DISTRIBUTED OPEN RELIABLE SYSTEMS ANALYSIS LAB (DORSAL)

A Novel Approach To Dynamic Instrumentation by exploiting compiler padding

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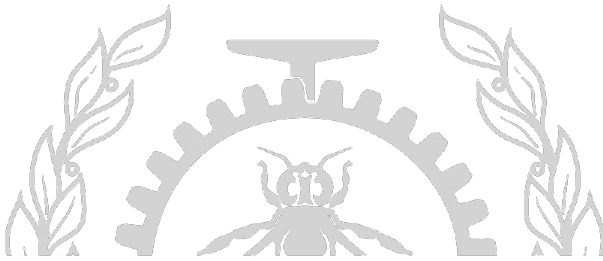
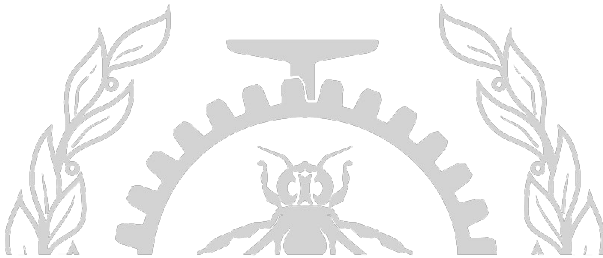


1. Problem definition

- Dynamic instrumentation of function entry and exit.
- Highly successful dynamic instrumentation.
- Fast dynamic tracepoints.
- Effective memory usage.



1. Problem definition

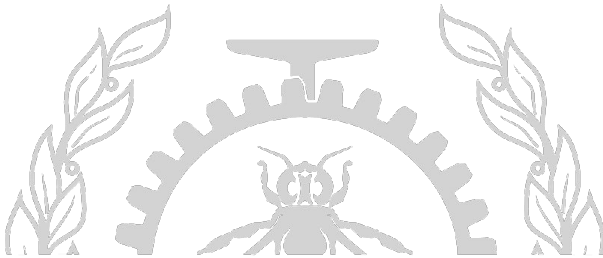
- Instrumentation is problematic when it overlaps more than one instruction:

```
e9 37 ff ff ff        jmpq   91763 <trace_entry>
```

```
0000000000084990 <ngx_http_fastcgi_create_key>:
   84990:       53                      push   %rbx
   84991:       48 8b 47 40             mov    0x40(%rdi),%rax
   84995:       48 89 fb                mov    %rdi,%rbx
   84998:       48 8d b8 c8 00 00 00    lea    0xc8(%rax),%rdi
   8499f:       e8 cc 65 f9 ff          callq  1af70 <ngx_array_push>
   849a4:       48 85 c0                test   %rax,%rax
   849a7:       74 37                   je     849e0 <ngx_http_fastcgi_create_key+0x50>
   849a9:       48 8b 53 28             mov    0x28(%rbx),%rdx
   849ad:       48 8b 0d cc 9c 23 00    mov    0x239ccc(%rip),%rcx        # 2be680 <ngx_
   849b4:       48 89 df                mov    %rbx,%rdi
   849b7:       48 8b 34 ca             mov    (%rdx,%rcx,8),%rsi
   849bb:       48 89 c2                mov    %rax,%rdx
   849be:       48 81 c6 50 02 00 00    add    $0x250,%rsi
   849c5:       e8 26 51 fd ff          callq  59af0 <ngx_http_complex_value>
   849ca:       48 85 c0                test   %rax,%rax
   849cd:       0f 95 c0                setne  %al
   849d0:       0f b6 c0                movzbl %al,%eax
   849d3:       48 f7 d8                neg    %rax
   849d6:       5b                      pop    %rbx
   849d7:       c3                      retq
   849d8:       0f 1f 84 00 00 00 00    nopl   0x0(%rax,%rax,1)
   849df:       00
   849e0:       48 c7 c0 ff ff ff ff    mov    $0xffffffffffffffff,%rax
   849e7:       5b                      pop    %rbx
   849e8:       c3                      retq
   849e9:       0f 1f 80 00 00 00 00    nopl   0x0(%rax)
```

2. Proposed solution

- To minimize the instrumentation overlapping instructions case:
  - We use a smaller instrumentation instructions.
  - Relative jump 2 bytes has lesser chance than a relative jump 5 bytes.
- But how can we reach the function that does the tracing with only a one byte displacement ?!



