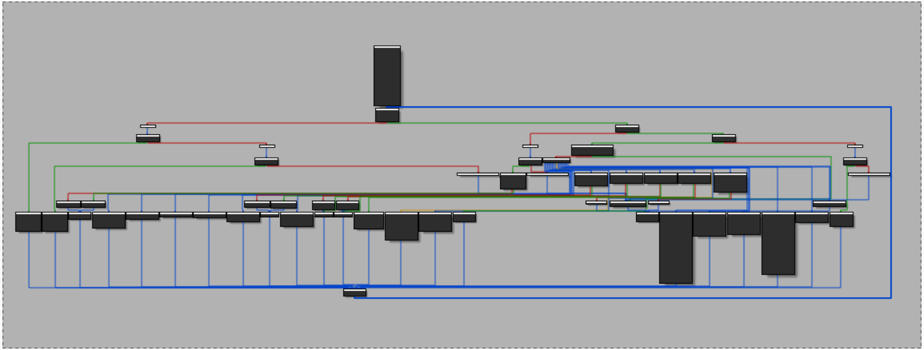

Figure 4: An example of a VM's CFG

Example: MBA and bitwise operations

- Objective: Transform the normal form of an expression to a more complex one
- The transformation output may also be transformed again and so one

$$a + b = (a \vee b) + (a \wedge b)$$

$$a * b = (a \wedge b) * (a \vee b) + (a \wedge \neg b) * (\neg a \wedge b)$$

$$a \oplus b = (a \wedge \neg b) \vee (\neg a \wedge b)$$

$$a \oplus b = ((a \wedge \neg a) \wedge (\neg b \vee \neg a)) \wedge ((a \vee b) \vee (\neg b \vee b))$$

$$0 = (a \vee b) - (a + b) + (a \wedge b)$$

Example: Use of uncommon instructions

- Objective:
  - Break your tools
  - Break your mind!
- May transform classic operations using AVX and SSE

```
public foo
proc near                          ; CODE XREF: main+23↓p
vmovd     xmm0, esi
vpxor     xmm1, xmm1, xmm1
vpshufb   xmm0, xmm0, xmm1
vpunpcklbw xmm0, xmm0, xmm1
vpmovzxwd xmm0, xmm0
vpaddd    xmm0, xmm0, xmm0
vmovd     xmm2, edi
vpshufb   xmm2, xmm2, xmm1
vpunpcklbw xmm1, xmm2, xmm1
vpmovzxwd xmm1, xmm1
vpaddd    xmm1, xmm1, xmm1
vpandn    xmm1, xmm0, xmm1
vpblendw  xmm0, xmm1, xmm0, 0CCh
vmovshdup xmm1, xmm0
vpermilpd xmm2, xmm0, 1
vpermilps xmm3, xmm0, 0E7h
vminss    xmm0, xmm3, xmm0
vminss    xmm0, xmm0, xmm1
vminss    xmm0, xmm0, xmm2
vmovd     eax, xmm0
vmovd     xmm0, eax
vpshufd   xmm0, xmm0, 0
vmovd     eax, xmm0
vpextrd   ecx, xmm0, 1
vpextrd   edx, xmm0, 2
sub       eax, ecx
add       eax, edx
movzx     eax, al
retn
```

Figure 5: Uncommon instructions

Dynamic Binary Analysis Introduction

What is a DBA?

- **D**ynamic **B**inary **A**nalysis
  - Any way to analyze a binary dynamically
  - Most popular analysis
    - Dynamic information extraction
    - Dynamic taint analysis [4]
    - Dynamic symbolic execution [3, 2, 6, 1]

Why use a DBA?

- To get runtime values at each program point
- To get the control flow for a given input
- To follow the spread of a specific data

What is a dynamic taint analysis?

- Taint analysis is used to follow a specific information through a data flow
  - Cell memory
  - Register
- The taint is spread at runtime
- At each program point you are able to know what cells and registers interact with your initial value

What is a dynamic symbolic execution?

