DRM obfuscation vs auxiliary attacks
Show me your trace and I’ll tell you who you are

REcon 2014
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- @CEA-DAM now
- Like working on obfuscation, RE, networks, algorithms, Water-Pony, ...

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- Enjoy RE, cryptography, DRM analysis, ...
We’ll speak about . . .

Reverse engineering

- DRM discovery (R&D)
- Attack methodology
We’ll speak about . . .

**Reverse engineering**
- DRM discovery (R&D)
- Attack methodology

**Execution trace**
- Context evolution collection during runtime
- Collected data management & analysis
We’ll speak about ...

**Reverse engineering**
- DRM discovery (R&D)
- Attack methodology

**Execution trace**
- Context evolution collection during runtime
- Collected data management & analysis

**Code obfuscation**
- What we (try to) fight
- Auxiliary attacks (based on execution trace)
A few words on obfuscation

**Purposes**

- Code protection (whole or part)
- Make the analysis harder and longer
- Raise RE costs
A few words on obfuscation

**Purposes**
- Code protection (whole or part)
- Make the analysis harder and longer
- Raise RE costs

**Some bad guys**
- Code flattening
- Data flow protection
- Junk code
- ...
Binary obfuscation is like an onion . . .
Network communication

- Packets content lookup
- High entropy data

⇒ Maybe some compression or crypto here :)}
Network communication

- Packets content lookup
- High entropy data

⇒ Maybe some compression or crypto here :)

Application’s binary analysis (static and dynamic)

- CFG is flattened
- Instructions in all basic blocks seem obfuscated
Introduction

1. First layer: Code flattening
   - Reminder
   - Methods

2. pTra

3. Algorithm reconstruction: RSA-OAEP

4. Rebuilding a cipher function "whiteboxed": AES-CBC

5. Ecofriendly step: Instruction substitution

6. Bonus
Introduction

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- Bonus
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Conclusion

Reminder

Normal CFG
Introduction
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Flattened CFG

Reminder
How to deal with this kind of protection?
How to deal with this kind of protection?
Introduction

First layer: Code flattening
- Reminder
- Methods

Methods

Agenda

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Two approaches are possible

**Study the protection itself**

- Symbolic/Concolic execution of target code
- Advantage: we can reuse know-how on other similar targets

If protection is too complex:

- Lot of resources needed
- Combinatory explosion
- Work in progress...
Two approaches are possible

Study the protection itself

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If protection is too complex:
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Study only one execution

- Produce an execution trace
- No more CFG but...
- We obtain just one path to analyze
- Advantage: code understanding is easier
What we did

Execution trace approach

1. Context evolution recording
   - registers state
   - executed instructions
   - memory accesses

2. We needed a tool to manage execution trace

3. We needed modules to extract information
**What we did**

### Execution trace approach

- **Context evolution recording**
  - registers state
  - executed instructions
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- We needed a tool to manage execution trace

- We needed modules to extract information

### Concepts to deal with

- Instrumentation: Execution’s data collection
- Database: Efficient trace storage
- Processsing: Relevant information access
What we did

Execution trace approach

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Concepts to deal with

- Instrumentation: Execution’s data collection
- Database: Efficient trace storage
- Processing: Relevant information access

That’s why we made pTra
Introduction

First layer: Code flattening

pTra

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Bonus
Introduction

First layer: Code flattening

What is this?

A few words on implementation

Miasm in 2 slides

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Bonus
pTra - What we want

**Python TRace Analyser**
- Execution trace management framework
- Purpose: provide an API for manipulating the trace
- Fully modular, scalable

**Constraints**
- Architecture independant (re-usability)
- Acceptable response time (usability)
Python TRace Analyser

- Execution trace management framework
- Purpose: provide an API for manipulating the trace
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Constraints

- Architecture independent (re-usability)
- Acceptable response time (usability)

⇒ Generally speaking, be able to quickly implement an idea
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   - Miasm in 2 slides

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Architecture “layered”

- Database
- Database Access Object (DAO)
- Models
- Analysers
- Parsers
- Human machine interface
- External tools
Implementation choices

