Reassembly Is Hard: A Reflection on Challenges and Strategies

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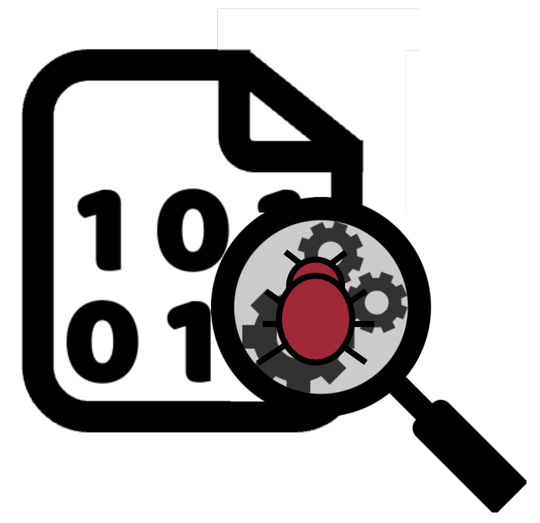
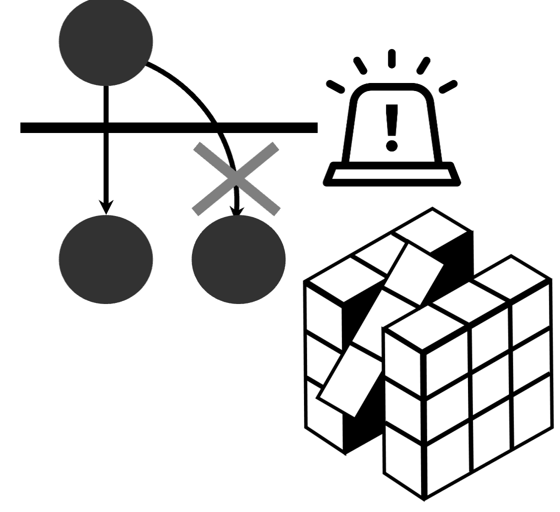
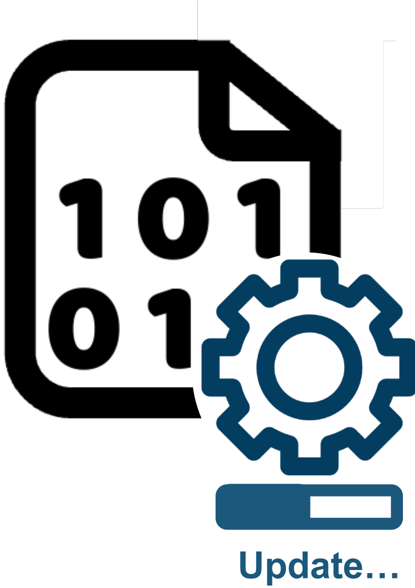
Static Binary Rewriting Is Imperative to SW Security



Malware Analysis
& Binary Testing



SW Hardening
(CFI Enforcement,
Code Randomization, …)



Code Repair
& Binary Debloating

Four Kinds of Static Binary Rewriting Techniques

	Applicable to COTS Binary	Fine-grained Instrumentation	Low Time & Space Overhead	Does it Really Work?
Compiler-assisted static rewriting	☹	☺	☺	☺
Patch-based static rewriting	☺	☹	☺	☺
Table-based static rewriting	☺	☺	☹	☺
Reassembly-based static rewriting	☺	☺	☺	?

Reassembly Is Error-Prone!

Symbolization errors produce a semantically incorrect binary

```
foo:
  push  ebp
  lea   eax, bar

bar:
  .byte  0x20, 0x12, 0x00, 0x00
  .long  foo
```

[Compiler-generated assembly]

```
0x1129:  55  ; push ebp
0x112a:  8d 05 10 40 00 00
             ; lea  eax, 0x4010

0x4010:  20 12 00 00
0x4014:  29 11 00 00
```

[Disassembled Code]

```
L1129:
  push  ebp
  lea   eax, 0x4010

L1220:

L4010:
  .long  L1220
  .long  L1129
```

