Hands-on binary (de)obfuscation

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Ringzer0 BOOTSTRAP25 - March 22, 2025 - Austin (TX)

arnaugamez.com/r0.zip

About

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Occupation

- Senior Expert Security Engineer @ Activision
- PhD @ City St George's, University of London
- Founder, Researcher & Trainer @ Fura Labs

Introduction

Software protection landscape

Context

Protection against Man-At-The-End (MATE) attacks.

The attacker has an instance of the program and controls the environment it is executed in.

Protection against end users

Technical

- Obfuscation
- Cryptography
- Server-side execution
- Trusted execution environment (TEE)
- Device attestation
- ...

Legal

- Lawyers
- Luck
  - Jurisdiction
  - Adversary's strength
- Patience
- ...

Obfuscation

Transform a (part of a) program P into a functionally equivalent (part of a) program P' which is harder to analyze and extract information from than P.

$$P \longrightarrow \boxed{\text{Obfuscation}} \longrightarrow P'$$

Motivation

~~Prevent~~ complicate reverse engineering.

Presence

Commercial software

- Intellectual property
- Digital Rights Management (DRM)
- (Anti-)cheating

Malware

- Avoid automatic signature detection
- Slow down analysis → time → money

Methodology

Semantics-preserving transformations to data-flow procedures and control-flow structures.

At different abstraction levels

- Source code
- Intermediate representation
- Assembly listing
- Compiled binary

At different target units

- Whole program
- Function
- Basic block
- Instruction

Remark: Several *weak* techniques can be combined to create *hard* obfuscation transformations.

Deobfuscation

Transform an obfuscated (part of a) program P' into a (part of a) program P'' which is easier to analyze and extract information from than P'.

$$P'' \longleftarrow \boxed{\text{Deobfuscation}} \longleftarrow P'$$

Ideally $P'' \approx P$, but this is rarely the case:

- Lack of access to original program P.
- Interest in specific parts rather than whole program.
- Interest in understanding rather than rebuilding.

Preliminary

SMT

Satisfiability Modulo Theories (SMT)

- **S**atisfiability (SAT): determine if a (boolean) formula can be satisfied (can be true).
- **M**odulo: take into account (not only boolean formulas but also)...
- **T**heories: ...integer numbers, real numbers, floating point, **bit vectors**, and more.

SMT solver

In practice: a *magic black-box* that can only answer a very simple question.

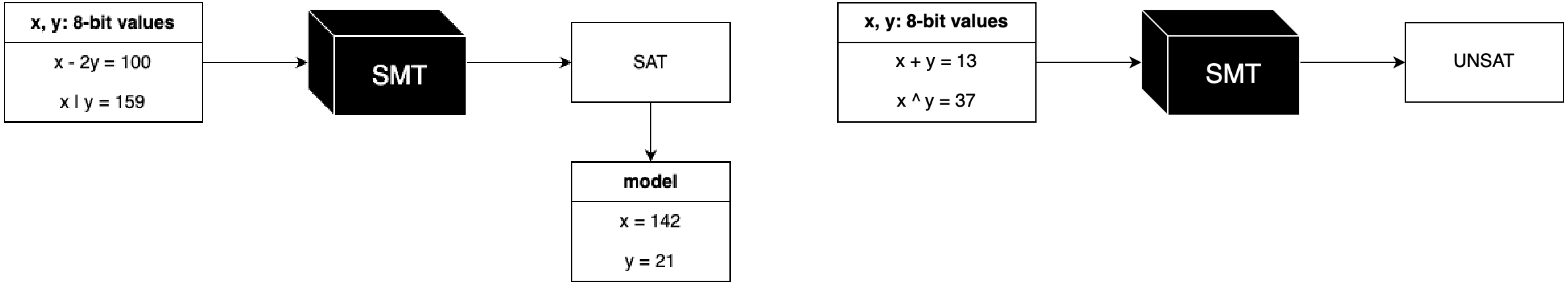
Question

Given some variables of some type, and some constraints on these variables:

- Is there any variable assignment that makes the set of constraints satisfiable, i.e. such that (all) the constraints hold true?