2. Proposed solution

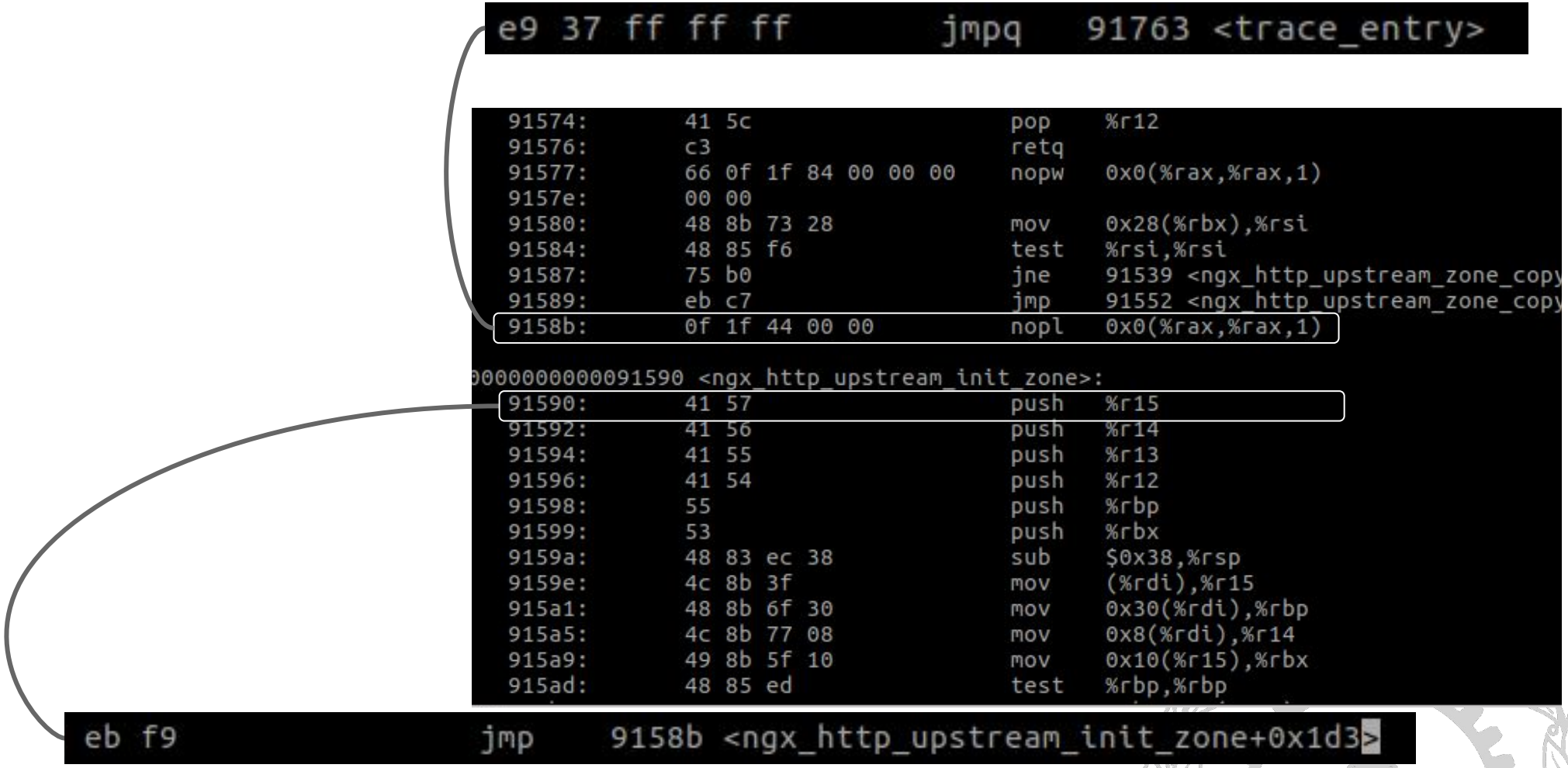
- Binaries built with the following options contain NOP instructions as padding for performance reasons:
  - -falign-functions
  - -falign-jumps
  - -falign-labels
  - -falign-loops
- -O2 and more
  - turns on all these option.

```
  91574:       41 5c                   pop    %r12
  91576:       c3                      retq
  91577:       66 0f 1f 84 00 00 00    nopw   0x0(%rax,%rax,1)
  9157e:       00 00
  91580:       48 8b 73 28             mov    0x28(%rbx),%rsi
  91584:       48 85 f6                test   %rsi,%rsi
  91587:       75 b0                   jne    91539 <ngx_http_upstream_zone_copy
  91589:       eb c7                   jmp    91552 <ngx_http_upstream_zone_copy
  9158b:       0f 1f 44 00 00          nopl   0x0(%rax,%rax,1)

0000000000091590 <ngx_http_upstream_init_zone>:
  91590:       41 57                   push   %r15
  91592:       41 56                   push   %r14
  91594:       41 55                   push   %r13
  91596:       41 54                   push   %r12
  91598:       55                      push   %rbp
  91599:       53                      push   %rbx
  9159a:       48 83 ec 38             sub    $0x38,%rsp
  9159e:       4c 8b 3f                mov    (%rdi),%r15
  915a1:       48 8b 6f 30             mov    0x30(%rdi),%rbp
  915a5:       4c 8b 77 08             mov    0x8(%rdi),%r14
  915a9:       49 8b 5f 10             mov    0x10(%r15),%rbx
  915ad:       48 85 ed                test   %rbp,%rbp
```

