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# CPS Project

# Insecure Edge Counting for Control-Flow Integrity

*Rocco Versace – m. 1138644*

*Alessandro Frullo – m. 1132704*


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# Main Goal

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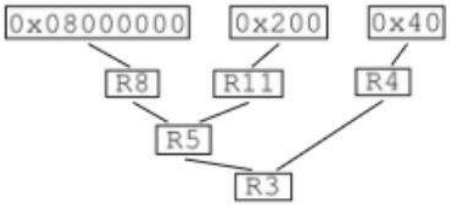
- This project aims at counting the number of indirect jumps and indirect calls to be protected in RISC-V binaries, excluding the ones which can be proven safe

***How can we verify if a jump is considered safe?***

***We need to retrieve the origin tree of the source operand of the target***

```
MOV R8, #1
LSL R8, R8, #27
MOV R11, 0x200
MOV R4, 0x40
ADD R5, R8, R11
ADD R3, R4, R5
BX R3
```

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# Starting Point

# Starting Point

- This project starts where previous research left off in *"PROLEPSIS: Binary Instrumentation Tool for Control-Flow Integrity in ARM and RISC-V"* https://webthesis.biblio.polito.it/secure/24598/1/tesi.pdf

- While the previous work focused on **static** analysis, there's room for enhancement in **dynamic** conditions in order to retrieve the targets of indirect jumps.

- For this project some benchmark have been run: https://github.com/embench/embench-iot.git

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# Instrumentation

# Instrumentation

- Benchmarks were compiled and run with a ***Qemu RISC-V32*** environment, obtaining the static assembly code of each program, together with their program counter dynamic record



- The data obtained from the benchmarks were then processed with ***Python*** scripts


# Obtaining assembly

```
riscv64-unknown-elf-objdump -D -S -M numeric main > main_DSnum.log
```

```
Disassembly of section .text:

00010074 <main>:
   10074:       1101                    addi    x2,x2,-32
   10076:       ce06                    sw      x1,28(x2)
   10078:       2a25                    jal     101b0 <initialise_board>
   1007a:       2a39                    jal     10198 <initialise_benchmark>
   1007c:       4505                    li      x10,1
   1007e:       2a31                    jal     1019a <warm_caches>
   10080:       2a15                    jal     101b4 <start_trigger>
   10082:       2a29                    jal     1019c <benchmark>
   10084:       c62a                    sw      x10,12(x2)
   10086:       2a0d                    jal     101b8 <stop_trigger>
   10088:       4532                    lw      x10,12(x2)
   1008a:       2a21                    jal     101a2 <verify_benchmark>
   1008c:       40f2                    lw      x1,28(x2)
   1008e:       00153513                seqz    x10,x10
   10092:       6105                    addi    x2,x2,32
   10094:       8082                    ret

00010096 <register_fini>:
   10096:       00000793                li      x15,0
   1009a:       c791                    beqz    x15,100a6 <register_fini+0x10>
   1009c:       00000517                auipc   x10,0x0
   100a0:       33450513                addi    x10,x10,820 # 103d0 <__libc_fini_array>
   100a4:       a695                    j       10408 <atexit>
   100a6:       8082                    ret
```

# Obtaining dynamic program counter

```
qemu-riscv32 -singlestep -d nochain,cpu main 2>main.log
grep -o 'pc\s*[0-9a-fA-F]\{8\}' main.log >main_pc.log
```

```
pc       000100a8
x0/zero  00000000 x1/ra   00000000 x2/sp   407fff30 x3/gp   00000000
x4/tp    00000000 x5/t0   00000000 x6/t1   00000000 x7/t2   00000000
x8/s0    00000000 x9/s1   00000000 x10/a0  00000000 x11/a1  00000000
x12/a2   00000000 x13/a3  00000000 x14/a4  00000000 x15/a5  00000000
x16/a6   00000000 x17/a7  00000000 x18/s2  00000000 x19/s3  00000000
x20/s4   00000000 x21/s5  00000000 x22/s6  00000000 x23/s7  00000000
x24/s8   00000000 x25/s9  00000000 x26/s10 00000000 x27/s11 00000000
x28/t3   00000000 x29/t4  00000000 x30/t5  00000000 x31/t6  00000000
pc       000100ac
x0/zero  00000000 x1/ra   00000000 x2/sp   407fff30 x3/gp   000120a8
x4/tp    00000000 x5/t0   00000000 x6/t1   00000000 x7/t2   00000000
x8/s0    00000000 x9/s1   00000000 x10/a0  00000000 x11/a1  00000000
x12/a2   00000000 x13/a3  00000000 x14/a4  00000000 x15/a5  00000000
x16/a6   00000000 x17/a7  00000000 x18/s2  00000000 x19/s3  00000000
x20/s4   00000000 x21/s5  00000000 x22/s6  00000000 x23/s7  00000000
x24/s8   00000000 x25/s9  00000000 x26/s10 00000000 x27/s11 00000000
x28/t3   00000000 x29/t4  00000000 x30/t5  00000000 x31/t6  00000000
pc       000100b0
x0/zero  00000000 x1/ra   00000000 x2/sp   407fff30 x3/gp   000120c0
x4/tp    00000000 x5/t0   00000000 x6/t1   00000000 x7/t2   00000000
x8/s0    00000000 x9/s1   00000000 x10/a0  00000000 x11/a1  00000000
x12/a2   00000000 x13/a3  00000000 x14/a4  00000000 x15/a5  00000000
x16/a6   00000000 x17/a7  00000000 x18/s2  00000000 x19/s3  00000000
x20/s4   00000000 x21/s5  00000000 x22/s6  00000000 x23/s7  00000000
x24/s8   00000000 x25/s9  00000000 x26/s10 00000000 x27/s11 00000000
x28/t3   00000000 x29/t4  00000000 x30/t5  00000000 x31/t6  00000000
pc       000100b4
```

```
 1 pc       000100a8
 2 pc       000100ac
 3 pc       000100b0
 4 pc       000100b4
 5 pc       000100b8
 6 pc       000100ba
 7 pc       000100bc
 8 pc       0001026a
 9 pc       0001026c
10 pc       0001026e
11 pc       00010272
12 pc       00010276
13 pc       000102f4
14 pc       000102f8
15 pc       000102fc
16 pc       000102fe
17 pc       00010300
18 pc       000102c0
19 pc       000102c4
20 pc       000102c8
21 pc       000102cc
22 pc       000102d0
23 pc       000102d4
24 pc       000102d8
25 pc       000102dc
26 pc       000102e0
27 pc       00010304
28 pc       00010306
29 pc       00010308
```