Database

- **MongoDB**
  - Scalable
  - Non relational, a good way to prototype
- A database per trace
  - Avoid inter-trace lock
  - Allow hypothesis on entries
Implementation choices

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- *MongoDB*
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Getting an execution trace
- Intel PIN
- Miasm sandbox
- IDA, ollydbg, ...
Implementation choices

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Disassembly engine
- *DiStorm*
  - Then Miasm, to be architecture independant . . . and have an IR
Memory model

- **Trace**
  - String name
  - Date creation_date

- **Image**
  - Integer base
  - String path

- **BasicBlock**
  - Instruction[] code
  - String label

- **Cache**
  - String name
  - String[] options

- **Scheduling**
  - Boolean running
  - Date since
  - String name
  - String[] options
  - Integer priority

- **Instruction**
  - Integer addr
  - Byte[] opcode
  - Integer ctx
  - MemAccess[] mem_access
  - Image img
  - Function function

- **Function**
  - Integer addr
  - String symb
  - Image img

- **MemAccess**
  - Boolean type
  - Integer addr
  - Integer size
  - Byte[] data

Detailed information available in [SSTIC 2014 - Actes]
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Bonus
Miasm in 2 slides

Context

- Developed by F. Desclaux
- Miasm v2 released in June 2014
- Available on http://code.google.com/p/miasm
Miasm in 2 slides - 1

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**Lego bricks**
1. Python
2. Assembly / Disassembly engine “easy-to-write”
3. Intermediate representation RE oriented (8 words)
4. JIT engine (TinyCC, LLVM, Python based)
5. Regression tests :/
Miasm in 2 slides - 2

Features

- Supported architectures
  - x86 \{16, 32, 64\} bits
  - ARMv7 / Thumb
  - MSP430
  - SH4
  - MIPS32
- Customizable simplification engine
- PE / ELF / shellcode sandboxing
- Common MSDN APIs simulation (or how to rewrite Windows architecture independant)
- ELF / PE binary manipulation thanks to Elfesteem
- Links with STP solver, debuggers, IDA viewer
Miasm in 2 slides - Demonstration

Demo: Shellcode sandboxing (Try & die approach)
Miasm in 2 slides - Demonstration

Demo: ARMv7 execution trace - MD5
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   - Constants detection
   - Dataflow obfuscation
   - Data slicing and functions rebuilding
4. Rebuilding a cipher function “whiteboxed”: AES-CBC
5. Ecofriendly step: Instruction substitution
6. Bonus
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Bonus
Algorithm reconstruction - Introduction

What we want to know

- Fully understand an algorithm
- What’s inside (encryption, derivations, ...)

⇒ pTra database contains all we need
Algorithm reconstruction - Introduction

What we want to know

- Fully understand an algorithm
- What’s inside (encryption, derivations, . . .)

⇒ pTra database contains all we need

How to proceed

- Identify all parts (functions, crypto)
- Find inputs and outputs of each part
- Understand links between them
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Conclusion

Constants detection

**Constants detection - Theory**

What we know

- A cryptographic algorithm can be composed of some “magic” constants
- Hash functions are a good example
- If an algorithm is present, we must find its constants
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Constants detection - Theory

What we know

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- If an algorithm is present, we must find its constants

Where can we find them?

Interesting places:

- Instructions (static analysis)
- Processor’s registers
- Memory accesses

⇒ pTra provides a direct access to these elements
## Constants detection - Practical

### Method

- Add a module to pTra
- Full research in database for known constants
- Avoid false positives
  - Low probability
  - We can group results to detect isolated constants
- Simple, quick and efficient

### Results

- Mersenne Twister identification (0x6c078965)
- SHA-1 identification (0x67452301, 0xefcdab89, 0x98badcfe, 0x10325476, 0xc3d2e1f0)

⇒ Adding SHA-1 primitives knowledge into our call graph (init, update, final)
Constants detection - Practical

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I/O identification - Theory

Purposes

- Unidentified functions:
  - Understanding I/Os can help us to identify them
- Already identified functions:
  - Find where arguments come from
  - Establish the link with other algorithms