2. Proposed solution

- NOPs after the previous function epilogue can be used (safetly) to insert a trampoline.

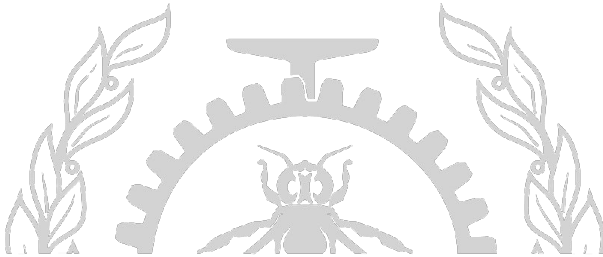


2. Proposed solution

- What if we don’t find a suitable NOP in the end of a function ?
- No problem ! NOPs used for padding loops, labels and jumps may be used as well.

```
   42186:       48 89 d8                mov    %rbx,%rax
   42189:       5b                      pop    %rbx
   4218a:       5d                      pop    %rbp
   4218b:       c3                      retq
   4218c:       0f 1f 40 00             nopl   0x0(%rax)

0000000000042190 <ngx_regex_malloc>:
   42190:       48 89 fe                mov    %rdi,%rsi
   42193:       48 8b 3d be 31 29 00    mov    0x2931be(%rip),%rdi        # 2d5358 <ngx_pcre_pool>
   4219a:       48 85 ff                test   %rdi,%rdi
   4219d:       74 09                   je     421a8 <ngx_regex_malloc+0x18>
   4219f:       e9 1c 8a fd ff          jmpq   1abc0 <ngx_palloc>
   421a4:       0f 1f 40 00             nopl   0x0(%rax)
   421a8:       31 c0                   xor    %eax,%eax
   421aa:       c3                      retq
```



2. Proposed solution

- All NOPs are not safe to use:

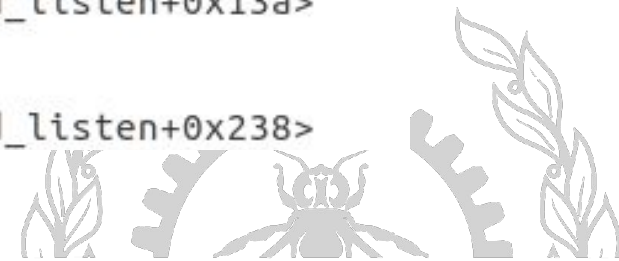
```
 432af:       31 c0                   xor    %eax,%eax
 432b1:       e8 4a 69 fd ff          callq  19c00 <ngx_log_error_core>
 432b6:       66 2e 0f 1f 84 00 00    nopw   %cs:0x0(%rax,%rax,1)
 432bd:       00 00 00
 432c0:       49 c7 c5 ff ff ff ff    mov    $0xffffffffffffffff,%r13
 42548:       49 39 6d 08             cmp    %rbp,0x8(%r13)
 4254c:       0f 87 6f ff ff ff       ja     424c1 <ngx_regex_exec_array+0x21>
 42552:       66 0f 1f 44 00 00       nopw   0x0(%rax,%rax,1)
 42558:       48 c7 c5 fb ff ff ff    mov    $0xfffffffffffffffb,%rbp
 4255f:       eb 91                   jmp    424f2 <ngx_regex_exec_array+0x52>
 42561:       66 2e 0f 1f 84 00 00    nopw   %cs:0x0(%rax,%rax,1)
 42568:       00 00 00
 4256b:       0f 1f 44 00 00          nopl   0x0(%rax,%rax,1)

0000000000042570 <ngx_http_merge_locations>:
 42570:       48 85 f6                test   %rsi,%rsi
 42573:       0f 84 ef 00 00 00       je     42668 <ngx_http_merge_locations+0xf8>
 42579:       41 57                   push   %r15
 4257b:       41 56                   push   %r14
 43312:       4c 89 ac 24 b8 00 00    mov    %r13,0xb8(%rsp)
 43319:       00
 4331a:       66 0f 1f 44 00 00       nopw   0x0(%rax,%rax,1)
 43320:       48 81 78 48 48 54 54    cmpq   $0x50545448,0x48(%rax)
 43327:       50
 43328:       0f 85 ad 01 00 00       jne    434db <ngx_http_block+0x59b>
```

2. Proposed solution

- Unreachable NOPs are safe to use:
  - If there is an unconditional branch instruction before it.
  - If there is **no** branching instruction in the function with the address of the NOP as a target.

```
4472a:       eb 9d                   jmp    446c9 <ngx_http_add_listen+0x99>
4472c:       0f 1f 40 00             nopl   0x0(%rax)
44730:       48 8b 8d 40 01 00 00    mov    0x140(%rbp),%rcx
44737:       48 85 c9                test   %rcx,%rcx
4473a:       0f 84 50 01 00 00       je     44890 <ngx_http_add_listen+0x260>
44740:       48 8b b5 48 01 00 00    mov    0x148(%rbp),%rsi
44747:       48 85 f6                test   %rsi,%rsi
4474a:       74 27                   je     44773 <ngx_http_add_listen+0x143>
4474c:       4c 3b 21                cmp    (%rcx),%r12
4474f:       0f 84 13 01 00 00       je     44868 <ngx_http_add_listen+0x238>
44755:       31 c0                   xor    %eax,%eax
44757:       eb 11                   jmp    4476a <ngx_http_add_listen+0x13a>
44759:       0f 1f 80 00 00 00 00    nopl   0x0(%rax)
44760:       4c 3b 24 c1             cmp    (%rcx,%rax,8),%r12
44764:       0f 84 fe 00 00 00       je     44868 <ngx_http_add_listen+0x238>
```

