NOPoutNG

Improving the Effectiveness of Hardware-assisted Control-flow Integrity via Dynamic Landing Pad Elision

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Memory Safety

Memory Errors

- Modern software is large and complex, often resulting in vulnerabilities
- Memory errors are among the most malefic:
  - They dominate the SANS institute's list of the "*top 25 most dangerous software errors*"*
  - Microsoft and Google report $\approx$ 70% of all product vulnerabilities stem from memory-safety problems[†‡§]

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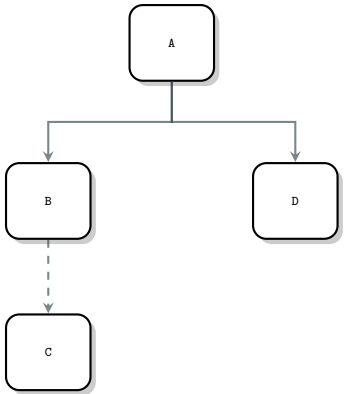

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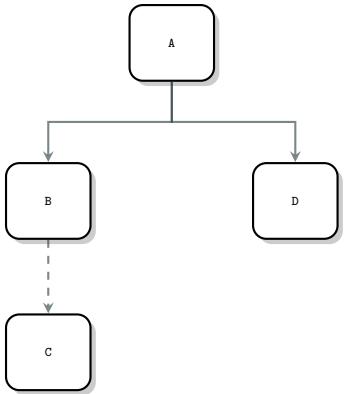

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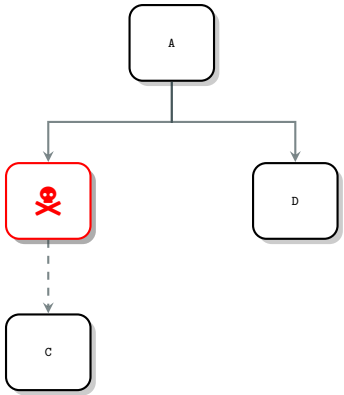

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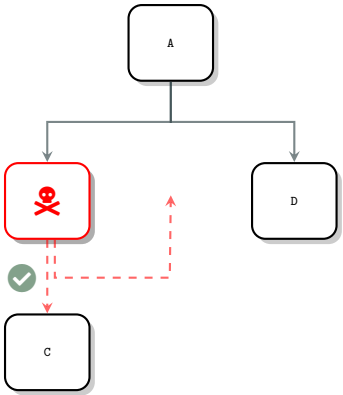

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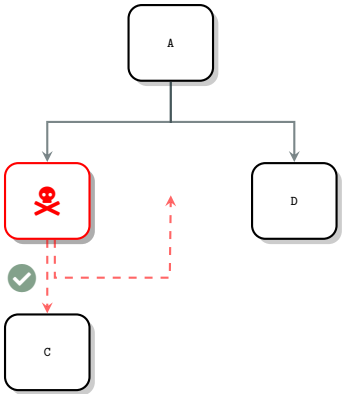

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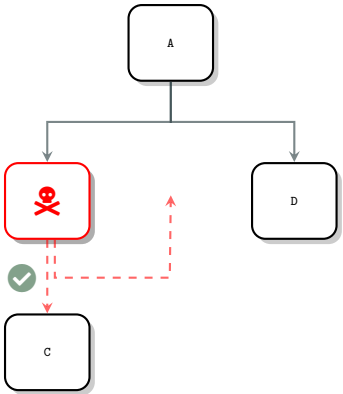

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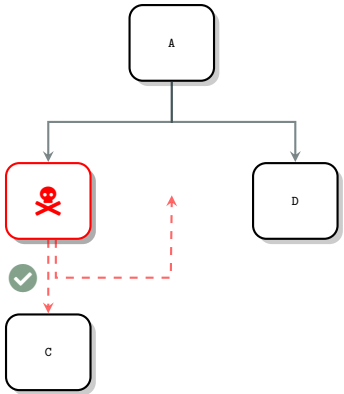

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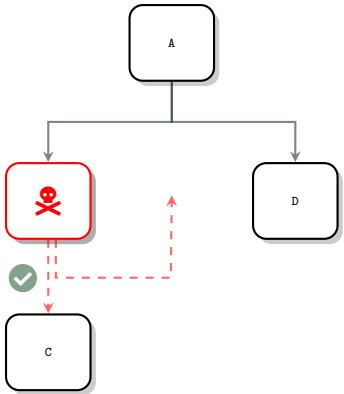

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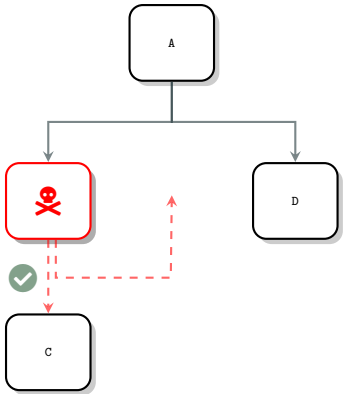
Fewer Targets ⟵ ⟶ More Targets
Fine-grain — Coarse-grain



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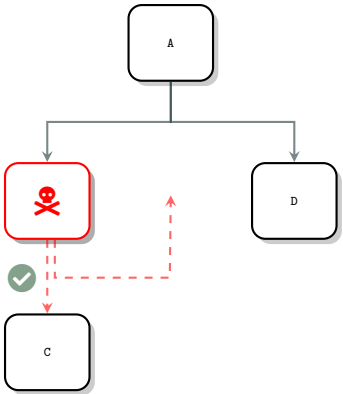
CFI Support