Invalid reference due to missing symbolization

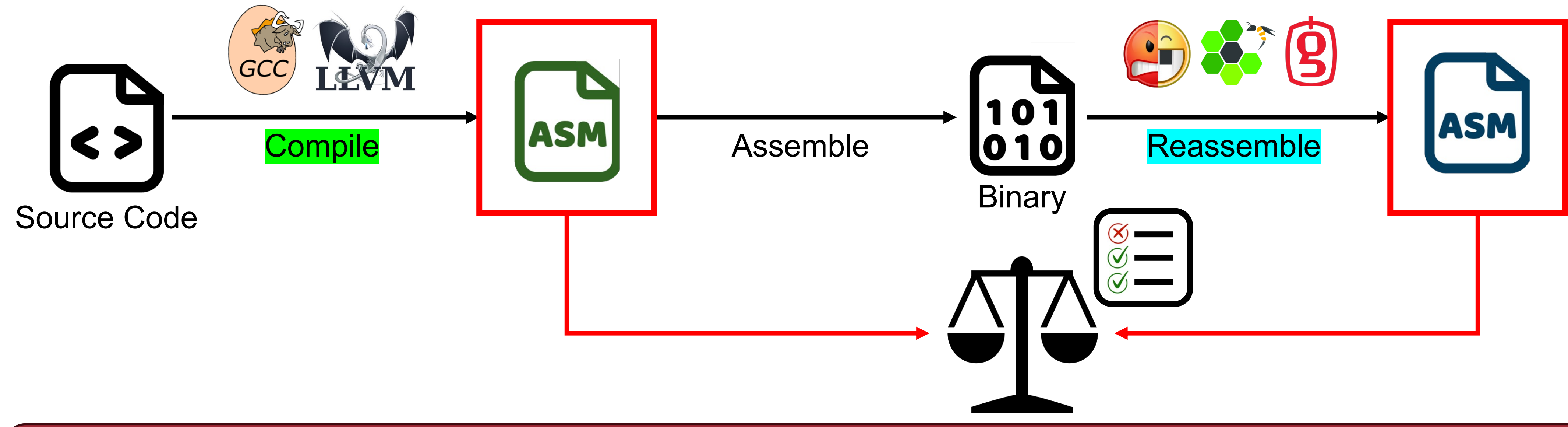
Data corruption due to falsely given symbol

[Reassembler-generated assembly]

Can We Assure the Correctness of Reassemblers?

Our Key Idea: Differential Testing

Comparing **compiler-generated assembly line** with **reassembly-generated assembly line** to identify errors



Challenges?

Challenge #1. Assembly Code Matching

Finding **the matched assembly code** is challenging due to the presence of duplicate function bodies and the discrepancies in opcode sequence

Duplicate function bodies

```
$ objdump -d gcc | grep ...

00000000003ca453 <analyze_function>:
  3ca453:     push    rbp
  3ca454:     mov     rbp,rdi
--
00000000003ce07e <analyze_function>:
  3ce07e:     push    r15
  3ce080:     push    r14
--
00000000003d028f <analyze_function>:
  3d028f:     push    r15
  3d0291:     push    r14
```

[Disassembled Code]

```
analyze_function:
analyze_function:
analyze_function:
    .loc 1 1946 1 is_stmt 1 view -0
    .loc 1 1947 3 view .LVU1207
    .loc 1 1946 1 is_stmt 0 view
.LVU1208
    push    rbp
    mov     rbp, rdi
    ...
```

[Compiler-generated assembly]

Opcode sequence mismatch

```
804b5c7:   sub    DWORD PTR [ebp-0x2a4],0x1
804b5ce:   jmp    804b772
804b5d3:   nop
804b5d4:   lea    esi,[esi+eiz*1+0x0]      mismatch
804b5d8:   sub    esp,0x8
804b5db:   push   DWORD PTR [ebp-0x2cc]
```

[Disassembled Code]

```
    sub     DWORD PTR [ebp-0x2a4],0x1
    jmp     .L1869
                                            mismatch
    sub     esp,0x8
    push    DWORD PTR [ebp-0x2cc]
```

[Compiler-generated assembly]

Challenge #2. Restoring Symbolic Expressions in Data Section

Not every data value has a debugging symbol

```
; data section

.Lswitch.table.convert_move:
  .long libfunc_table
  .long libfunc_table+4
  .long libfunc_table+8
```

