emproof

Unveiling Secrets in Binaries using Code Detection Strategies

Tim Blazytko

@mr_phrazer
synthesis.to
tim@blazytko.to

About Tim

- Chief Scientist, co-founder of emproof
- designs software protections for embedded devices
- trainer for (de)obfuscation and reverse engineering techniques

- Navigating in Large Binaries
- Common Strategies
- Code Detection Heuristics

Large Binary

Analysis Challenges

- locating **complex state machines** and protocol logic

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vulnerability discovery

Analysis Challenges

- locating **complex state machines** and protocol logic
- detecting **cryptographic implementations**

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$\boxed{\text{malware \& vulnerability analysis}}$

Analysis Challenges

- locating **complex state machines** and protocol logic
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- discovering **C&C server communication** and **string decryption routines**

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malware analysis

Analysis Challenges

- locating **complex state machines** and protocol logic
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- discovering **C&C server communication** and **string decryption routines**
- pinpointing **obfuscated code** in commercial applications

Analysis Challenges

- locating **complex state machines** and protocol logic
- detecting **cryptographic implementations**
- discovering **C&C server** [illegible]**ption routines**
- pinpointing **obfuscated code** in commercial applications

software piracy

Analysis Challenges

- locating **complex state machines** and protocol logic
- detecting **cryptographic implementations**
- discovering **C&C server communication** and **string decryption routines**
- pinpointing **obfuscated code** in commercial applications
- identifying **API functions** in **statically-linked executables**

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embedded firmware analysis

Analysis Challenges

- locating **complex state machines** and protocol logic
- detecting **cryptographic implementations**
- pinpointing **obfuscated code** in commercial applications
- identifying **API functions** in **statically-linked executables**

Goal: Identifying interesting code locations

Where to start?

Common Approaches

- function symbols

- function symbols

```
validate_serial()
```

Common Approaches

- function symbols
- meaningful strings

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- meaningful strings

“https://evildomain.com”

Common Approaches

- function symbols
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- interesting API functions

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`GetAsyncKeyState`

Common Approaches

- function symbols
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- interesting API functions

Not always applicable

→ Code Detection Heuristics

Code Detection Heuristics

Identification of **interesting** code constructs

Code Detection Heuristics

Identification of **interesting** code constructs

- **guide** manual analysis

Code Detection Heuristics

Identification of **interesting** code constructs

- **guide** manual

False positives will occur

Code Detection Heuristics

Identification of **interesting** code constructs

- **guide** manual analysis
- architecture-agnostic

Identification of **interesting** code constructs

All architectures supported by the disassembler

- architecture-agnostic

Code Detection Heuristics

Identification of **interesting** code constructs

- **guide** manual analysis
- architecture-agnostic
- efficient to compute

Code Detection Heuristics

Identification of **interesting** code constructs

- guide
- architecture-agnostic
- efficient to compute

Applicable to ~100,000 functions

How?

Code Complexity and Statistical Analysis

Interesting code is

- (artificially) complex
- frequently executed
- uncommon

Code Complexity and Statistical Analysis

Interesting code is

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- basic block/function size

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Code Complexity and Statistical Analysis

Interesting code is

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- basic block/function size
- control-flow graph characteristics

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underlying code constructs

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(un)common code patterns

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- usage of intermediate representations

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architecture-agnostic instruction patterns

- basic block/function size
- control-flow graph characteristics
- frequency analysis
- usage of intermediate representations

Detection Heuristics

Heuristics

1. large basic blocks
2. complex functions
3. frequently called functions
4. state machines
5. uncommon instruction sequences

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- most heuristics **relative** to all functions in the binary

Detection Heuristics

Heuristics

1. large basic blocks
2. complex functions
3. frequently called functions
4. state machines
5. un

Clear separation between functions

- most heuristics **relative** to all functions in the binary

Detection Heuristics

Heuristics

1. large basic blocks
2. complex functions
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- most heuristics **relative** to all functions in the binary
- each heuristic detects **different** patterns

Detection Heuristics

Heuristics
1. large basic blocks
2. complex functions
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Know what to use & when