- A DSE is used to represent the control and the data flow of an execution into arithmetical expressions
- These expressions may contain symbolic variables instead of concrete values
- Using a SMT solver [2][3] on these expressions, we are able to determine an input for a desired state

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[2]https://en.wikipedia.org/wiki/Satisfiability_modulo_theories#SMT_solvers
[3]http://smtlib.cs.uiowa.edu

SBA vs DBA

- **S**tatic **B**inary **A**nalysis
  - Full CFG
  - No concrete value
  - Often based on abstract analysis
    - Scalable
    - False positive
  - Too complicated for analyze obfuscated code

- **D**ynamic **B**inary **A**nalysis
  - Partial CFG (only one path at time)
  - Concrete values
  - Often based on concrete analysis
    - Not scalable
    - Less false positive
  - Lots of static protections may be broken

Online vs offline analysis

- Online analysis
  - Extract runtime information
  - Inject runtime values
  - Interact and modify the control flow
  - **Good for fuzzing**
- Offline analysis
  - Store the context of each program point into a database
  - Apply post analysis
  - Display the context information using both static and dynamic paradigms
  - **Good for reverse**

Offline analysis good for reverse

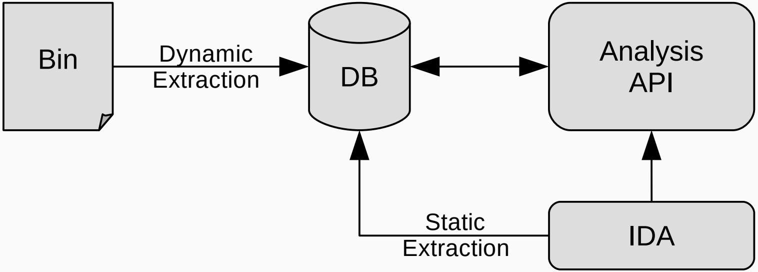


Figure 6: Example of an offline analysis infrastructure

Offline analysis and symbolic emulation

- Explore more than one path using symbolic emulation from a concrete path
  - From one path emulate them *all*

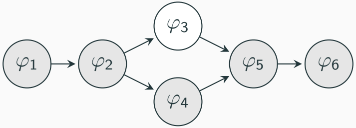


Figure 7: Concrete execution

Offline analysis and symbolic emulation

- Keep both concrete and symbolic values of each symbolic variable
- Use the concrete value for the emulation part and the symbolic value for expressions and models
- Get the model of the new branch and restore the concrete value of the symbolic variable

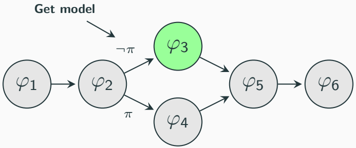


Figure 8: Symbolic emulation from a concrete path

Offline analysis and symbolic emulation

- Concrete and emulated paths are merged with disjunctions to get a coverage expression

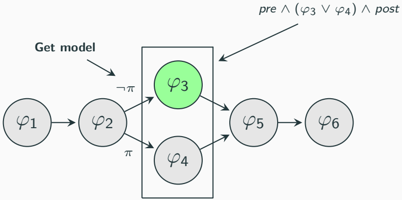


Figure 9: Disjunction of paths

The Triton [5] framework

Triton in a nutshell

- **D**ynamic **B**inary **A**nalysis Framework
  - x86 and x86_64 binaries analysis
  - Dynamic Taint Analysis
  - Dynamic Symbolic Execution
  - Partial Symbolic Emulation
  - Python or SMT semantics representation
  - Simplification passes
  - Python and C++ API
- Tracer independent
  - A Pintool [4] is shipped with the project
- Free and opensource [5]

[4] https://software.intel.com/en-us/articles/pintool/
[5] http://triton.quarkslab.com