Outcomes

- **SAT**: there is a variable assignment that makes all the constraints hold true.
  - It actually finds a *model*, which is a particular solution (a concrete variable assignment).
- **UNSAT**: there is NO variable assignment that makes all the constraints hold true.
- **UNKNOWN**: unable to answer the question (usually due to a time-out).


x, y: 8-bit values
x - 2y = 100
x | y = 159
SMT
SAT
model
x = 142
y = 21
x, y: 8-bit values
x + y = 13
x ^ y = 37
SMT
UNSAT

Program analysis with an SMT solver

- Check semantic equivalence
- Simplification engine
- Solve complex constraints
- Input crafting
- Model counting

Limitations

- Resource exhaustion.
- Since SAT is NP-complete, SMT problems are *at least* NP-complete.
- Expression complexity.
  - Due to underlying semantic complexity (e.g. any decent cryptosystem).
  - Due to deliberate obfuscation (e.g. complex algebraic transformations).

Part I

Mixed Boolean-Arithmetic (MBA) obfuscation

MBA expressions

Algebraic expressions composed of integer arithmetic operators $(+, -, \times)$ and bitwise operators $(\wedge, \vee, \oplus, \neg)$.

Operation	Math	Code
AND	$\wedge$	&
OR	$\vee$	|
XOR	$\oplus$	^
NOT	$\neg$	~

Note: I will use interchangeably the terms *boolean*, *bitwise* and *logic* operators.

Linear MBA expressions

$$(x \oplus y) + 2 \times (x \wedge y)$$

Polynomial MBA expressions

$$43(x \wedge y \vee z)^2((x \oplus y) \wedge z \vee t) + 2x + 123(x \vee y)zt^2$$

Obfuscate expressions

Given an MBA expression E_1, generate an expression E_2 that is:

- Semantically equivalent to E_1.
- Syntactically more complex than E_1.

For that, we have ***rewrite rules*** and ***insertion of identities***.

Rewrite rules

Replace an expression with an equivalent (more complex) one.

$$x + y \to (x \oplus y) + 2 \times (x \wedge y)$$

Note: They can be applied iteratively (due to composability of polynomial MBA expressions).

$$x + y \rightarrow (x \oplus y) + 2(x \wedge y)$$

$$\circlearrowright$$

$$x' + y'$$

$$x' = (x \oplus y)$$
$$y' = 2(x \wedge y)$$

$$x' + y' \to (x' \oplus y') + 2(x' \land y') \equiv ((x \oplus y) \oplus 2(x \land y)) + 2((x \oplus y) \land 2(x \land y))$$

$$\circlearrowright$$

$$x' + y'$$

$$x' = ((x \oplus y) \oplus 2(x \land y))$$
$$y' = 2((x \oplus y) \land 2(x \land y))$$

Insertion of identities

Wrap an expression with a pair of invertible mappings.

$$e = (x \oplus y) + 2 \times (x \wedge y) \qquad f : x \mapsto 39x + 23 \qquad f^{-1} : x \mapsto 151x + 111$$

$$f^{-1}(f(e)) = 151 \times (39 \times ((x \oplus y) + 2 \times (x \wedge y)) + 23) + 111$$

Note: In general, affine functions (or permutation polynomials).

Obfuscate constants

Replace a constant by a computational process (expression) on a given number of variables that will always evaluate to the target constant at runtime.

Opaque constants

- K constant
- P, Q inverse permutation polynomials
- E non-trivially equal to zero MBA expression

Conceal constant: $K \equiv P(E + Q(K))$

Proof:

$$P(E + Q(K)) = P(0 + Q(K)) = P(Q(K)) = K$$

$$
\begin{aligned}
K &= 123 \\
P(X) &= 97X + 248X^2 \\
Q(X) &= 161X + 136X^2 \\
E(x, y) &= x - y + 2(\neg x \wedge y) - (x \oplus y)
\end{aligned}
$$

$$
\begin{aligned}
P(E + Q(K)) = {} & 195 + 97x + 159y + 194\neg(x \vee \neg y) + 159(x \oplus y) \\
& + (163 + x + 255y + 2\neg(x \vee \neg y) + 255(x \oplus y)) \\
& \times (232 + 248x + 8y + 240\neg(x \vee \neg y) + 8(x \oplus y))
\end{aligned}
$$

Fact

State-of-the-art software protection leverages MBA transformations to obfuscate code.