Symbolic Expressions

[Compiler-generated assembly]

```
; data section

0x8...
0x8...          ..., 0x29, 0x08
0x8...  ...yte 0x10, 0x7e, 0x29, 0x08
```

No debug symbol for .Lswitch.table.convert_move

[Disassembled code]

KAIST

Challenge #3. Comparing Labels

Same labels can have different representation for each tool

ASM

```
.L4984:
    lea    rdx,[rip + __FUNCTION__.10544 ]

.L4895:
    mov    rax,  [rdx+0x8]

 __FUNCTION__.10544:
   .string "reg_overlap_mentioned_p"

.L4896:
   .long  .L4895  -  .L4896
   .long  .L4894  -  .L4896
```

[Compiler-generated assembly]

ASM

```
.L_2c7758:
    lea    rdx,[rip + .L_3c7750 ]

.L_2c8204:
    test   eax,  eax

.L_3c7750:
    .string "reg_overlap_mentioned_p"

.L_3c75cc:
   .long  .L_2c8204  -  .L_3c53e0
   .long  .L_2c7758  -  .L_3c75cc
```

[Reassembler-generated assembly]

Solution for Assembly Code Matching (C1)

The approach for identifying the matched function
- Search for functions by comparing **opcode sequence** with **debug info.**
- **Permit non-matching**, specifically for **no-op instructions**

```
0000000000516820 <analyze_function>:
  516820: push rbp
  516821: mov  rbp,rdi
  516824: push rbx
  516825: sub  rsp,0x8
  516829: mov  rax, QWORD PTR [rdi]
  51682c: mov  rdi, QWORD PTR [rax+0xb8]
```

[Disassembled code]

```
0x00516820  [1946, 1]
0x00516820  [1947, 3]
0x00516820  [1946, 1]
0x00516829  [1947, 3]
```

[Line number information in Debug section]

```
analyze_function:
  .loc 1 1946 1 is_stmt 1 view -0
  .loc 1 1947 3 view .LVU1207
  .loc 1 1946 1 is_stmt 0 view .LVU1208
  push    rbp
  mov     rbp, rdi
  push    rbx
  sub     rbp, 0x8
  .loc 1 1947 3 view .LVU1209
  mov     rax, QWORD PTR [rdi]
  mov     rdi, QWORD PTR [rax+0xb8]
```

[Compiler-generated assembly]

Solution for Symbolic Expression Restoring in Data Section (C2)

The method for calculating data addresses

- **Search for instructions** that references the local symbols
- Locate the corresponding instruction in binary & **calculate data address**

```
; code section
  mov  eax, [eax * 4 + Lswitch.table.convert_move ]
  jmp  .LBB8_169

; data section
.Lswitch.table.convert_move:
 .long  libfunc_table
 .long  libfunc_table+4
 .long  libfunc_table+8
```