The Triton's design

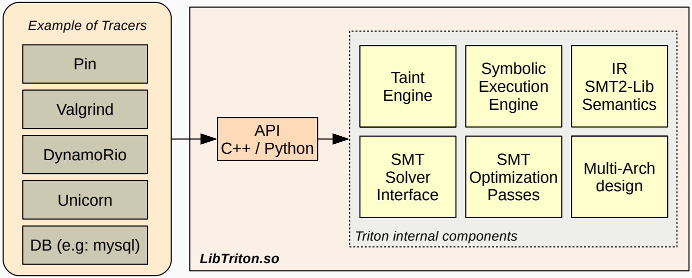


Figure 10: The Triton's design

The Triton's design

- **libpintool.so**
  - Used as tracer to give the execution context to the Triton library
  - Python bindings on some Pin's features
- **libtriton.so**
  - Takes as input opcodes and a potential context
  - Contains all engines and analysis
  - Python and C++ API

In what scenarios should I use Triton?

- If I want to use basic Pin's features with Python bindings
- If I'm working on a trace and want to perform a taint or symbolic analysis
- If I want to simplify expressions using my own rules or those of z3 [6]

[6] https://github.com/Z3Prover/z3

The classic count_inst example

```
count = 0
def mycb(inst):
    global count
    count += 1

def fini():
    print count

if __name__ == '__main__':
    setArchitecture(ARCH.X86_64)
    startAnalysisFromEntry()
    addCallback(mycb, CALLBACK.BEFORE)
    addCallback(fini, CALLBACK.FINI)
    runProgram()
```

Can I use the libTriton into IDA?

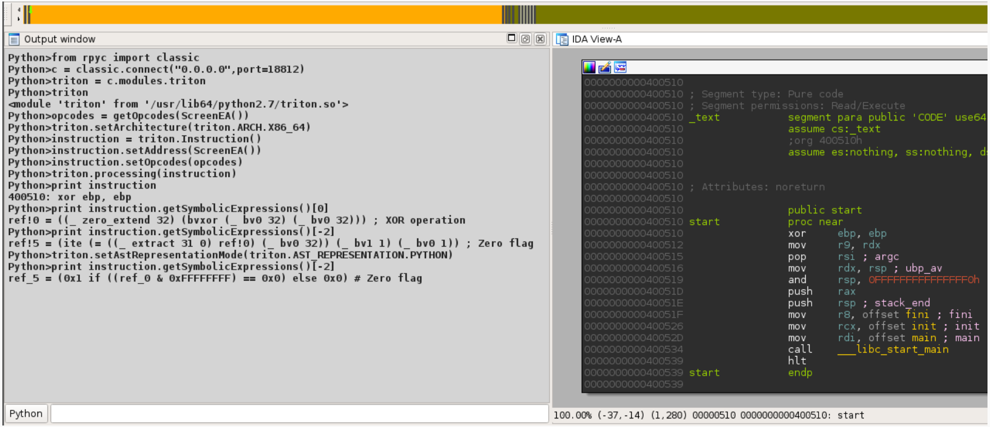


Figure 11: Triton and RPyC [7]

[7] https://rpyc.readthedocs.org

Can I emulate code via the libTriton into IDA?