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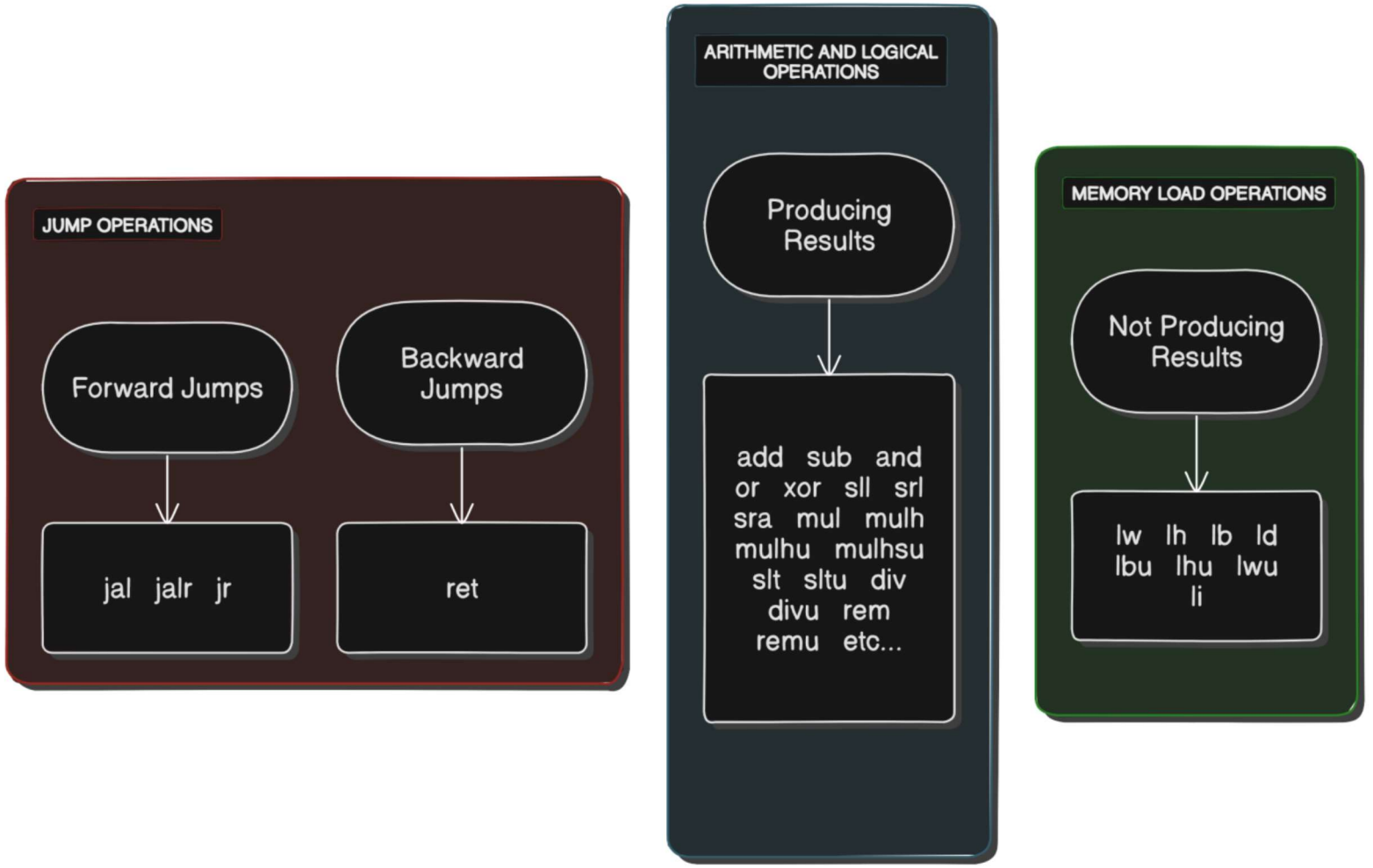
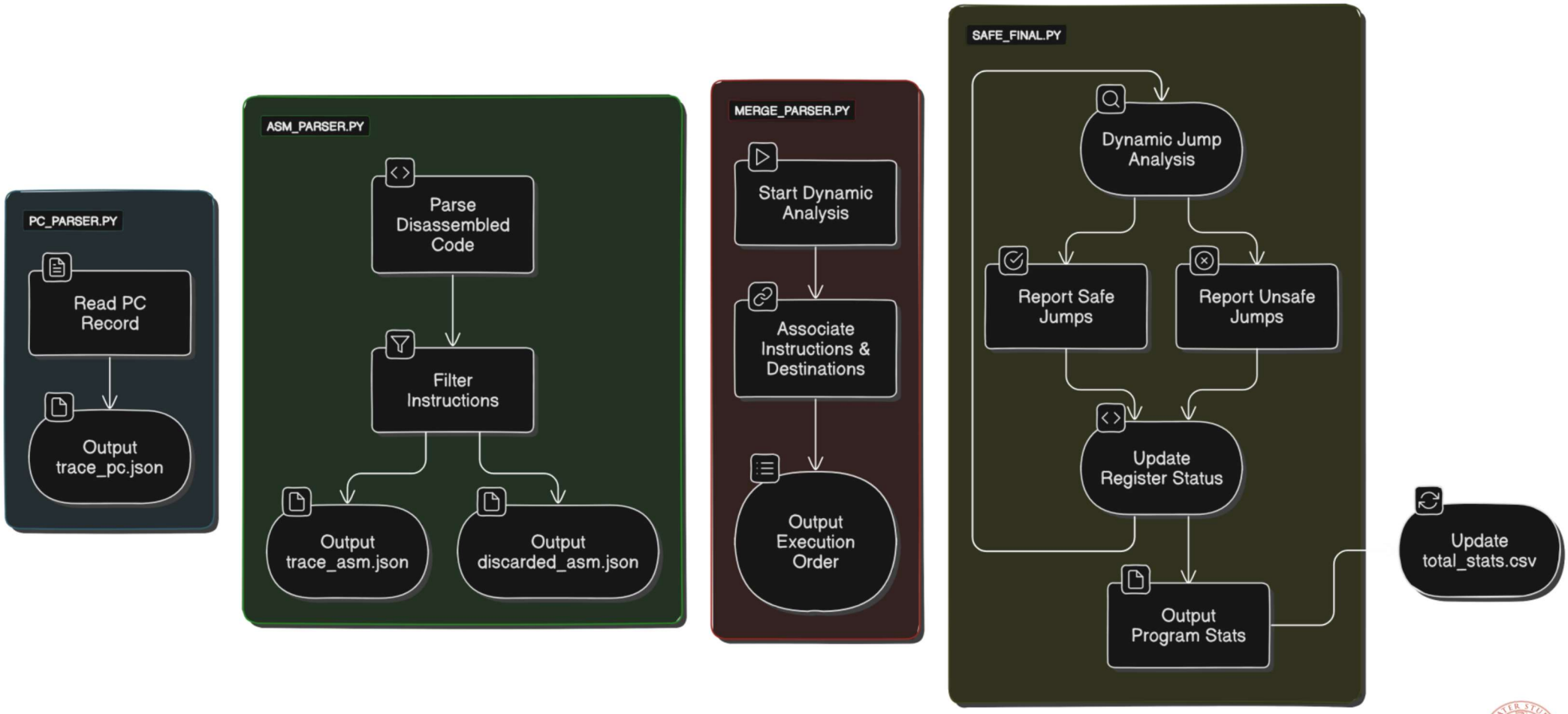
# Instructions classification