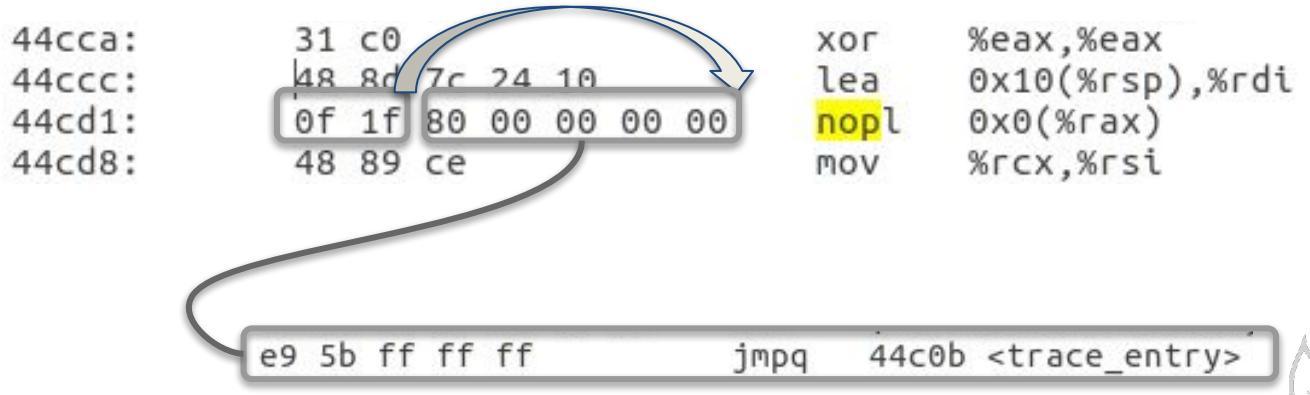


2. Proposed solution

- What if the NOP is reachable ?

```
432af:      31 c0                   xor    %eax,%eax
432b1:      e8 4a 69 fd ff          callq  19c00 <ngx_log_error_core>
432b6:      66 2e 0f 1f 84 00 00    nopw   %cs:0x0(%rax,%rax,1)
432bd:      00 00 00
432c0:      49 c7 c5 ff ff ff ff    mov    $0xffffffffffffffff,%r13
```

- We can still use it if its size is superior to 7:
  - By using a 2 bytes jump to jump over the nop and use the rest as a trampoline:



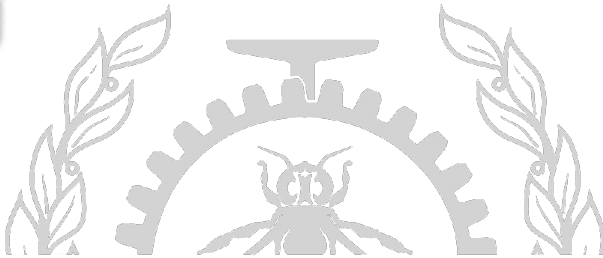
2. Proposed solution

- We can still use it if its size is superior to 7:
  - By changing the operand and leaving the opcode untouched, thus embedding the trampoline in the operand:

```
432af:      31 c0                   xor    %eax,%eax
432b1:      e8 4a 69 fd ff          callq  19c00 <ngx_log_error_core>
432b6:      66 2e 0f 1f 84 00 00    nopw   %cs:0x0(%rax,%rax,1)
432bd:      00 00 00
432c0:      49 c7 c5 ff ff ff ff    mov    $0xffffffffffffffff,%r13
```

```
432af:      31 c0                   xor    %eax,%eax
432b1:      e8 4a 69 fd ff          callq  19c00 <ngx_log_error_core>
432b6:      66 2e 0f 1f 84 e9 5b    nopw   %cs:0x8(%rcx,%rbp,0xa5)
432bd:      ff ff ff
432c0:      49 c7 c5 ff ff ff ff    mov    $0xffffffffffffffff,%r13
```

```
e9 5b ff ff ff          jmpq   44c0b <trace_entry>
```