Why?

Combinations of operators from these different fields *do not interact well together*.

- No general rules (distributivity, factorization...) or theory.
- Computer algebra systems do not support bitwise operators with symbolic variables.

SMT solvers support for mixing operators (*bit vector* theory).

- Reasonably good at proving semantic equivalence.
    - Easily thwarted with deliberate MBA transformations, though.
- Pretty bad at simplification for general MBA expressions.

Hands-on

Part II

Analysis - Symbolic execution

Calculator

Concrete calculations.

$$\begin{vmatrix} 1 & 2 \\ 3 & 4 \end{vmatrix} = 4 - 2 \cdot 3 = -2$$

Computer Algebra System (CAS)

Symbolic calculation and manipulation.

$$\begin{vmatrix} 1 & 2 \\ a & 4 \end{vmatrix} = 4 - 2a = 2(2 - a)$$

What is symbolic execution?

Roughly speaking, just a **computer algebra system** for:

- Programming languages: C, C++, Java, Rust...
- Assembly languages: x86, x86-64, ARM64, MIPS, RISC-V...
- Intermediate languages: LLVM-IR, SMT-LIB, r2 ESIL, IDA Microcode, $YOUR_OWN...

More specifically, symbolic execution is a **program analysis technique**:

1. Represent inputs as *symbolic* variables instead of *concrete* values.
2. Derive constraints that encode control-flow and data-flow with respect to them.
3. Use these constraints to reason about and extract information from the program.

But how does it *actually* work?

1. Define two data structures:
    - **state_map**: symbolic mapping for the variables (registers, memory locations).
    - **path_constraint**: conditions required to reach current instruction.
2. Extract the semantics of each statement (instruction).
3. Update the data structures to account for the effects of the *executed* statement (instruction).
4. If there is control-flow branching, *fork* these structures to track different execution paths.

The **state_map** represents *data-flow* updates, i.e. the (computational) process through which a variable ends up holding a certain value at a given point in the program execution.

The **path_constraint** represents *control-flow* tracking, i.e. the set of constraints (conditions) on the variables that need to be satisfied for the execution to reach a given point in the program.

Visual example

```
_start:
    mov rax, 123  <=0=
    add rax, rsi
    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
    add rax, rdi
```

```
    cmp rax, 1337
    jnz bad

good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> rax
                 rbx -> rbx
                 rdi -> rdi
                 rsi -> rsi
                 zf  -> zf
```

```
_start:
    mov rax, 123
    add rax, rsi  <=0=
    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
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```

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_start:
    mov rax, 123
    add rax, rsi
    xor rax, rdi  <=0=
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
    add rax, rdi
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    cmp rax, 1337
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good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> (123 + rsi)
                 rbx -> rbx
                 rdi -> rdi
                 rsi -> rsi
                 zf  -> zf
```

```
_start:
    mov rax, 123
    add rax, rsi
    xor rax, rdi
    mov rbx, 2      <=0=
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
    add rax, rdi
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    cmp rax, 1337
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    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> ((123 + rsi) ^ rdi)
                 rbx -> rbx
                 rdi -> rdi
                 rsi -> rsi
                 zf  -> zf
```

```
_start:
    mov rax, 123
    add rax, rsi
    xor rax, rdi
    mov rbx, 2
    add rax, rbx  <=0=
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
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    mov rbx, 2
    add rax, rbx
    mov rdi, 3     <=0=
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
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good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> (((123 + rsi) ^ rdi) + 2)
                 rbx -> 2
                 rdi -> rdi
                 rsi -> rsi
                 zf  -> zf
```

```
_start:
    mov rax, 123
    add rax, rsi
    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax  <=0=
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
    add rax, rdi
    cmp rax, 1337
    jnz bad

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exit:
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    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx  <=0=
    xor rax, rdi
    mov rbx, 7
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    mov rdi, 1336
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    syscall
```