# Program Flow

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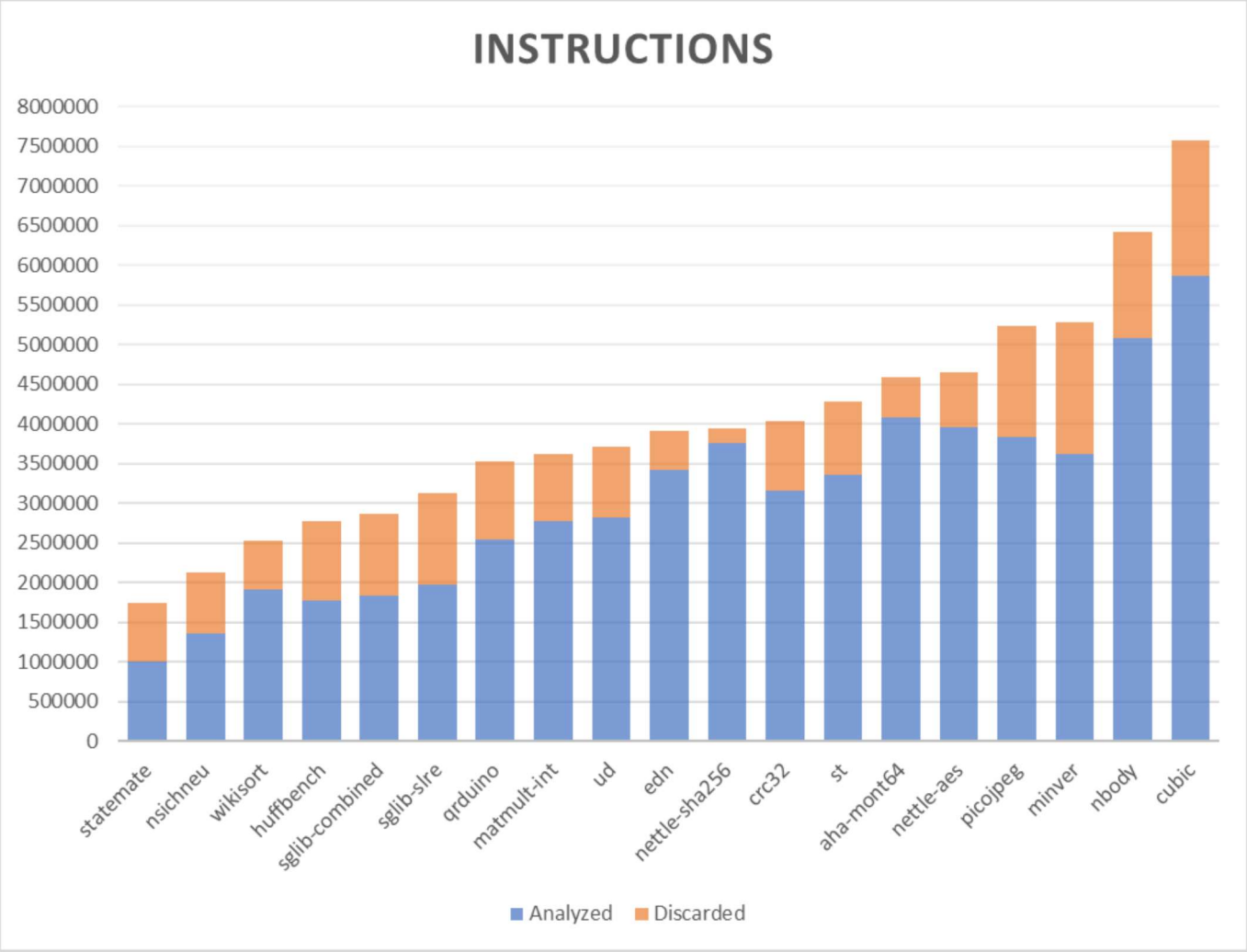
# Results

# Results




On average, 75% of instructions are analyzed and 25% are discarded:

- ***nettle-sha256***: 95% of instructions are analyzed due to the need for many result-producing instructions
- ***statemate***: Only 58% of instructions are analyzed, with a large portion being non-result-producing instructions