- most heuristics **relative** to all functions in the binary
- each heuristic detects **different** patterns

Large Basic Blocks

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Identification of functions with large basic blocks

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- ~5-7 instructions per basic block (on average)

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Large Basic Blocks

Identification of functions with large basic blocks

- ~5-7 instructions per basic block (on average)
- larger basic blocks indicate **complex straight-line code**
- compute per function:

$$\frac{\#\text{instructions}}{\#\text{basic blocks}}$$

Complex Straight-Line Code

- unrolled loops
- cryptographic implementations
- initialization routines
- arithmetic obfuscation

Example: Anti-Cheat I

average #instructions / block per function (in descending order):

1,456
198
68
63
59
55
52
51
49
46

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average #instructions/block per function (in descending order):

1,456
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arithmetic and virtualization-based obfuscation

55
52
51
49
46

Example: `ntoskrnl.exe` (Windows Kernel)

functions and their corresponding avergage #instructions/block (in descending order):

`SepInitSystemDacls`	491
`SymCryptSha256AppendBlocks_ul1`	236
`HalpRestoreHvEnlightenment`	147
`MiInitializeDummyPages`	133
`HalpBlkInitializeProcessorState`	103

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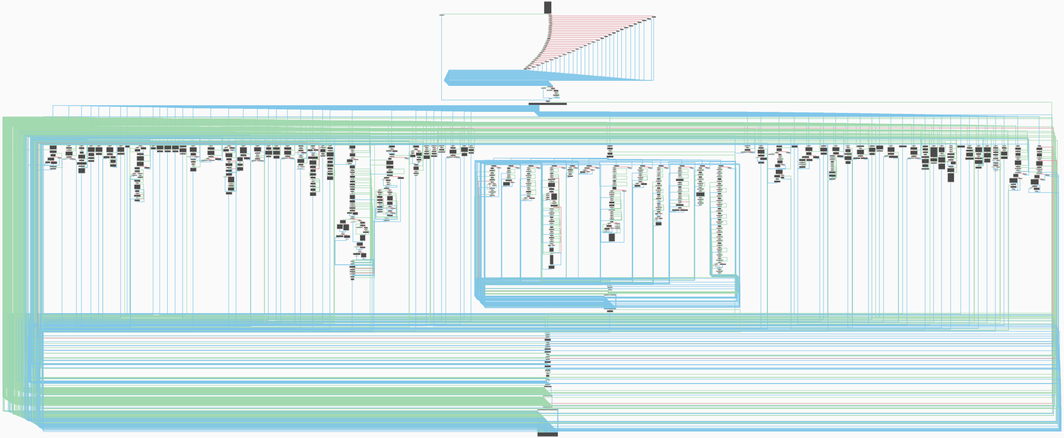
cryptographic implementations

Complex Functions



Complex Functions

Identification of functions with large control-flow graphs

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- large functions indicate a **complex code logic**
  - file parsing
  - dispatching routines and network protocols
  - obfuscation

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- large functions indicate a **complex code logic**
    - file parsing
    - dispatching routines and network protocols
    - obfuscation
- efficient metric: **cyclomatic complexity**

Cyclomatic Complexity

$$\#\text{edges} - \#\text{basic blocks} + 2$$

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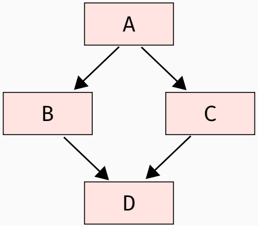
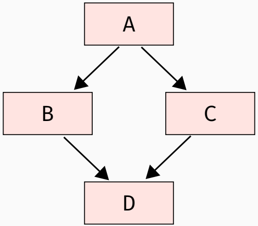


- 4 basic blocks
- 4 edges

Cyclomatic Complexity

$$\#\text{edges} - \#\text{basic blocks} + 2$$



- 4 basic blocks
- 4 edges

cyclomatic complexity: 2

Example: `ntoskrnl.exe` (Windows Kernel)

cyclomatic complexity per function (in descending order):

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2,371
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Example: `ntoskrnl.exe` (Windows Kernel)

cyclomatic complexity per function (in descending order):