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path_constraint  true
state_map        rax -> ((((123 + rsi) ^ rdi) + 2) + 2)
                 rbx -> 2
                 rdi -> 3
                 rsi -> (((123 + rsi) ^ rdi) + 2)
                 zf  -> zf
```

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    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7    <=0=
    and rax, rbx
    mov rdi, 1336
    add rax, rdi
```

```
    cmp rax, 1337
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good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> (((((123 + rsi) ^ rdi) + 2) + 2) ^ 3)
                 rbx -> 2
                 rdi -> 3
                 rsi -> (((123 + rsi) ^ rdi) + 2)
                 zf  -> zf
```

```
_start:
    mov rax, 123
    add rax, rsi
    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx  <=0=
    mov rdi, 1336
    add rax, rdi
    cmp rax, 1337
    jnz bad

good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> (((((123 + rsi) ^ rdi) + 2) + 2) ^ 3)
                 rbx -> 7
                 rdi -> 3
                 rsi -> (((123 + rsi) ^ rdi) + 2)
                 zf  -> zf
```

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    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336 <=0=
    add rax, rdi
```

```
    cmp rax, 1337
    jnz bad

good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> ((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7)
                 rbx -> 7
                 rdi -> 3
                 rsi -> (((123 + rsi) ^ rdi) + 2)
                 zf  -> zf
```

```
_start:
    mov rax, 123
    add rax, rsi
    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
    add rax, rdi  <=0=
```

```
    cmp rax, 1337
    jnz bad

good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> ((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7)
                 rbx -> 7
                 rdi -> 1336
                 rsi -> (((123 + rsi) ^ rdi) + 2)
                 zf  -> zf
```

```
_start:
    mov rax, 123
    add rax, rsi
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    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
    add rax, rdi
    cmp rax, 1337 <=0=
    jnz bad

good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> (((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7) + 1336)
                 rbx -> 7
                 rdi -> 1336
                 rsi -> (((123 + rsi) ^ rdi) + 2)
                 zf  -> zf
```

```
_start:
    mov rax, 123
    add rax, rsi
    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
    add rax, rdi
```

```
    cmp rax, 1337
    jnz bad        <=0=

good:
    xor rdi, rdi
    jmp exit

bad:
    mov rdi, 1

exit:
    mov rax, 60
    syscall
```

```
path_constraint  true
state_map        rax -> (((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7) + 1336)
                 rbx -> 7
                 rdi -> 1336
                 rsi -> (((123 + rsi) ^ rdi) + 2)
                 zf  -> (((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7) + 1336) == 1337 ? 1 : 0
```

```
_start:
    mov rax, 123
    add rax, rsi
    xor rax, rdi
    mov rbx, 2
    add rax, rbx
    mov rdi, 3
    mov rsi, rax
    add rax, rbx
    xor rax, rdi
    mov rbx, 7
    and rax, rbx
    mov rdi, 1336
    add rax, rdi
    cmp rax, 1337
    jnz bad