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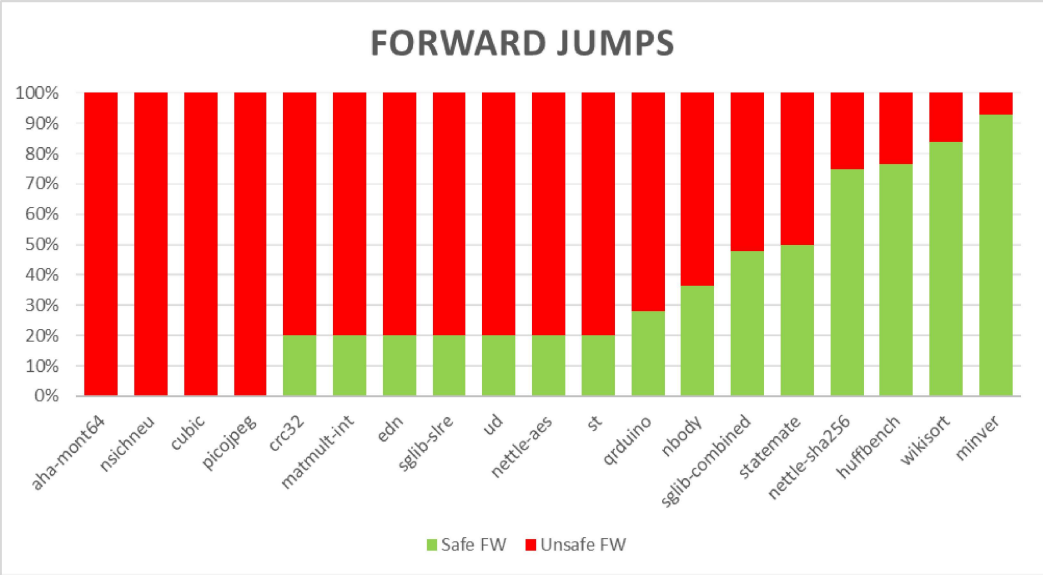
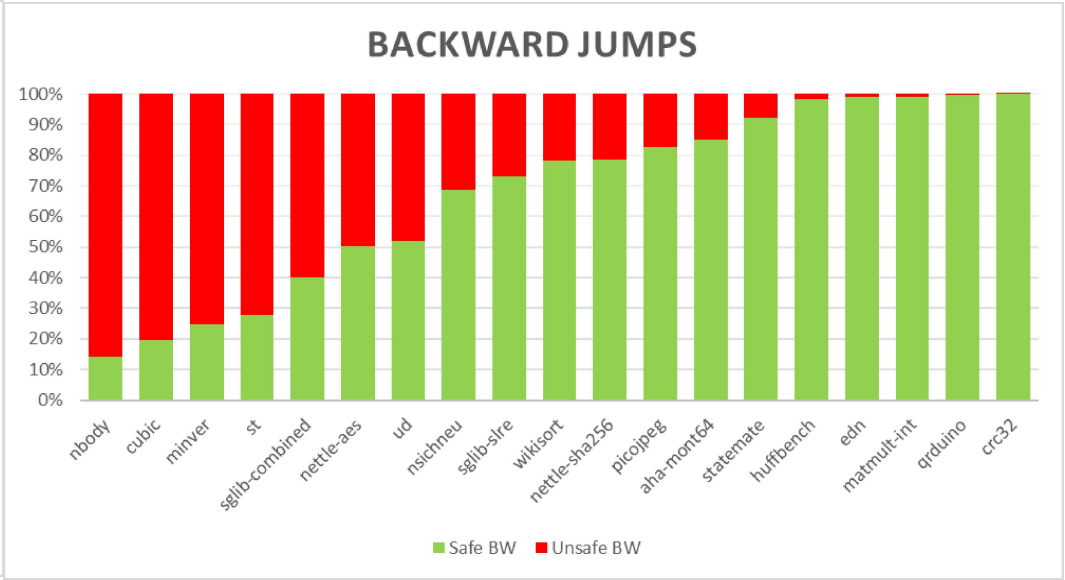
# Results




- **Forward jumps**: On average, 94% of jumps are **unsafe**, and only 6% are **safe**.
- **Backward jumps**: The majority (94%) are **safe**.

The predominance of backward jumps is attributed to the frequent use of "*ret*" instructions (used to return from routines)

# Results - *statemate*

```
Total jumps:      29498

Total fw jumps:   3935 (13.3%)
Safe fw:          1967 (50.0%)
Unsafe fw:        1968 (50.0%)
```