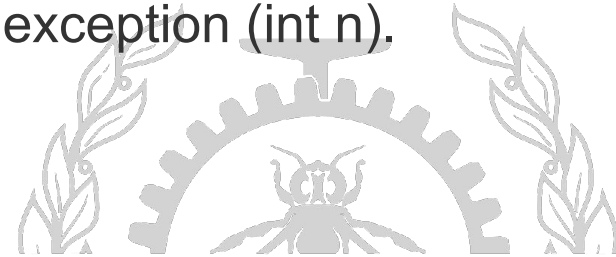
2. Proposed solution

- What if we don't find any NOP near the instrumented point ?
- We use a relative jump 32 as an instrumentation instruction instead of relative jump 8:

```
e9 5b ff ff ff          jmpq   44c0b <trace_entry>
```

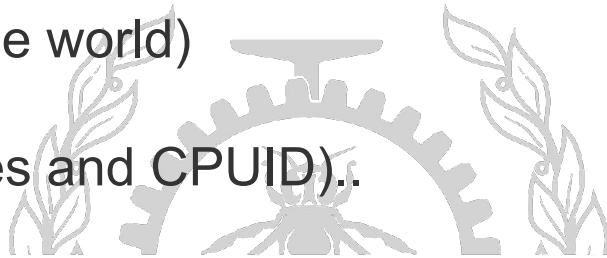
```
0000000000042da0 <ngx_http_init_static_location_trees.isra.7>:
   42da0:       31 c0                   xor    %eax,%eax
   42da2:       48 85 d2                test   %rdx,%rdx
   42da5:       0f 84 5d 01 00 00       je     42f08 <ngx_http_init_static_location_trees.isra.7+0x168>
   42dab:       4c 8b 02                mov    (%rdx),%r8
   42dae:       49 39 d0                cmp    %rdx,%r8
   42db1:       0f 84 51 01 00 00       je     42f08 <ngx_http_init_static_location_trees.isra.7+0x168>
   42db7:       41 56                   push   %r14
```

- There should be no branching to the patched area.
- No indirect branching in the function.
- Function contains no instruction that causes an exception (int n).



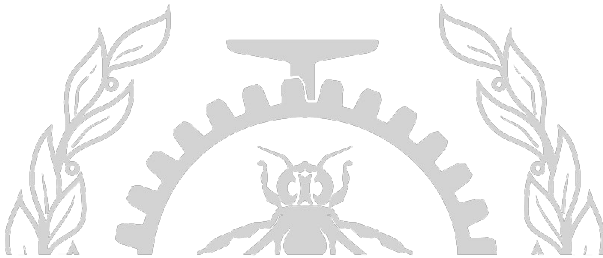
2. Proposed solution

- For dynamic tracing, instrumentation should be done on the fly:
  - The jump 2 bytes used for the entry function is done atomically.
  - If the NOP is unreachable which is the case 95% of the time, we just patch it without worrying about multi-thread problems.
  - If it's reachable and has a size superior to 7, we can embed a trampoline in it without worrying about corrupting the NOP. If the size is inferior to 8 we do it atomicly (in x64 at least).
  - Needs addressing some simultaneous execution issues on preemptive kernel.. (preferably without stopping the world)
  - And cross self-modifying issues (cache boundaries and CPUID)..



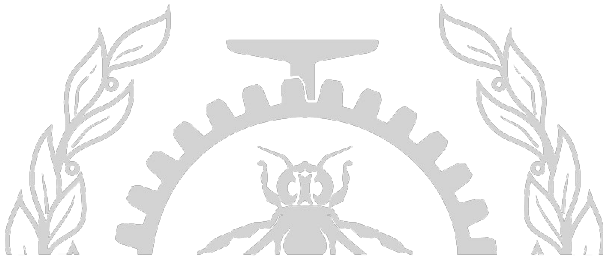
2. Proposed solution

- Results:
  - Success rate:
    - uftrace: 86%
    - nginx: 89%
    - Git: 82%
    - V8 JavaScript engine (Google chrome): 90.46%



3. Limitations and Problems

- Limited to function entry and exit.
- If the binary is not optimized, NOPs will be missing.
- A greedy algorithm is used to find a suitable NOP. An optimal algorithm may be used to increase the success rate even more.



Demonstration 1

Questions?

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https://github.com/AnsBal/