2,964
2,371
1,506

related to PatchGuard (anti-tamper protection)

435
414
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Frequently Called Functions

```
call 0xdeadbeef  call 0xdeadbeef  call 0xdeadbeef  call 0xdeadbeef
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Frequently Called Functions

Identification of functions which are **frequently called** from **different functions**

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What kind of functions are called frequently?

Frequently Called Functions

Identification of functions which are **frequently called** from **different functions**

- allows the identification of **API functions** in **statically-linked executables**

Frequently Called Functions

Identification of functions which are **frequently called** from **different functions**

- allows the identification of **API functions** in **statically-linked executables**
- can sometimes also detect **string decryption & hash functions** in malware

Frequently Called API Functions

- memory management
- data movement
- string operations
- file I/O operations

Example: XOR DDoS (Malware)

Most called functions (from **unique** callers) in the **statically-linked** malware:

`free`	293
`memcpy`	191
`strlen`	184
`memset`	174
`__libc_malloc`	151
`__lll_unlock_wake_private`	148
`__lll_lock_wait_private`	122
`ptmalloc_init`	114
`__strtol_internal`	99
`strcmp`	93

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frequently called API functions

Example: PlugX (Malware)

Most called functions (from **unique** callers) and their number of calls:

`crc32`	1253
`LoadLibraryA`	1253
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Most called functions (from **unique** callers) and their number of calls:

hash-based import hiding

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Most called functions (from **unique** callers) and their number of calls:

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`LoadLibraryA`	1253
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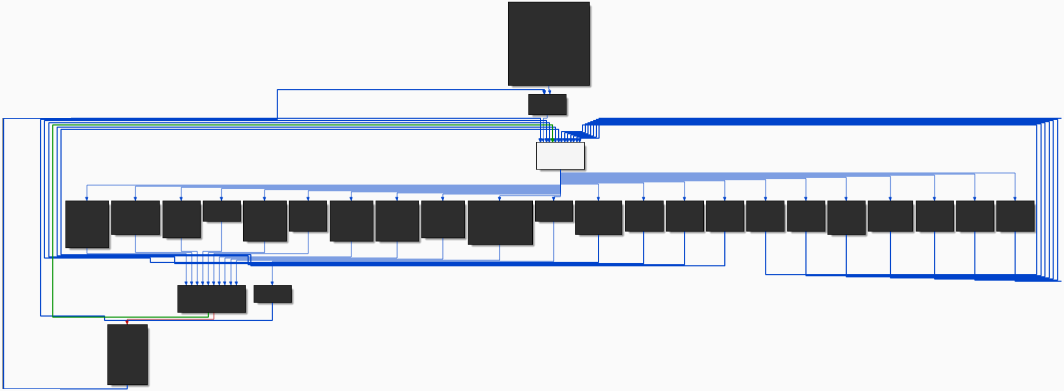
Most called functions (from **unique** callers) and their number of calls:

potential clustering of functions

`__seterrormode` 320

Identification of State Machines

State Machine Heuristic



Identification of functions with **loop-based dispatching routines**

State Machines

Identification of functions with **loop-based dispatching routines**

```
while(true) {
   switch(state) {
      case state_0: ...
      case state_1: ...
      ...
      case state_n: ...
   }
}
```

State Machines

Identification of functions with **loop-based dispatching routines**