Balance between forward **safe** and **unsafe** jumps

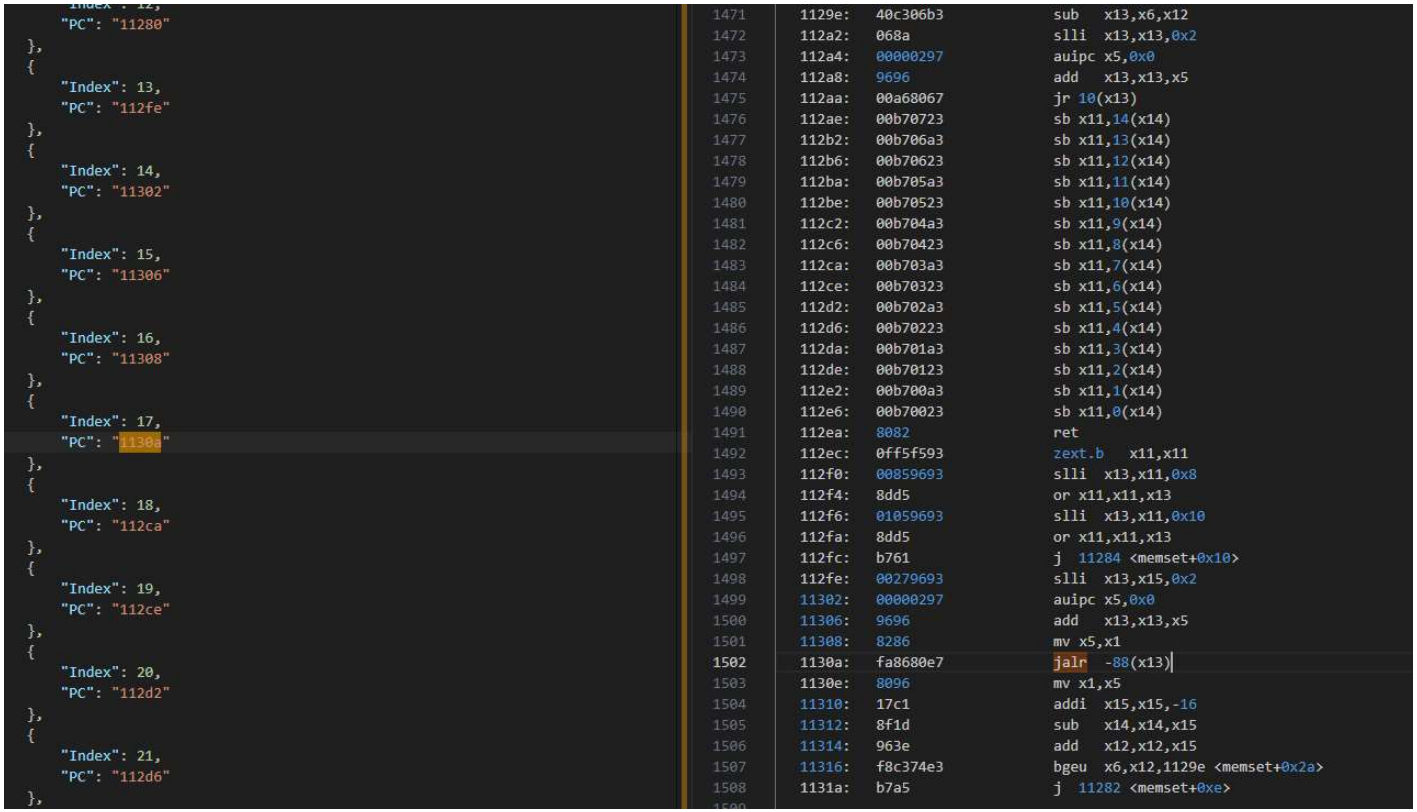
```
Enter the PC value:
112aa
The PC value '112aa' occurs 1965 times in 'statemate/merge_list.json'.
```

```
},
{
    "Index": 287,
    "PC": "112a2"
},
{
    "Index": 288,
    "PC": "112a4"
},
{
    "Index": 289,
    "PC": "112a8"
},
{
    "Index": 290,
    "PC": "112aa"
},
{
    "Index": 291,
    "PC": "112ca"
},
{
    "Index": 292,
    "PC": "112ce"
},
{
    "Index": 293,
    "PC": "112d2"
},
{
```

```
00011274 <memset>:
   11274:   433d            li x6,15
   11276:   872a            mv x14,x10
   11278:   02c37363        bgeu  x6,x12,1129e <memset+0x2a>
   1127c:   00f77793        andi  x15,x14,15
   11280:   efbd            bnez  x15,112fe <memset+0x8a>
   11282:   e5ad            bnez  x11,112ec <memset+0x78>
   11284:   ff067693        andi  x13,x12,-16
   11288:   8a3d            andi  x12,x12,15
   1128a:   96ba            add   x13,x13,x14
   1128c:   c30c            sw x11,0(x14)
   1128e:   c34c            sw x11,4(x14)
   11290:   c70c            sw x11,8(x14)
   11292:   c74c            sw x11,12(x14)
   11294:   0741            addi  x14,x14,16
   11296:   fed76be3        bltu  x14,x13,1128c <memset+0x18>
   1129a:   e211            bnez  x12,1129e <memset+0x2a>
   1129c:   8082            ret
   1129e:   40c306b3        sub   x13,x6,x12
   112a2:   068a            slli  x13,x13,0x2
   112a4:   00000297        auipc x5,0x0
   112a8:   9696            add   x13,x13,x5
   112aa:   00a68067        jr 10(x13)
   112ae:   00b70723        sb x11,14(x14)
   112b2:   00b706a3        sb x11,13(x14)
   112b6:   00b70623        sb x11,12(x14)
   112ba:   00b705a3        sb x11,11(x14)
   112be:   00b70523        sb x11,10(x14)
   112c2:   00b704a3        sb x11,9(x14)
```

# Results – *statemate*

```
Enter the PC value:
1130a
The PC value '1130a' occurs 1966 times in 'statemate/merge_list.json'.
```



```
    "PC": "11280"
},
{
    "Index": 13,
    "PC": "112fe"
},
{
    "Index": 14,
    "PC": "11302"
},
{
    "Index": 15,
    "PC": "11306"
},
{
    "Index": 16,
    "PC": "11308"
},
{
    "Index": 17,
    "PC": "1130a"
},
{
    "Index": 18,
    "PC": "112ca"
},
{
    "Index": 19,
    "PC": "112ce"
},
{
    "Index": 20,
    "PC": "112d2"
},
{
    "Index": 21,
    "PC": "112d6"
},
```

```
1471    1129e:  40c306b3        sub   x13,x6,x12
1472    112a2:  068a            slli  x13,x13,0x2
1473    112a4:  00000297        auipc x5,0x0
1474    112a8:  9696            add   x13,x13,x5
1475    112aa:  00a68067        jr 10(x13)
1476    112ae:  00b70723        sb x11,14(x14)
1477    112b2:  00b706a3        sb x11,13(x14)
1478    112b6:  00b70623        sb x11,12(x14)
1479    112ba:  00b705a3        sb x11,11(x14)
1480    112be:  00b70523        sb x11,10(x14)
1481    112c2:  00b704a3        sb x11,9(x14)
1482    112c6:  00b70423        sb x11,8(x14)
1483    112ca:  00b703a3        sb x11,7(x14)
1484    112ce:  00b70323        sb x11,6(x14)
1485    112d2:  00b702a3        sb x11,5(x14)
1486    112d6:  00b70223        sb x11,4(x14)
1487    112da:  00b701a3        sb x11,3(x14)
1488    112de:  00b70123        sb x11,2(x14)
1489    112e2:  00b700a3        sb x11,1(x14)
1490    112e6:  00b70023        sb x11,0(x14)
1491    112ea:  8082            ret
1492    112ec:  0ff5f593        zext.b   x11,x11
1493    112f0:  00859693        slli  x13,x11,0x8
1494    112f4:  8dd5            or x11,x11,x13
1495    112f6:  01059693        slli  x13,x11,0x10
1496    112fa:  8dd5            or x11,x11,x13
1497    112fc:  b761            j  11284 <memset+0x10>
1498    112fe:  00279693        slli  x13,x15,0x2
1499    11302:  00000297        auipc x5,0x0
1500    11306:  9696            add   x13,x13,x5
1501    11308:  8286            mv x5,x1
1502    1130a:  fa8680e7        jalr  -88(x13)
1503    1130e:  8096            mv x1,x5
1504    11310:  17c1            addi  x15,x15,-16
1505    11312:  8f1d            sub   x14,x14,x15
1506    11314:  963e            add   x12,x12,x15
1507    11316:  f8c374e3        bgeu  x6,x12,1129e <memset+0x2a>
1508    1131a:  b7a5            j  11282 <memset+0xe>
```