⇒ We must find functions input and output
I/O identification - Theory

**Purposes**

- **Unidentified functions:**
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  - Establish the link with other algorithms

⇒ We must find functions input and output

**What we know**

By studying memory accesses of a function:

- If a data is processed, it will be read
- Results (outputs) will be written

⇒ pTra can help us to find them
I/O identification - Practical

Methods

- To identify outputs:
  - Memory diff
  - (state after) - (state before)
  - We can remove data written and read before the end (temporary data)

- To identify inputs:
  - Data read for the first time by the function
  - We can add several heuristics (pointers detection, blocks grouping, entropy computing, . . .)
I/O identification - Results

Facts

- Very efficient method to link algorithms parts between them
- We found another protection by looking for I/Os: transformed memory
  - Data in memory never appear in clear format
  - No pattern identified in the code
  - There is a derivation function per memory area
I/O identification - Results

Facts

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- We found another protection by looking for I/Os: transformed memory
  - Data in memory never appear in clear format
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Identified algorithms

- Identified SHA-1 inputs/output verified
- SHA-1 inputs : Certificates ⇒ Cert-chain validation
- RSA-SHA1 signature algorithm is used
  ⇒ We have to identify RSA function
I/O identification - RSA identification

Main idea
- Destroy modular exponentiation effect of RSA
- Compare execution traces
I/O identification - RSA identification

Main idea

- Destroy modular exponentiation effect of RSA
- Compare execution traces

Steps

1. We know RSA algorithm is used (at least) in cert-chain validation
2. Patch all certificates pub exponents to 1
3. Patch all certificates pub modulus to max value (0xFF..FF)
4. Produce a new execution trace
5. Locate some functions differences (in number of instructions)
6. RSA located (±50 million instructions)
7. ⇒ Add RSA knowledge to the call-graph
Introduction

First layer: Code flattening

pTra

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Bonus
Definitions

- **Data tainting**: find all elements that *depend* on a given one
- **Data slicing**: find all elements *influencing* a given one

Data tainting is forward, and slicing is backward
Data slicing and functions rebuilding

Definitions

- **Data tainting**: find all elements that *depend* on a given one
- **Data slicing**: find all elements *influencing* a given one

Data tainting is forward, and slicing is backward

Data slicing implementation

Using Miasm IR:

1. Symbolic execution of basic block containing target element
2. We get dependencies of its equation
3. Search for latest writes of each ones
4. And so on.

For data tainting, we proceed almost the same way. We just target elements whose contain the target in their dependencies.
Demo: pTra - Slicing as a commercial (with colors)
Algorithm reconstruction: RSA-OAEP

Data slicing and functions rebuilding

RSA-OAEP

- R5
- SHA1(R5 + "\x00\x00\x00\x00")
- SHA1(R5 + "\x00\x00\x00\x01")
- SHA1(R5 + "\x00\x00\x00\x0b")

XOR
- Block1
  - SHA1(X1 + "\x00\x00\x00\x00\x00")
- Block2
  - SHA1(X1 + "\x00\x00\x00\x01")

C1
- XOR
- X1

C2
- SHA1(""")
- "\x00\x00...\x00\x01"
- R2
- R4

R2, R4, R5: Random values
Agenda

1. First layer: Code flattening

2. pTra

3. Algorithm reconstruction: RSA-OAEP

4. Rebuilding a cipher function “whiteboxed”: AES-CBC
   - Some clues
   - Dynamic AES-CBC WhiteBox identification
   - Results

5. Ecofriendly step: Instruction substitution

6. Bonus
Introduction

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Some clues

Dynamic AES-CBC WhiteBox identification

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Bonus Conclusion

Some clues

Dependencies graph

![Dependencies Graph Image]
Equivalence class

Equivalence class statement

Data $d_1$ and $d_2$ are equivalent if and only if their first reads are done by the same instruction. Two instructions are said the same if and only if they share the same address.
Equivalence class

Equivalence class statement

Data d1 and d2 are equivalent if and only if their first reads are done by the same instruction. Two instructions are said the same if and only if they share the same address.