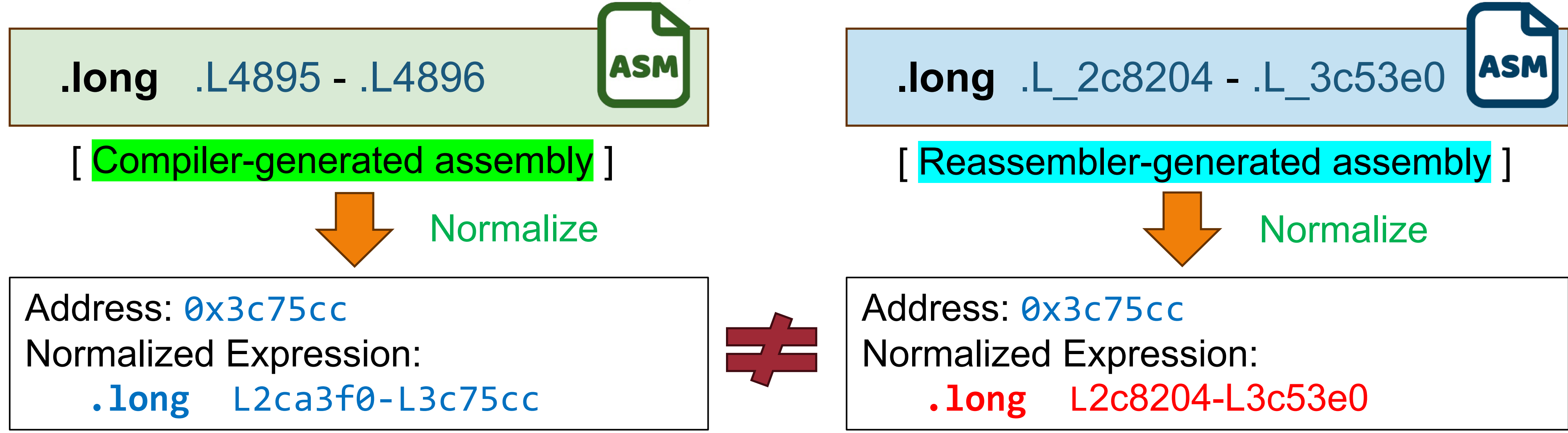
[Compiler-generated Assembly]

```
 ; code section
80d248e:  mov   eax, [ eax * 4+ 0x8238874 ]
80d2495:  jmp   80d255c

; data section

8238874:  .long  0x08297e08
8238878:  .long  0x08297e0c
823887c:  .long  0x08297e10
```

[Disassembled Code]

Solution for Label Comparisons (C3)

The approach for normalizing assembly lines
- Examine the definition (address) of symbolic label
- Convert labels to have **normalized names** with the corresponding address



Design of REASSESSOR

Normalize assembly code (Solution for C3)

Map assembly line to binary address (Solution for C1, C2)

Concatenate compiler-generated assembly files

Identify & classify errors

Remove debug symbol

Source Code

Compiler

.s

CONCAT

α_c

ASM

β

β

101 010

STRIP

β′

Reassembler

α_r

ASM

Preprocessing

NORALIZER

α'_c

ADDRMAPPER

ADDRMAPPER

α'_r

NORALIZER

α''_c

α''_r

DIFFER

Bugs

Reassessor

Experimental Setup

- Dataset: **14,688 Binaries**
  - Packages: GNU Coreutils v8.30, GNU Binutils v2.31.1, SPEC CPU 2006 v1.1
  - Compilers: GCC v7.5.0, Clang v12.0
  - Linker: GNU ld v2.30, GNU gold v1.15
  - Architectures: Intel x86, x86-64
  - Optimization levels: O0, O1, O2, O3, Ofast, Os
- Reassembly Tools
  - **Ramblr** (commit 613562, Apr. 2022): **Only support non-PIE binaries**
  - **RetroWrite** (commit 613562, Apr. 2022): **Only support x86-64 PIE binaries**
  - **Ddisasm** v1.5.3 (docker a803c9, Apr. 2022): **Support all binaries**

Research Questions

- RQ1. Can the current state-of-the-art reassemblers always produce compilable assembly files?
- RQ2. How accurate is reassembler-generated code?
- RQ3. Can the current state-of-the-art reassemblers always soundly reassemble x86-64 Position Independent Executable (PIE) binaries?

RQ1. Can the Current SOTA Reassemblers Always Produce Compilable Assembly Files?

- No.
- Reassembly tools emit **compilable** code **only for 91.6% binaries**
  - Reassembly tools **failed** to reassemble **2.2% of the binary files**
  - **6.2% of reassembler-generated files** were **non-compilable** due to syntax errors and undefined label references

[Success rate of compilation]

	Ramblr	RetroWrite	Ddisasm	Total
Total Succeed binaries	6,191	3,497	13,850	23,538
Total tried binaries	7,344	3,672	14,688	25,704
Total Succeed Rate	84.3%	95.2%	94.3%	91.6%

RQ2. How Accurate Is Reassembler-generated Code?