good:
    xor rdi, rdi <=1=
    jmp exit

bad:
    mov rdi, 1   <=2=

exit:
    mov rax, 60
    syscall
```

```
path_constraint  (((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7) + 1336) == 1337
state_map        ...
                 zf  -> 1
path_constraint  (((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7) + 1336) != 1337
state_map        ...
                 zf  -> 0
```

How do we *reason* about this information?

With an SMT solver

Mostly

Data-flow analysis

1. The symbolic execution engine is used to extract the formula of the return value of a function with respect to its inputs parameters: check its value in the `state_map`.

2. The formula is fed into the SMT solver.

3. The SMT can:

    - Attempt to simplify the formula to get a nicer representation.
    - Craft inputs value that will make the formula evaluate to a desired output (i.e. inputs that will make the function return a desired value).

Compiler optimization techniques

Embedded into the `state_map` population process:

- Constant propagation: by construction.
- Constant folding: evaluate intermediate expressions on constant values.
- Reaching definitions: calculate at a given point the set of definitions that reach it.
- Liveness analysis: calculate at a given point the *live* variables (may be read before updated).

Control-flow analysis

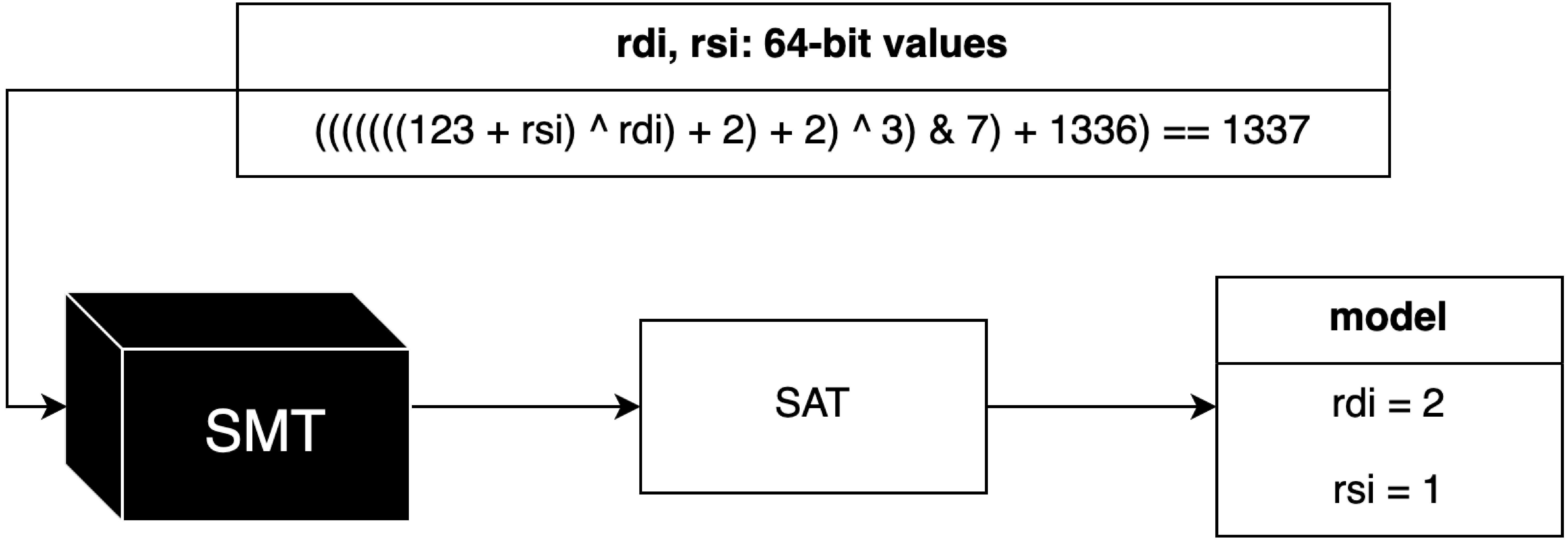
1. The symbolic execution engine is used to extract the formulae (constraints) for a given path branching to happen: check its `path_constraint`.
2. The constraints are fed into the SMT solver.
3. The SMT solver can prove the feasibility of the constraints (path reachability):
    - SAT: retrieve a model for it, i.e. concrete input values that reach the path
    - UNSAT: an obfuscating opaque predicate is detected -> ignore/patch it away

Example

```
path_constraint: (((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7) + 1336) == 1337
```

Given 64-bit variables `rdi` and `rsi`:

- Is there any variable assignment (for `rdi` and `rsi`) that makes the `path_constraint` satisfiable?


rdi, rsi: 64-bit values
(((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7) + 1336) == 1337
SMT
SAT
model
rdi = 2
rsi = 1