Example

<table>
<thead>
<tr>
<th>Class:</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
<th>05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data:</td>
<td>63</td>
<td>66</td>
<td>F5</td>
<td>F3</td>
<td>76</td>
<td>DC</td>
<td>B1</td>
<td>C1</td>
<td>F6</td>
<td>BC</td>
<td>4D</td>
<td>21</td>
<td>7E</td>
</tr>
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</table>
Equivalence class

Equivalence class statement

Data d1 and d2 are equivalent if and only if their first reads are done by the same instruction. Two instructions are said the same if and only if they share the same address.

Example

Class: 01 02 03 04 01 02 03 04 01 02 03 04 05
Data: 63 66 F5 F3 76 DC B1 C1 F6 BC 4D 21 7E

Grouping

63 66 F5 F3
76 DC B1 C1
F6 BC 4D 21

7E
Some clues

Equivalence class

Applied to dataset

1 16 bytes

+-------------------+
| Block 1 |
+-------------------+
| Block 2 |
+-------------------+
| Block 3: Group of 16 bytes block |
+-------------------+
Equivalence class

**Applied to dataset**

1 16 bytes

+-------------------+
| Block 1           |
+-------------------+

+-------------------+
| Block 2           |
+-------------------+

+-------------------+
| Block 3:          |
| Group of 16 bytes |
| block            |
+-------------------+

**Applied to output block (reversed way, last write)**

1 2 16 bytes

++++
|  | /* 2 bytes blocks */
++++

++++
|--|

| Bytes group |

++++
| Bytes on the output, but never read */

Some clues

Applied to dataset

1 16 bytes

+-------------------+
| Block 1           |
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Applied to output block (reversed way, last write)

1 2 16 bytes

++++
|  | /* 2 bytes blocks */
++++

++++
|--|

| Bytes group |

++++
| Bytes on the output, but never read */
def make_C3(inp):
    C3 = [inp]
    for i in xrange(10):
        tmp = []
        tmp.append(inp[0] ^ table1[(0x100*i)+inp[13]])
        tmp.append(inp[1] ^ table2[inp[14]])
        tmp.append(inp[3] ^ table2[inp[12]])
        tmp.append(inp[4] ^ tmp[0])
        tmp.append(inp[5] ^ tmp[1])
        tmp.append(inp[7] ^ tmp[3])
        tmp.append(inp[8] ^ tmp[4])
        tmp.append(inp[9] ^ tmp[5])
        tmp.append(inp[10] ^ tmp[6])
        tmp.append(inp[12] ^ tmp[8])
        tmp.append(inp[13] ^ tmp[9])
        tmp.append(inp[14] ^ tmp[10])
    C3.append(tmp)
    inp = tmp
    return C3
Comparison between make_c3 and AES key scheduling

def make_C3(self, inp):
    C3 = [inp]
    for i in range(10):
        tmp = []
        tmp.append(inp[0] ^ table1[(0x100*i)+inp[13]])
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AES Key expansion

for size in range(expandedKeySize):
    for k in range(4):
        word[k] = expandedKey[(size - 4) + k]
    if size % sizeKey == 0:
        word = rotate(word)
        for i in range(4):
            word[i] = getSBoxValue(word[i])
        word[0] = word[0] ^ getRconValue(rconIteration)
        rconIteration += 1;
    for m in range(4):
        expandedKey[size] = expandedKey[size - sizeKey] ^ t[m] size += 1
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   - Dynamic AES-CBC WhiteBox identification
   - Results
5. Ecofriendly step: Instruction substitution
6. Bonus
Dynamic AES-CBC WhiteBox identification

**Identification**

- Try to reproduce inputs/outputs
- ⇒ Results don’t match
- ⇒ Encryption steps are completely done on modified states, key in input list
- ⇒ “Dynamic” whitebox
Dynamic AES-CBC WhiteBox identification

Identification

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- ⇒ Results don’t match
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Interest in a DRM