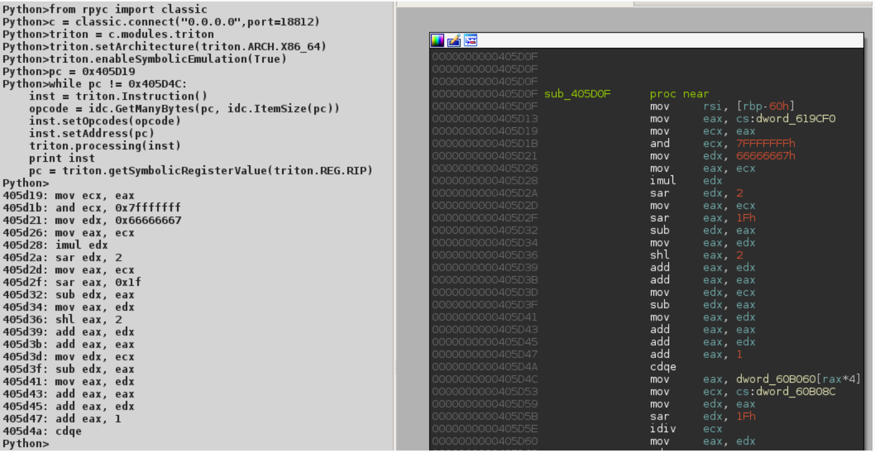


Figure 12: Symbolic Emulation into IDA

Simplify expressions

Simplify expressions

- Simplification passes may be applied at different levels:
  - Runtime node assignment (registers, memory cells, volatile)
  - Specific isolated expressions
- Triton allows you to:
  - Apply your own transformation rules based on *smart* patterns
  - Use z3 [8] to apply transformations

[8] `(simplify <expr>)`

Simplification passes at different levels

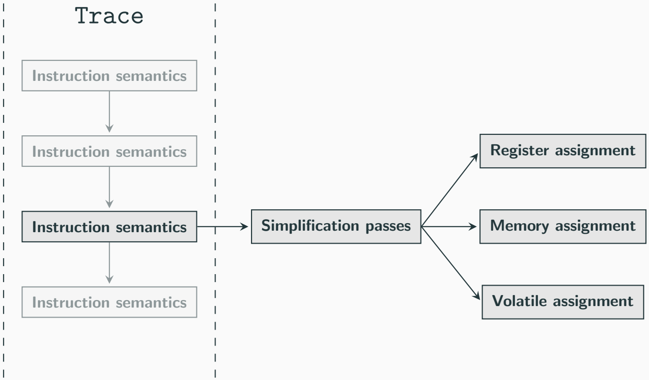


Figure 13: Runtime simplification

Simplify expressions with your own rules

Rule example: $A \oplus A \rightarrow A = 0$

```
def xor(node):
    if node.getKind() == AST_NODE.BVXOR:
        if node.getChilds()[0] == node.getChilds()[1]:
            return bv(0, node.getBitvectorSize())
    return node

if __name__ == '__main__':
    # [...]
    recordSimplificationCallback(xor)
    # [...]
```

Smart patterns matching

- Commutativity and patterns matching
  - A smart equality (==) operator

```
>>> a                      | >>> a                            | >>> a
((0x1 * 0x2) & 0xFF)       | (((0x1 * 0x2) & 0xFF) ^ 0x3)     | (0x1 / 0x2)
>>> b                      | >>> b                            | >>> b
((0x2 * 0x1) & 0xFF)       | (0x3 ^ ((0x2 * 0x1) & 0xFF))     | (0x2 / 0x1)
>>> a == b                 | >>> a == b                       | >>> a == b
True                       | True                             | False
```