```
while(true) {
   switch(state) {
      case state_0: ...
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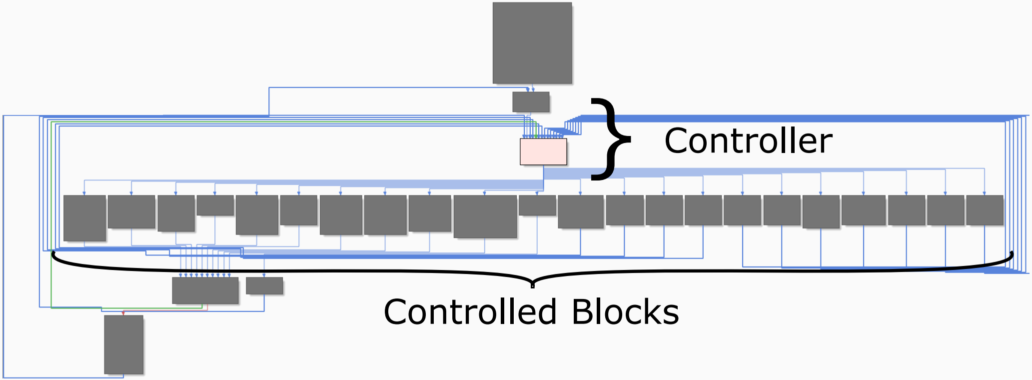
      ...
      case state_n: ...
   }
}
```

- state machines often implement a **complex program logic**

Complex State Machines

- file format parsing
- input validation & sanitization
- network protocol dispatching
- C&C server communication & command dispatching
- data encoding/decoding

State Machine Heuristic



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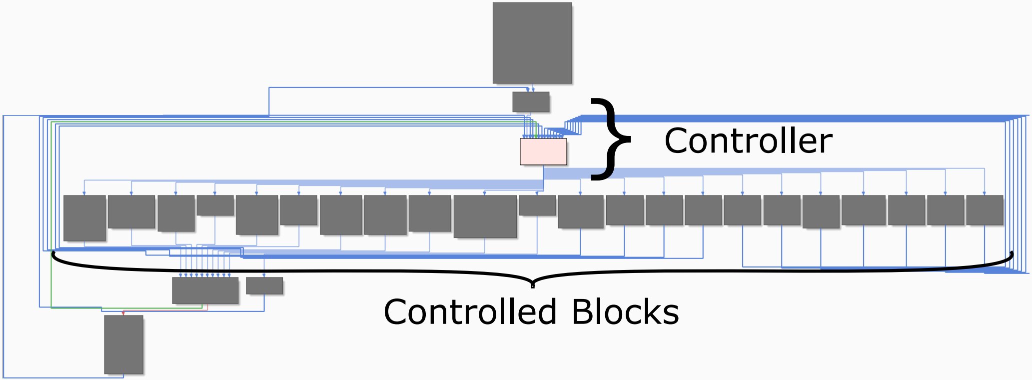

$$\frac{\#\text{controlled blocks}}{\#\text{blocks in the function}}$$

Examples

PlugX (Malware)
• C&C communication & command dispatching

Examples

PlugX (Malware)

- C&C communication & command dispatching

`ls`

- recursive directory traversal

Examples

PlugX (Malware)

- C&C communication & command dispatching

`ls`

- recursive directory traversal

`gcc`

- file parsing and tokenizing

Uncommon Instruction Sequences

```
mov     eax, dword [rbp]
mov     ecx, dword [rbp + 4]
cmp     r11w, r13w
sub     rbp, 4
not     eax
clc
cmc
cmp     rdx, 0x28b105fa
not     ecx
cmp     r12b, r9b
cmc
and     eax, ecx
jmp     0xc239
mov     word [rbp + 8], eax
pushfq
movzx   eax, r10w
and     ax, di
pop     qword [rbp]
sub     rsi, 4
shld    rax, rdx, 0x1b
xor     ah, 0x4d
mov     eax, dword [rsi]
cmp     ecx, r11d
test    r10, 0x179708d5
xor     eax, ebx
```

```
jmp     0xffffffffff63380
dec     eax
stc
ror     eax, 1
jmp     0xfffffffffff2a70
dec     eax
clc
bswap   eax
test    bp, 0x5124
neg     eax
test    dil, 0xe9
cmp     bx, r14w
cmc
push    rbx
sub     bx, 0x49f8
xor     dword [rsp], eax
and     bh, 0xaf
pop     rbx
movsxd  rax, eax
test    r13b, 0x94
add     rdi, rax
jmp     0xffffffffffc67c7
lea     rax, [rsp + 0x140]
cmp     rbp, rax
ja      0x6557b
jmp     rdi
```

Observation

Statistical Analysis of Assembly Code

Common Instruction Sequences