```python
import z3

rdi, rsi = z3.BitVecs('rdi rsi', 64)
path_constraint = (((((((123 + rsi) ^ rdi) + 2) + 2) ^ 3) & 7) + 1336) == 1337

solver = z3.Solver()
solver.add(path_constraint)

if solver.check() == z3.sat:
    print(solver.model())
```

```
[rdi = 2, rsi = 1]
```

Tooling

Welcome to the jungle

Implementation technology

- **Interpreter based**: Miasm, Triton, Angr, Maat, radius2
- **Instrumentation based**: QSYM
- **Compiler based**: KLEE, SymCC, SymQEMU

Target

- **Binary**: Miasm, Triton, Angr, Maat, radius2, QSYM, SymQEMU
- **Source code**: KLEE, SymCC

Focus

- **Analysis**: Miasm, Triton, Maat, (Angr?)
- **Automagic**: Angr, radius2
- **Test generation**: QSYM, KLEE, SymCC, SymQEMU

Limitations

And some ideas to overcome them

Path explosion

The number of control-flow paths grows exponentially ($\rightarrow \infty$ for unbounded loops).

Approach

- Manual location of interesting code.
- Concolic (**con**crete + symb**olic**) execution.

Environment support

Syscalls, winapi, standard C library...

Approach

- Same as with any emulator: hooks and stubs.

Limits of SMT solvers

Complex expressions (MBA alternation, high algebraic degree...).

Approach

- Program synthesis
- Math™
- Imagination

Hands-on

Part III

Analysis - Program synthesis

Motivating example

Consider the following obfuscated expression:

$$f(x, y, z) = (((x \oplus y) + ((x \wedge y) \times 2)) \vee z) + (((x \oplus y) + ((x \wedge y) \times 2)) \wedge z)$$

Treat f as a *black-box* and observe its behavior:

$$(1, 1, 1) \longrightarrow \boxed{f(x, y, z)} \longrightarrow 3$$

$$(2, 3, 1) \longrightarrow \boxed{f(x, y, z)} \longrightarrow 6$$

$$(0, -7, 2) \longrightarrow \boxed{f(x, y, z)} \longrightarrow -5$$

$$\dots$$

We want to *synthesize* a simpler function with the same I/O behavior:

$$h(x, y, z) = x + y + z$$

What is program synthesis?

The process of automatically constructing *programs* (code, expressions, etc.) that satisfy a given specification.

Specification

Describe the expected behavior of the resulting synthesized candidate.

The implementation details are carried out by the synthesizer.

- Formal specification in some logic (e.g. first-order logic):

$$\forall x \in \mathbb{Z}/2^{64}\mathbb{Z}, \quad P(x) = x + 7$$

- A set of I/O pairs that describe the program behavior:

$$(0, 7), (-4, 3), (123, 130), (-368, -361), \ldots$$

- A reference implementation (oracle) to generate I/O pairs.

Synthesis approach

Enumerative program synthesis (oracle-guided)

1. (Pre)generate an (offline) exhaustive list of potential candidates.
2. Generate a set of I/O pairs from the obfuscated code (oracle).
3. Select the candidates that match the oracle's I/O behavior.
4. If possible, verify semantic equivalence.

No candidates?

- Extend the pool of candidates (warning: exponential growth).

Multiple candidates?

- Check for semantic equivalence between them.
- Generate more I/O pairs.

QSynth

Combines symbolic execution and enumerative program synthesis iteratively.

1. Split an obfuscated expression into smaller subexpressions.
2. Synthesize the subexpressions individually.
3. Reconstruct the overall simplified expression.

Paper: https://profs.scienze.univr.it/~ceccato/papers/2020/bar2020.pdf

Tooling

Public implementations of the QSynth algorithm.

msynth

Built on top of Miasm.

qsynthesis

Built on top of Triton.

Limitations

- Semantic complexity (e.g., non-toy cryptography).
- Non-determinism ¯_(ツ)_/¯.
- Point functions: constant output except for a single distinguished (small finite set of) input(s).

Hands-on

Thank you

Archive

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