- Wasting analysts time
- Hiding inputs and outputs
- Difficulty to reproduce the algorithm on another system (apart from ripping it)
- Reverse algorithm is hard to find
Introduction

First layer: Code flattening

Algorithm reconstruction: RSA-OAEP

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Ecofriendly step: Instruction substitution

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Results

**Attack**

- Homomorphic algorithm (to XOR)
- Mathematic properties needed
- A limited set of candidates

⇒ Derivation functions computation

We are finally able to read/alter values encrypted by the algorithm, which is a 128 bits AES-CBC.
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5. Ecofriendly step: Instruction substitution
   - Introduction
   - Industrial version
6. Bonus
Introduction

First layer: Code flattening

pTra

Algorithm reconstruction : RSA-OAEP

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Bonus
Instruction substitution - Basics

Trivial method

For \( x \in [0, 2^{32} - 1] \):

\[
f(x) = (16 \times x + 16) \mod 2^{32}
\]

could be rewritten as:

\[
f(x) = 129441535 - 1793574399 \times (1584987567 \times (3781768432 \times x + 2881946191) - 4282621936)
\]
Instruction substitution - Basics

Trivial method

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$$f(x) = (16 \times x + 16) \mod 2^{32}$$

could be rewritten as:

$$f(x) = 129441535 - 1793574399 \times (1584987567 \times (3781768432 \times x + 2881946191) - 4282621936)$$

Simplification

Function simplified by modern compilation passes (particularly constant folding)
Instruction substitution - Advanced

**MBA : Mixed Boolean Arithmetic**

By mixing logical and arithmetical transformations:

\[(x + y) \equiv ((x \land y) + (x \lor y))\]

\[(x + y) \equiv ((x \oplus y) + 2 \times (x \land y))\]

\[(x \oplus y) - y \equiv (x \land \neg y) - (x \land y)\]
Instruction substitution - Advanced

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Simplification

- Nothing from compiler passes
- Nothing more from MatLab, Maple, Mathematica or Z3
### Instruction substitution - Advanced

#### MBA : Mixed Boolean Arithmetic

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\[(x \oplus y) - y \equiv (x \land \neg y) - (x \land y)\]

#### Simplification

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#### Effective simplification

- Once equations are identified, capitalize them thanks to Miasm simplification engine
- By using the generation algorithm of these expressions
MBA generation

Construction

- A matrix $A$ in \{x, y, x \oplus y, \ldots\} base (expressions are represented by their truth table)
- An associated vector $v$ composed of \{1, -1\} standing for operation between elements
- Equation is valid / generalizable to $2^n$ iff a linear combination of $A$’s columns is equal to null element
MBA generation

Construction

- A matrix $A$ in $\{x, y, x \oplus y, \ldots\}$ base (expressions are represented by their truth table)
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Example

$$x + y - (x \oplus y)$$

$$A = (f_1, f_2, f_3)$$

$$v = (+1, +1, -1)$$

$$f_1 = x = (0, 0, 1, 1)$$

$$f_2 = y = (0, 1, 0, 1)$$

$$f_3 = x \oplus y = (0, 1, 1, 0)$$
MBA simplification

Example

\[ x + \neg x - (x \land y) - (x \oplus y) + \neg y \]
MBA simplification

Example

\[ x + \neg x - (x \land y) - (x \oplus y) + \neg y \]

\[
A = \begin{cases} 
0 & 1 & 0 & 0 & 1 \\
0 & 1 & 0 & 1 & 0 \\
1 & 0 & 0 & 1 & 1 \\
1 & 0 & 1 & 0 & 0 \\
\end{cases}
\]

\[ v = (+1, +1, -1, -1, +1) \]
MBA simplification

Example

\[ x + \neg x - (x \land y) - (x \lor y) + \neg y \]

\[
\begin{align*}
A &= \begin{bmatrix}
0 & 1 & 0 & 0 & 1 \\
0 & 1 & 0 & 1 & 0 \\
1 & 0 & 0 & 1 & 1 \\
1 & 0 & 1 & 0 & 0
\end{bmatrix} \\
\nu &= (+1, +1, -1, -1, +1)
\end{align*}
\]