The program's execution path depends on the outcome of branches

*112aa* and *1130a* instructions both use ***x13*** as their destination register

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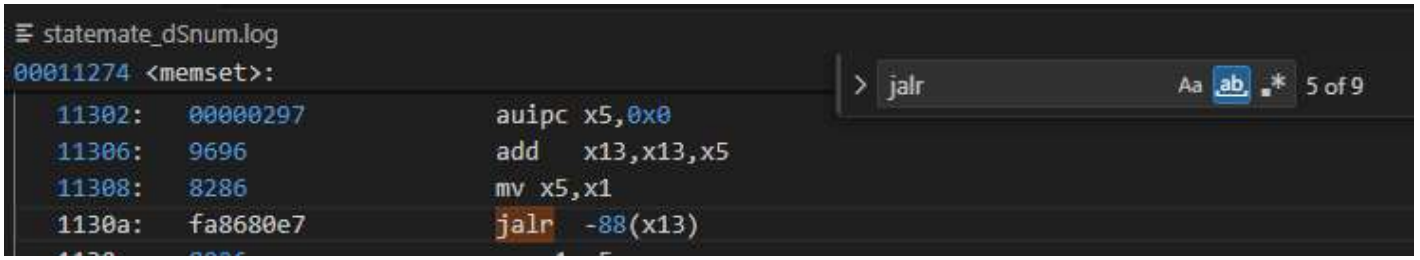
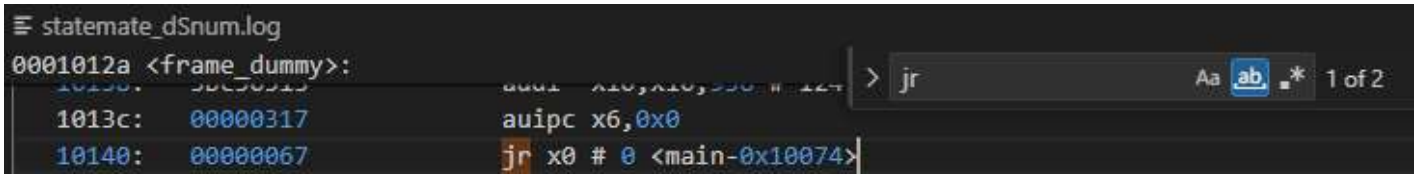
# Results – Static vs Dynamic Analysis