Triton to Z3 and vice versa

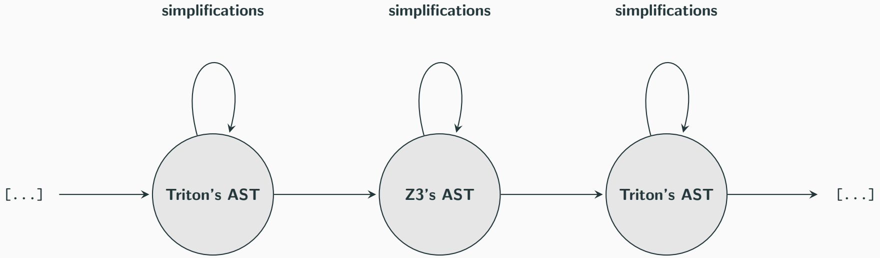


Figure 14: $AST_{triton} \longleftrightarrow AST_{z3}$

Simplify expressions via z3

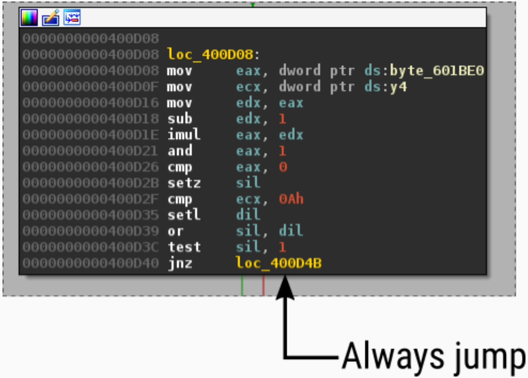
```
>>> enableSymbolicZ3Simplification(True)
>>> a = ast.variable(newSymbolicVariable(8))
>>> b = ast.bv(0x38, 8)
>>> c = ast.bv(0xde, 8)
>>> d = ast.bv(0x4f, 8)
>>> e = a * ((b & c) | d)
>>> print e
(bvmul SymVar_0 (bvor (bvand (_ bv56 8) (_ bv222 8)) (_ bv79 8)))
>>> f = simplify(e)
>>> print f
(bvmul (_ bv95 8) SymVar_0)
```

Simplify expressions via z3

Note that solvers' simplification does not converge to a more human readable expression.

Analyse opaque predicates

Analyse opaque predicates



Analyse opaque predicates

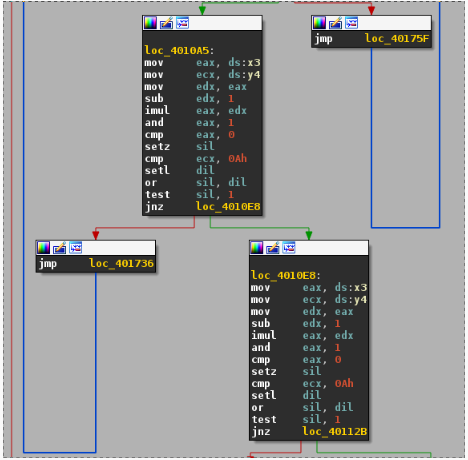


Figure 15: Bogus Flow Control

Analyse opaque predicates

$$\forall x, y \ (y < 10 \ \vee \ x(x+1) \mod 2 == 0) \text{ is True}$$

Analyse opaque predicates

```
Convert x and y as symbolic variable;
for basic block in graph do
    for instruction in basic block do
        triton.emulate(instruction);
        if instruction.type is conditionnal jump and zf expression is symbolized then
            Check if zf has solutions ;
        end
    end
end
```

Analyse opaque predicates (1)

```
x_addr = 0x601BE0
y_addr = 0x601BDC

x_symVar = convertMemyToSymVar(Memory(x_addr, CPUSIZE.DWORD))
y_symVar = convertMemyToSymVar(Memory(y_addr, CPUSIZE.DWORD))
```

Analyse opaque predicates (2)

```
graph  = idaapi.FlowChart(idaapi.get_func(FUNCTION_ADDRESS))
for block in graph:
  if block.startEA != 0x401637:
    analyse_basic_block(block)
```

Analyse opaque predicates (3)

```
def analyse_basic_block(BB):
  pc = BB.startEA
  while pc <= BB.endEA:
    instruction = triton.emulate(pc)
    pc = triton.getSymbolicRegisterValue(triton.REG.RIP)
    if instruction.isControlFlow():
      break
  ...
  zf_expr = triton.getFullAst(zf_expr.getAst())

  eq_false = ast.assert_(ast.equal(zf_expr, ast.bvfalse()))
  eq_true  = ast.assert_(ast.equal(zf_expr, ast.bvtrue()))
```

Analyse opaque predicates (3)

```
models_true  = triton.getModels(eq_true,  4)
models_false = triton.getModels(eq_false, 4)

addr_next = instruction.getNextAddress()
addr_jmp  = instruction.getFirstOperand().getValue()

if len(models_true) != 0:  # addr_jmp is not taken
  bb = get_basic_block(addr_jmp)
  dead_blocks.append(bb)
if len(models_false) != 0: # addr_next is not taken
  bb = get_basic_block(addr_next)
  dead_blocks.append(bb)
```