```
push rbp
mov rbp, rsp
push rbx
push rax
mov rbx, qword [rdi+0x30]
mov edi, dword [rdi+0x38]
call _strerror
lea rdi, [0x7bc6]
mov rsi, rbx
mov rdx, rax
xor eax, eax
call _warnx
mov byte [0x8678], 0x1
add rsp, 0x8
pop rbx
pop rbp
retn
```

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prologues and epilogues

```
mov rsi, rbx
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function calls

Common Instruction Sequences

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data movement

```
mov rsi, rbx
mov rdx, rax
xor eax, eax
call _warnx
mov byte [0x8678], 0x1
add rsp, 0x8
pop rbx
pop rbp
retn
```

Uncommon Instruction Sequences

Identification of functions with a large number of **unusual** instruction sequences

- intensive use of **floating-point** instructions
- cryptographic implementations
- obfuscated code

ground truth of the **1,000 most common** instruction sequences:

```
mov  mov   mov
mov  call  mov
mov  mov   call
        ...
sar  mov   mov
```

Statistical Analysis

ground truth of the **1,000 most common** instruction sequences:

```
mov   mov    mov
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        ...
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How many instruction sequences are **not** in the ground truth?

ground truth of the **1,000 most common** instruction sequences:

```
mov   mov    mov
mov   call   mov
mov   mov    call
```

architecture-agnostic implementation based on intermediate representations

```
sar   mov    mov
```

How many instruction sequences are **not** in the ground truth?

Example: `ci.dll` (Windows Kernel Module)

Functions with the most uncommon instruction sequences (in descending order):

```
MinCryptIsFileRevoked
__security_check_cookie
SymCryptFdefMaskedCopyAsm
SymCryptSha256AppendBlocks_shani
SymCryptFdefRawMulMulx1024
SymCryptParallelSha256AppendBlocks_ymm
SymCryptParallelSha256AppendBlocks_xmm
SymCryptModElementIsZero
SymCryptFdefMontgomeryReduceMulx1024
CipIsSigningLevelRuntimeCustomizable
SymCryptFdefMontgomeryReduceMulx
Gvd5e6c0
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virtualization-based obfuscation

```
SymCryptParallelSha256AppendBlocks_xmm
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CipIsSigningLevelRuntimeCustomizable
SymCryptFdefMontgomeryReduceMulx
Gvd5e6c0
```

Conclusion

Takeaways

1. efficient and architecture-agnostic heuristics
2. detects a wide range of **interesting** code constructs
3. false positives will occur

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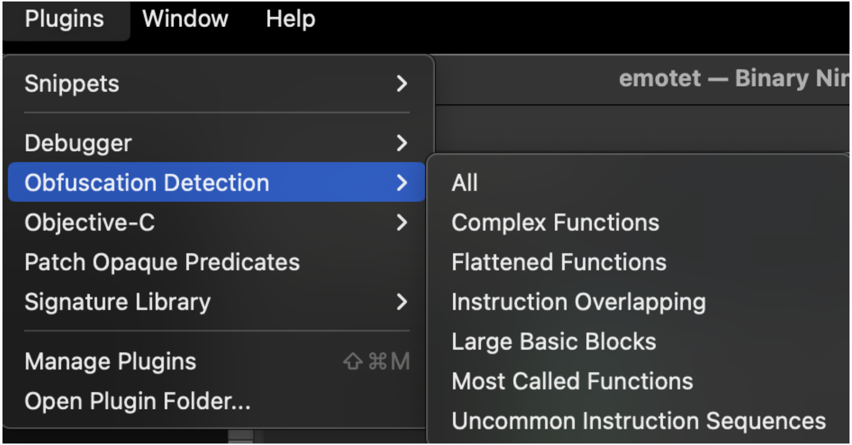
Useful methods to guide manual analysis in unknown binaries.