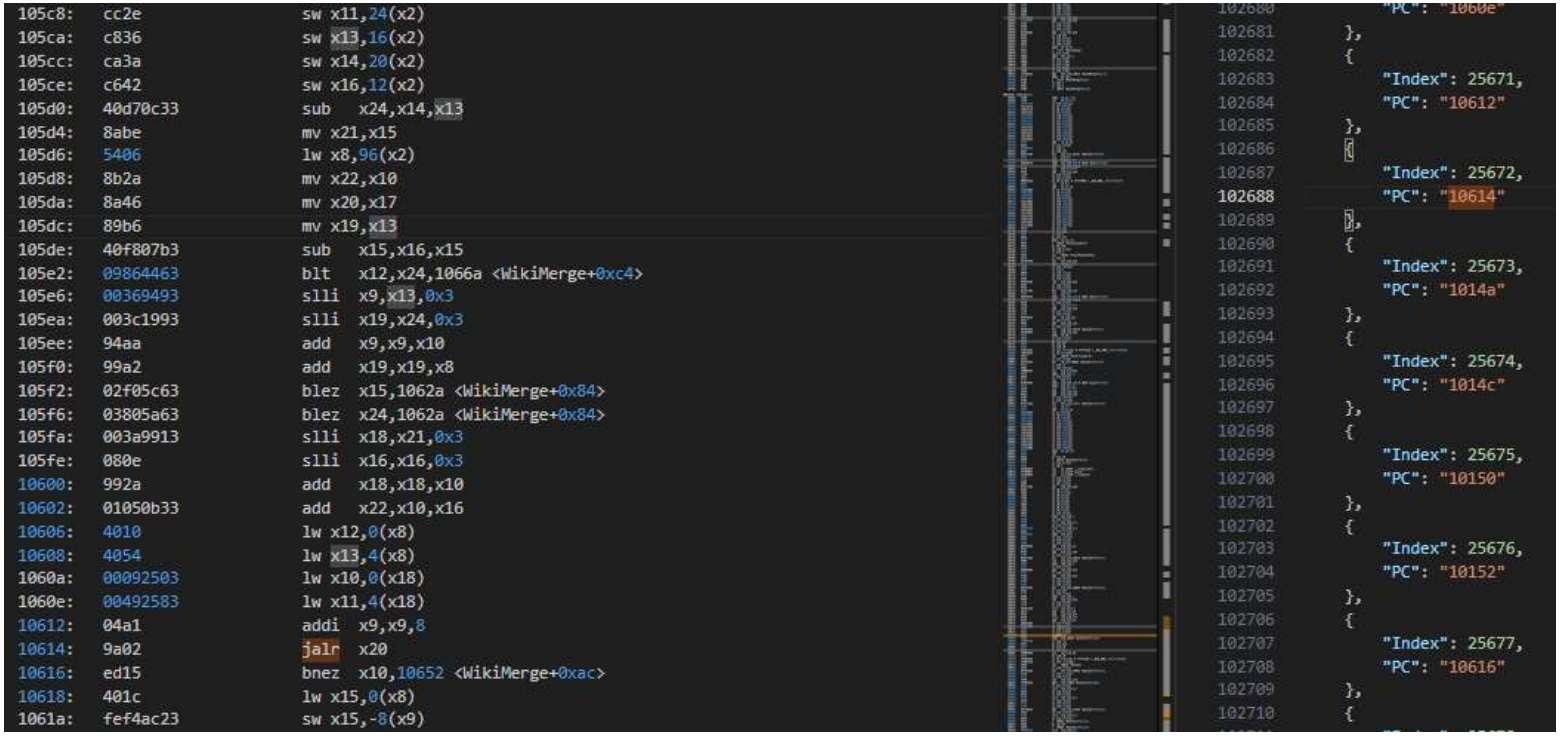



A static analysis would have reported **2 safe jumps** and **9 unsafe jumps**, not highlighting the safeness balance observed in dynamic analysis of program execution.

# Results - *Forward jumps*

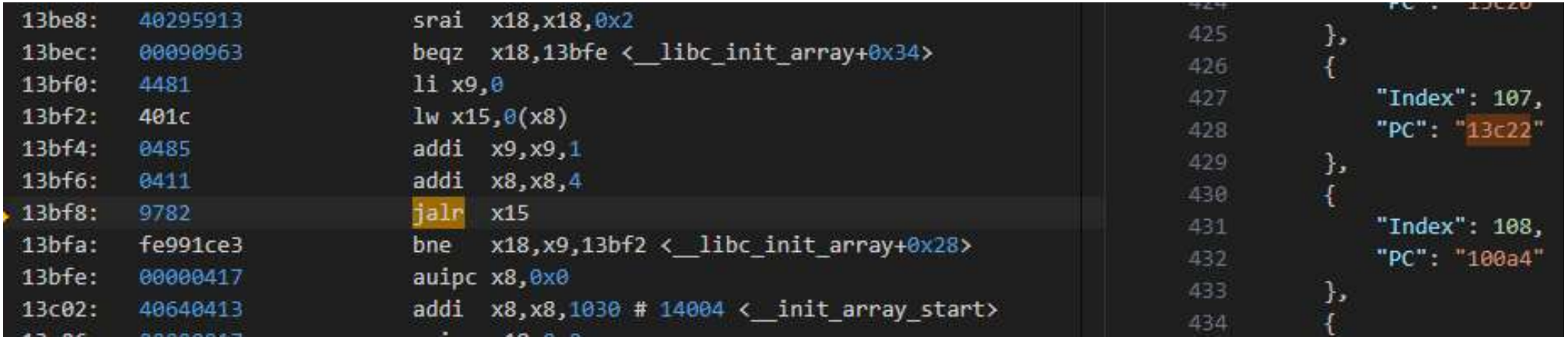
In *wikisort,* program the forward jumps turn out to be 84% **safe** compared to 16% **unsafe** forward jumps




The *jalr* (forward safe jump case) is executed about 7000 times, and a total of 47000 *jalr* are executed in the program with a similar construct

# Results - *Forward jumps*

In the *nsichneu* program the forward jumps turn out to be 100% unsafe.



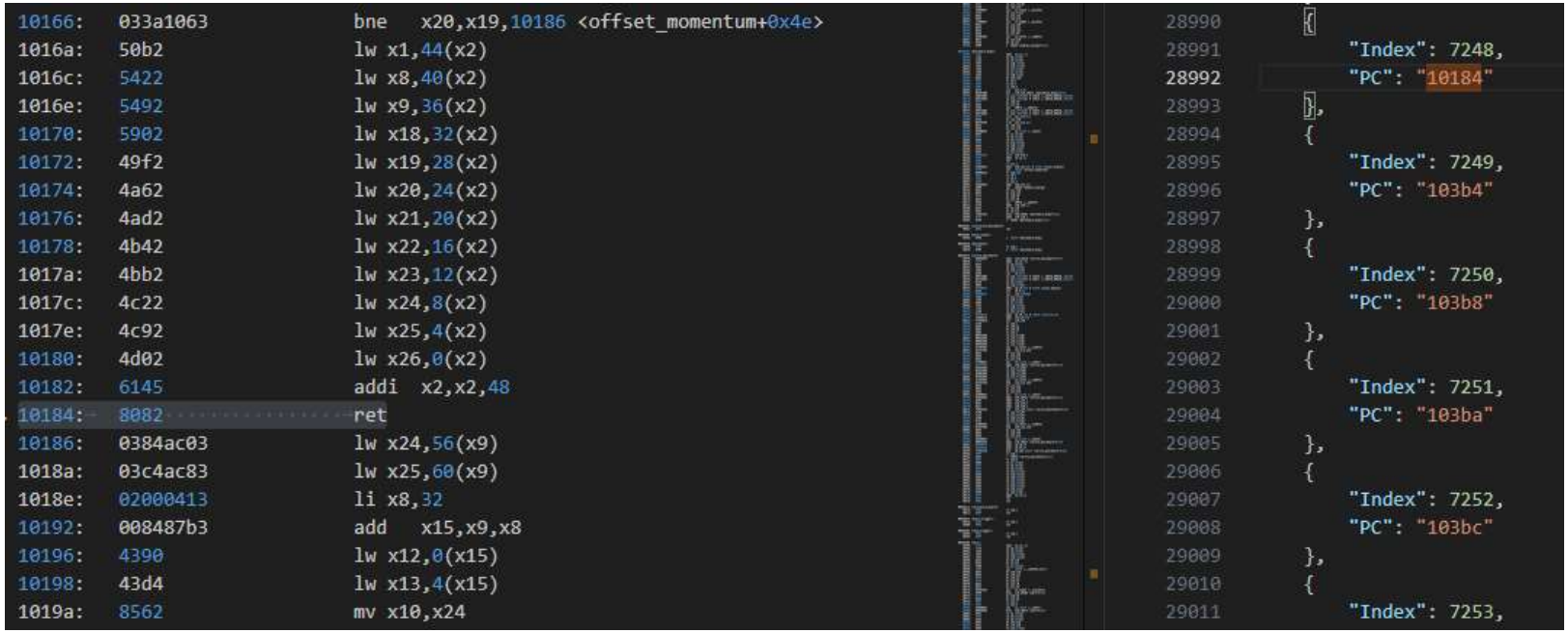
```
13be8:   40295913          srai  x18,x18,0x2
13bec:   00090963          beqz  x18,13bfe <__libc_init_array+0x34>
13bf0:   4481              li x9,0
13bf2:   401c              lw x15,0(x8)
13bf4:   0485              addi  x9,x9,1
13bf6:   0411              addi  x8,x8,4
13bf8:   9782              jalr  x15
13bfa:   fe991ce3          bne   x18,x9,13bf2 <__libc_init_array+0x28>
13bfe:   00000417          auipc x8,0x0
13c02:   40640413          addi  x8,x8,1030 # 14004 <__init_array_start>
```

```
425     },
426     {
427         "Index": 107,
428         "PC": "13c22"
429     },
430     {
431         "Index": 108,
432         "PC": "100a4"
433     },
434     {
```