Analyse opaque predicates

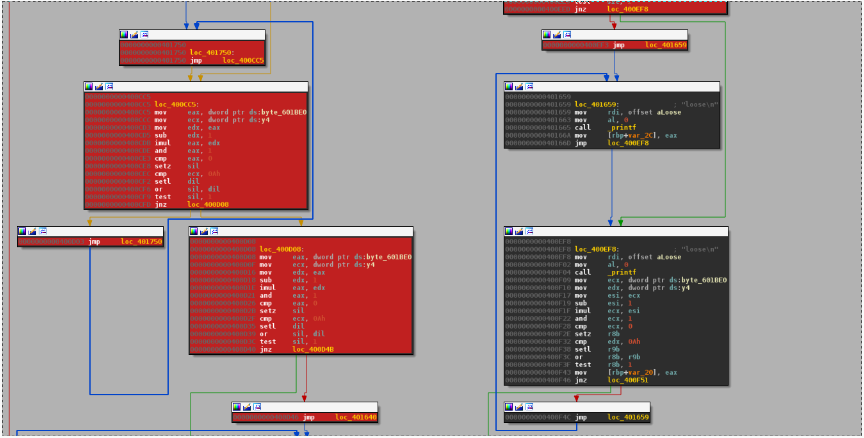


Figure 16: Bogus Flow Control simplified with Triton

First demo!

Reconstruct a CFG from trace differential

Reconstruct a CFG from trace differential

Problem: Given two sequences what is the minimal edition distance?

T_1 : A T C T G A T

T_2 : A A T C T G A T

Reconstruct a CFG from trace differential

Levenshtein algorithm (dynamic programming)

T_1 : A - T C T G A T
T_2 : A A T C T G A T

Reconstruct a CFG from trace differential

We can see a trace as a DNA sequence on a bigger alphabet. Many algorithms have been developed to analyze/compare a DNA sequence and they can be used on traces.

- Levenshtein algorithm: optimal alignment, `if`, `else` detection
- Suffix Tree: Longest repeated factor, loops detection

Reconstruct a CFG from trace differential

```c
int f(int x) {
  int result = 0;
  result = x;
  result = result >> 3;
  if (result % 4 == 2) {
    result += 5;
    result = result + x;
  }
  result = result * 7;
  return result;
}
```

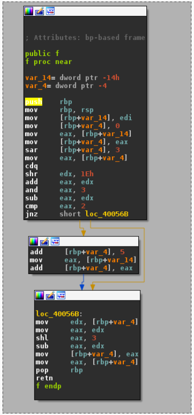


Figure 17: Function *f*

```
0x400536 push rbp
0x400537 mov rbp, rsp
0x40053a mov dword ptr [rbp - 0x14], edi
0x40053d mov dword ptr [rbp - 4], 0
0x400544 mov eax, dword ptr [rbp - 0x14]
0x400547 mov dword ptr [rbp - 4], eax
0x40054a sar dword ptr [rbp - 4], 3
0x40054e mov eax, dword ptr [rbp - 4]
0x400551 cdq
0x400552 shr edx, 0x1e
0x400555 add eax, edx
0x400557 and eax, 3
0x40055a sub eax, edx
0x40055c cmp eax, 2
0x40055f jne 0x40056b
```

```
0x400561 add dword ptr [rbp - 4], 5
0x400565 mov eax, dword ptr [rbp - 0x14]
0x400568 add dword ptr [rbp - 4], eax
```

```
0x40056b mov edx, dword ptr [rbp - 4]
0x40056e mov eax, edx
0x400570 shl eax, 3
0x400573 sub eax, edx
0x400575 mov dword ptr [rbp - 4], eax
0x400578 mov eax, dword ptr [rbp - 4]
0x40057b pop rbp
```

Recover the algorithm of a VM

Recover the algorithm of a VM

Problem: Given a *very secret* algorithm obfuscated with a VM. How can we recover the algorithm without fully reversing the VM?