Binary Ninja Plugin



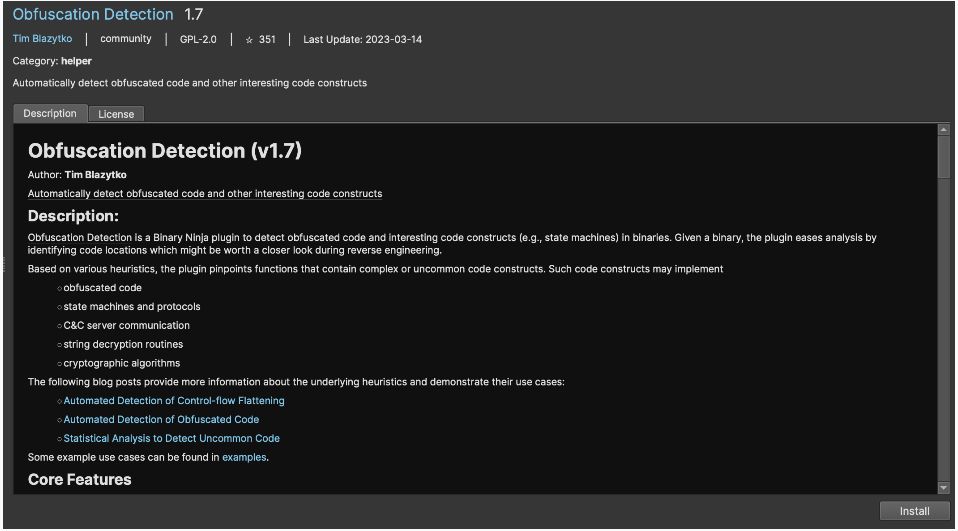
https://github.com/mrphrazer/obfuscation_detection

Binary Ninja Plugin

```
Log    Python Console
Search log
[Default] ==============================================================================
[Default] Control Flow Flattening
[Default] Function 0x4063f0 (sub_4063f0) has a flattening score of 0.9929577464788732.
[Default] Function 0x4012a0 (sub_4012a0) has a flattening score of 0.9855072463768116.
[Default] Function 0x402b60 (sub_402b60) has a flattening score of 0.9855072463768116.
[Default] Function 0x409e20 (sub_409e20) has a flattening score of 0.9846153846153847.
[Default] Function 0x40a4b0 (sub_40a4b0) has a flattening score of 0.9821428571428571.
[Default] Function 0x404f50 (sub_404f50) has a flattening score of 0.9818181818181818.
[Default] Function 0x402210 (sub_402210) has a flattening score of 0.9807692307692307.
[Default] Function 0x4025a0 (sub_4025a0) has a flattening score of 0.9787234042553191.
[Default] Function 0x40a9d0 (sub_40a9d0) has a flattening score of 0.9772727272727273.
[Default] Function 0x409530 (sub_409530) has a flattening score of 0.9761904761904762.
[Default] Function 0x407060 (sub_407060) has a flattening score of 0.975609756097561.
[Default] Function 0x401fa0 (sub_401fa0) has a flattening score of 0.975609756097561.
[Default] Function 0x406080 (sub_406080) has a flattening score of 0.975.
[Default] Function 0x4038b0 (sub_4038b0) has a flattening score of 0.975.
[Default] Function 0x401940 (sub_401940) has a flattening score of 0.9736842105263158.
[Default] Function 0x408660 (sub_408660) has a flattening score of 0.972972972972973.
[Default] Function 0x408f30 (sub_408f30) has a flattening score of 0.972972972972973.
[Default] Function 0x409860 (sub_409860) has a flattening score of 0.9714285714285714.
```

https://github.com/mrphrazer/obfuscation_detection

Plugin Manager



Summary

- common approaches to navigate in large binaries
- architecture-agnostic detection heuristics to pinpoint intesting code constructs
- useful in many reverse engieering scenarios

`https://github.com/mrphrazer/obfuscation_detection/`

Tim Blazytko

`@mr_phrazer`

`synthesis.to`

tim@blazytko.to

References

- "Automated Detection of Obfuscated Code" by Tim Blazytko
  `https://synthesis.to/2021/08/10/obfuscation_detection.html`
- "Automated Detection of Control-flow Flattening" by Tim Blazytko
  `https://synthesis.to/2021/03/03/flattening_detection.html`
- "Statistical Analysis to Detect Uncommon Code" by Tim Blazytko
  `https://synthesis.to/2023/01/26/uncommon_instruction_sequences.html`