There are standard constructs, such as the one above, that are repeated several times in the code and lead to an unsafe jump

# Results - *Backward jumps*

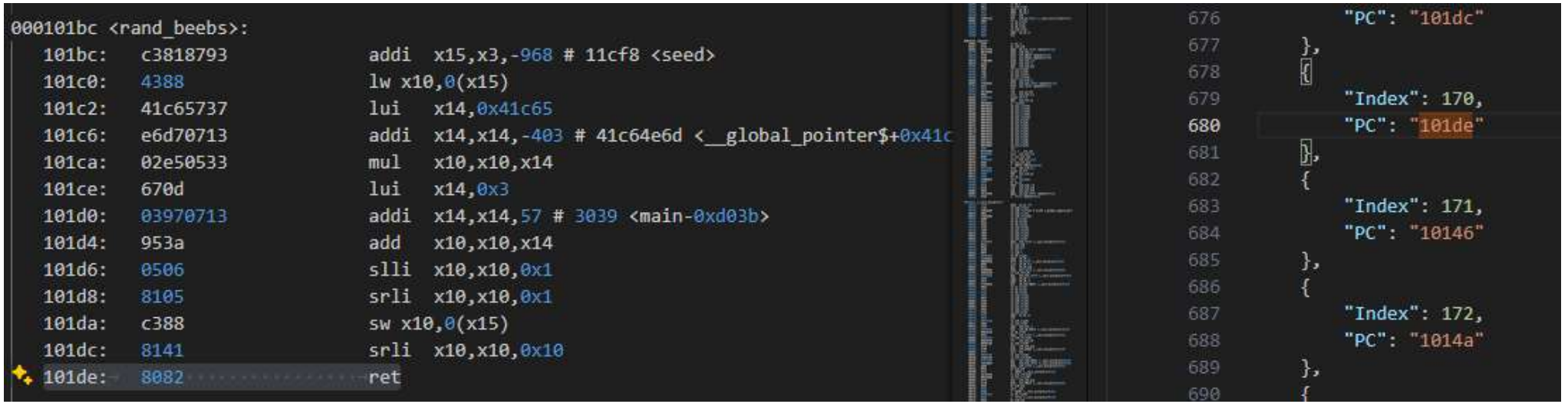
In *nbody*, **unsafe** backward jumps represent 86% of the total backward jumps




Register **x1** (*return address*) is modified with a load (unsafe operation) and before the execution of the "*ret*" instruction, x1 is loaded with potential unsafe content and the corresponding backward jump is unsafe

# Results - *Backward jumps*

In *crc32*, backward **safe** jumps correspond to almost all backward jumps (99.9%)



```
000101bc <rand_beebs>:
   101bc:   c3818793            addi  x15,x3,-968 # 11cf8 <seed>
   101c0:   4388                lw x10,0(x15)
   101c2:   41c65737            lui   x14,0x41c65
   101c6:   e6d70713            addi  x14,x14,-403 # 41c64e6d <__global_pointer$+0x41c
   101ca:   02e50533            mul   x10,x10,x14
   101ce:   670d                lui   x14,0x3
   101d0:   03970713            addi  x14,x14,57 # 3039 <main-0xd03b>
   101d4:   953a                add   x10,x10,x14
   101d6:   0506                slli  x10,x10,0x1
   101d8:   8105                srli  x10,x10,0x1
   101da:   c388                sw x10,0(x15)
   101dc:   8141                srli  x10,x10,0x10
   101de:   8082                ret
```

```
676             "PC": "101dc"
677         },
678         {
679             "Index": 170,
680             "PC": "101de"
681         },
682         {
683             "Index": 171,
684             "PC": "10146"
685         },
686         {
687             "Index": 172,
688             "PC": "1014a"
689         },
690         {
```

The instruction highlighted is executed many times (about 175000 out of a total of 175500 "ret") and the return address is never overwritten, leading to a backward safe jump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# Conclusions

# Conclusions

**Reached objectives:**

- Successfully compiled *Embench IoT* benchmark programs to retrieve the dynamic traces
- Successfully counted the number of insecure edges in executed RISC-V benchmark programs
- Results confirmed by patterns identified in the program trace
- Processed data stored in a CSV file, useful for further analysis
- First experience with Python code design

**Future developments:**

- Extend process to *Mibench* benchmark programs
- Refine the criteria chosen for defining safe edge and unsafe edge

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