Recover the algorithm of a VM

```
$ ./vm 1234
3920664950602727424

$ ./vm 326423564
16724117216240346858
```

Recover the algorithm of a VM

- The VM is too big to be analyzed statically in few minutes
- One trace gives you all information that you need

Recover the algorithm of a VM

- Use taint analysis to isolate VM's handlers and their goal

```
mov     rcx, [rax]
mov     rax, [rbp-60h]
add     rax, 10h
mov     eax, [rax]
cdqe
mov     rax, [rbp+rax*8-330h]
add     rax, rcx
mov     [rdx], rax
mov     rax, [rbp-60h]
add     rax, 18h
mov     eax, [rax]
mov     rdx, [rbp-70h]
sub     rdx, 8
mov     rdx, [rdx]
```

Figure 18: VM handler and a taint analysis

Recover the algorithm of a VM

Triton tool

```
from triton import *

def sym(instruction):
    if instruction.getAddress() == 0x4099B5:
        taintRegister(REG.RAX)

def before(instruction):
    if instruction.isTainted():
        print instruction

if __name__ == '__main__':
    setArchitecture(ARCH.X86_64)
    startAnalysisFromEntry()
    addCallback(sym,    CALLBACK.BEFORE_SYMPROC)
    addCallback(before, CALLBACK.BEFORE)
    runProgram()
```

Output

```
mov rdx, qword ptr [rbp + rax*8 - 0x330]
shr rdx, cl ; First handler, RDX = 1234
mov qword ptr [rbp + rax*8 - 0x330], rdx
mov rax, qword ptr [rbp + rax*8 - 0x330]
mov qword ptr [rdx], rax
... ; All others VM's handlers
mov rdx, qword ptr [rax]
mov rax, qword ptr [rax]
mov ecx, eax
shl rdx, cl ; Last handler, RDX = 3920664950602727424
mov qword ptr [rbp + rax*8 - 0x330], rdx
```

Recover the algorithm of a VM

- Use symbolic execution to extract the expression of the algorithm
  - Create a script *input* $\longleftrightarrow$ *hash*

Recover the algorithm of a VM

Triton tool

```
def sym(instruction):
    if instruction.getAddress() == 0x4099B5:
        convertRegisterToSymbolicVariable(REG.RAX)

def before(instruction):
    if instruction.getAddress() == 0x409A0B:
        raxAst = getFullAst(
                    getSymbolicExpressionFromId(
                        getSymbolicRegisterId(REG.RAX)
                    ).getAst())

        print '\n[+] Generating input_to_hash.py.'
        fd = open('./input_to_hash.py', 'w')
        fd.write(TEMPLATE_GENERATE_HASH % (raxAst))
        fd.close()

        print '\n[+] Generating hash_to_input.py.'
        fd = open('./hash_to_input.py', 'w')
        fd.write(TEMPLATE_GENERATE_INPUT % (raxAst))
        fd.close()
```

Output

```
$ ./triton ./solve-vm.py ./vm 1234
[+] Generating input_to_hash.py.
[+] Generating hash_to_input.py.
$ python ./input_to_hash.py 1234
3920664950602727424
$ python ./input_to_hash.py 8347324
15528411515173474176
$ python ./hash_to_input.py 15528411515173474176
...
[SymVar_0 = 2095535]
[SymVar_0 = 2093487]
[SymVar_0 = 2027951]
[SymVar_0 = 2029999]
[SymVar_0 = 2060719]
[SymVar_0 = 2062767]
$ ./vm 2093487
15528411515173474176
$ ./vm 2027951
15528411515173474176
$ ./vm 2060719
15528411515173474176
```

Second demo!

Conclusion

Conclusion

- Lots of static protections may be broken from an unique trace
- Taint and symbolic analysis are really useful when reversing obfuscated code
- The best protection is MBA and bitwise operation
    - Hard to detect patterns automatically
    - Hard to simplify

Future Works

Future Works

- **libTriton**
  - Improve the emulation part
  - Paths and expressions merging
    - Restructured DFG/CFG via a Python representation (WIP #282 #287)
    - Trace differential on DNA-based algorithms
  - Pattern matching via formal proof
  - Internal GC to scale the memory consumption

Thanks

Any Questions?

Contact us

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