3.95% of symbolic expressions was not symbolized (**FN**), and **3.28%** of them was symbolized w/ different expressions (**FP**)

- 45.11% of symbolization errors are reparable when disallowing data instrumentation
- **54.99% of the symbolization errors** are problematic regardless of data instrumentation

Demo: The Impact of Symbolization Errors

```
ssh hskim@143.248.6.165 -p 22222
[hskim@usec2023:~/demo]
# make recompile
gcc -ldl -pthread -m32 reassem.s -o new_ls
[hskim@usec2023:~/demo]
# ls
Makefile  bin  new_ls  reassem.s
[hskim@usec2023:~/demo]
# ./new_ls
Makefile  bin  new_ls  reassem.s
[hskim@usec2023:~/demo]
# ./new_ls -a
.  ..  Makefile  bin  new_ls  reassem.s
[hskim@usec2023:~/demo]
# ./new_ls -R
Segmentation fault (core dumped)
[hskim@usec2023:~/demo]
#
```

RQ3. Can the SOTA Reassemblers Soundly Reassemble x86-64 PIE Binaries?

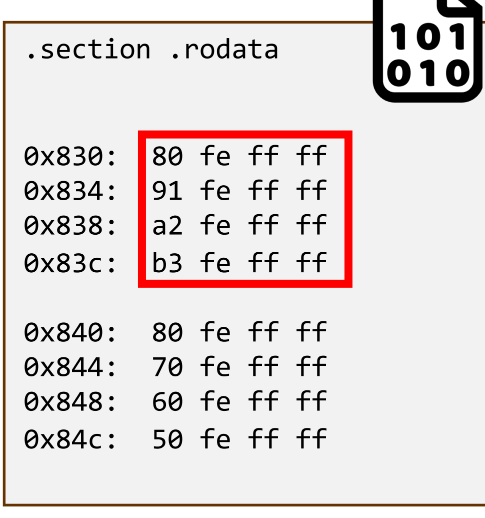
- No, not always.
- In x86-64 PIE binaries, **6.9% of symbolic expressions** represented **jump table entries**, and **none of reassemblers** perfectly symbolized them

```c
int output=0;
const int bar[]={-0x180,-0x190,-0x1a0,-0x1b0};
void foo(unsigned int input) {
  int *p = (int *)bar - 3;
  switch(input){
   case 0:  output = bar[0]; break;
   case 1:  output = bar[1]; break;
   case 2:  output = bar[2]; break;
   case 3:  output = bar[3]; break;
   default:
       if(input < 7) output = p[input]; break;
  }
  printf("In:%x, Out:%x\n", input, output);
}
```

[Source code in C]

```
.section .rodata

.LJTI0_0:
     .long  .LBB0_1-.LJTI0_0
     .long  .LBB0_2-.LJTI0_0
     .long  .LBB0_3-.LJTI0_0
     .long  .LBB0_4-.LJTI0_0
bar:
     .long  0xfffffe80
     .long  0xfffffe70
     .long  0xfffffe60
     .long  0xfffffe50
```

[Compiler-generated assembly]



[Disassembled Code]

Contributions to Improving Reassemblers

We made PR and issues to resolve the errors we found

– Special Thanks to *Fish Wang* and *Antonio Flores-Montoya*

Hi Fish,

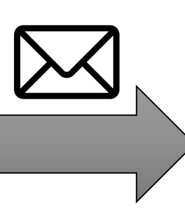
I am sending you an email to ask a question about Ramblr. My research team is doing some research about reassembly,

…

My student created a GitHub issue here, too:
https://github.com/angr/patcherex/issues/39

Thank you in advance!

Best wishes,
Sang Kil



Hi Sang Kil,

Good to hear from you!

I have answered your students' questions on GitHub.

...

Please send more questions my way if Reassembler fails on any binaries in your benchmark!
Also, let me know if you need more insights about reassembling in general.

Best,
Fish

Open Science

https://github.com/SoftSec-KAIST/Reassessor

Code | Issues | Pull requests | Actions | Projects | Wiki | Security | ...

Reassessor Public | Edit Pins | Watch 2 | Fork 1 | Starred 21

Conclusion

- We propose a **formal framework** and present **REASSESSOR**, the first automated system for reassembler testing
  - We publicize REASSESSOR and our benchmark
- Through REASSESSOR, we **found various reassembly errors** with previously unknown patterns
  - We contributed to **improving the state-of-the-art reassemblers**
- Lastly, we **validated strategies and challenges** in reassembly

Question?