Linear combination

\[ +2 \\
+0 \\
+1 \\
+0 \]
MBA simplification

Smallest addition to nullify

\[
\begin{align*}
A &= \begin{bmatrix} 1 & 1 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \end{bmatrix} \\
\nu &= (-1, -1)
\end{align*}
\]

Final equation

\[
x + \neg x - (x \land y) - (x \lor y) + \neg y - \neg y - \neg (x \lor y) = 0
\]
MBA simplification

Smallest addition to nullify

\[
\begin{align*}
A &= \begin{pmatrix} 1 & 1 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \end{pmatrix} \\
\nu &= (-1, -1)
\end{align*}
\]

Final equation

\[
x + \neg x - (x \land y) - (x \oplus y) + \neg y - \neg y - \neg (x \lor y) = 0
\]

\[
x + \neg x - (x \land y) - (x \oplus y) + \neg y = \neg y + \neg (x \lor y)
\]
Introduction

First layer: Code flattening

pTra

Algorithm reconstruction: RSA-OAEP

Rebuilding a cipher function "whiteboxed": AES-CBC

Ecofriendly step: Instruction substitution

Bonus
int f(int x) {
    int result = 0;
    result = ((x << 8) & 0xFF) | (x & 0xFF);
    return result;
}
int f(int x) {
    x = (0xe5*x + 0xF7) % 0x100;
    v1 = 0x0;
    v2 = 0xFE;
    v0 = (x&0xFF + ( v1 << 8)&0xFFFFFFFF);
    v3 = (((v0*0xFFFFFFFFE6)+0x55)&v2)+(v0*0xED)+0xD6)&0xFF&0xFF + ( v1 << 8)&0xFFFFFFFF;
    v4 = (((((v3*0x2)+0xFF)&v2)+v3)*0xE87A503)+0xB717A54D);
    v5 = (((v4*0xAD17DB56)+0x0BA982A4)&0xFFFFFFFF46)*0xA57C144B)+(v4*0x09C02E7)+0xB5ED2776;
    v7 = (((v5*0xC463D53A)+0x3C8878AF)&0xC44B4F4)+(v5*0x1DCE1563)+0xFB99692E);
    v6 = (v7&0x94);
    v8 = (((v6+v6+- (v7&0xFF&0xFF + ( v1 << 8)&0xFFFFFFFF)))*0x67000000)+0xD0000000) >> 0x18);
    result = ((v8*0xFFFFFFFF2D)+((v8*0xAE)*0x22)*0xE5)+0xC2)&0xFF & 0xFFFFFFFF;
    result = (0xed*(result-0xF7)) % 0x100;
}

return result;

int f(int x) {
    return (x & 0xFF) ^ 0x5C;
Introduction

First layer: Code flattening

Algorithm reconstruction: RSA-OAEP

Rebuilding a cipher function "whiteboxed": AES-CBC

Ecofriendly step: Instruction substitution

Bonus
Graphing memory accesses over the time

- Read
- Write
- Read + Write

Memory addresses

Time

Binary/Rdata
Heap
Stack
Zoom on stack, loop detection
Introduction
First layer: Code flattening
Algorithm reconstruction: RSA-OAEP
Rebuilding a cipher function "whiteboxed": AES-CBC

O-LLVM

Why O-LLVM?
- Open-source
- Recent project

Implemented protections
- Instruction substitution
- Opaque predicates (*Bogus control flow*)
- Code flattening
Initial function: addition
After code flattening
CFG rebuilding (using symbolic execution)
So ...
Conclusion

Approach interests
- Allowed us to analyse state of the art obfuscation mechanisms
- One more method in analyst’s toolbox
- Can be used in other cases such as malware analysis, vulnerability research, ...
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Obfuscation
- More and more used nowadays
- Public initiative O-LLVM, still too young
- Devices, even mobile ones, got enough resources to waste them
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Obfuscation

- More and more used nowadays
- Public initiative O-LLVM, still too young
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Our approach isn’t better than others; it’s just another way to proceed :)
Questions?

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