- Hardware support: Intel CET, ARM BTI
- Toolchain support: MSVC, LLVM, GCC
- OS support: GNU/Linux, Windows



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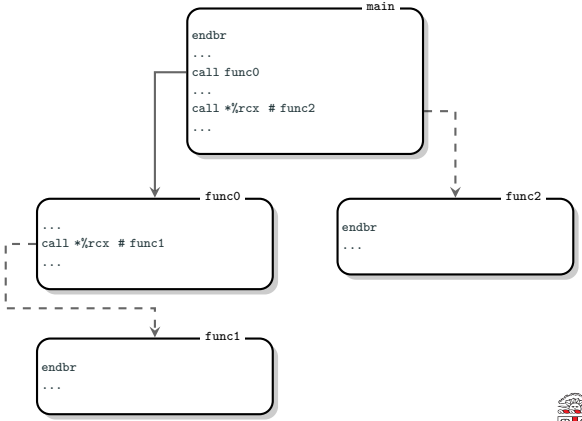

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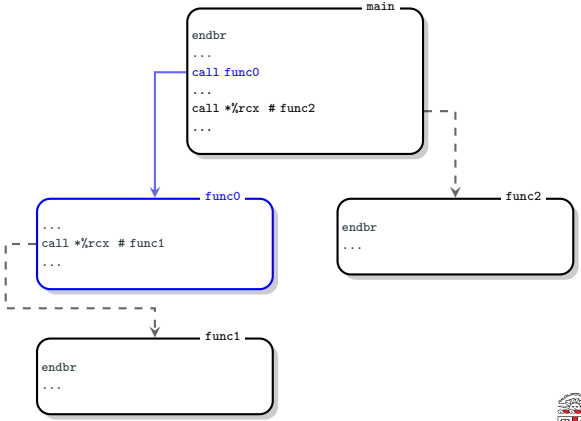

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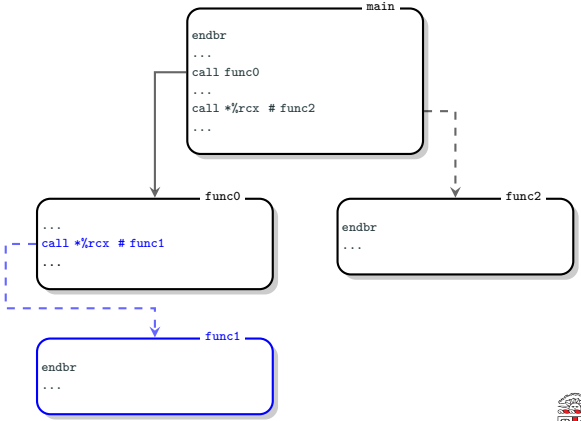

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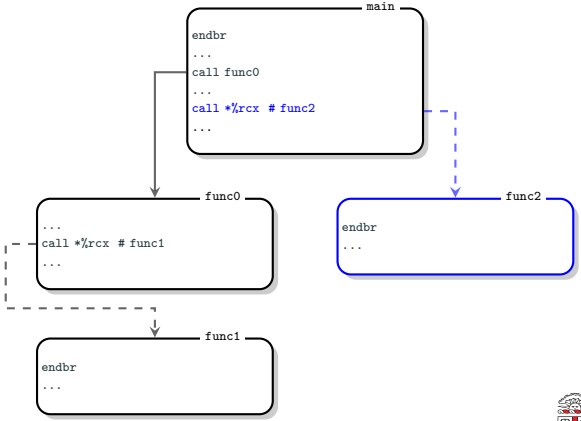

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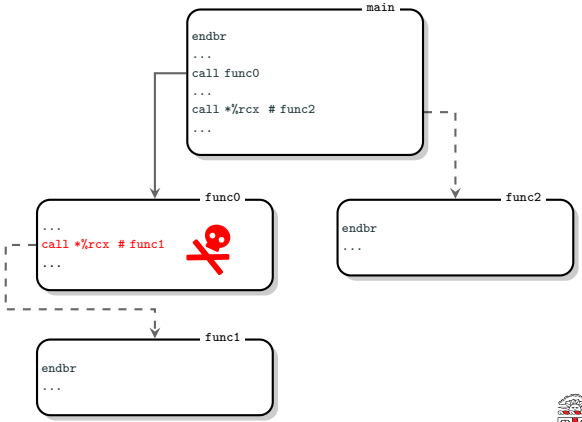

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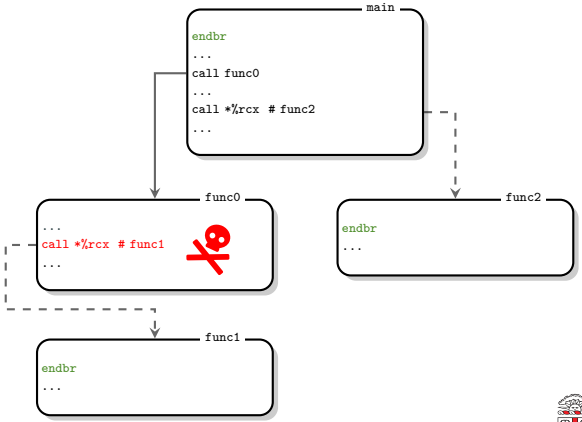

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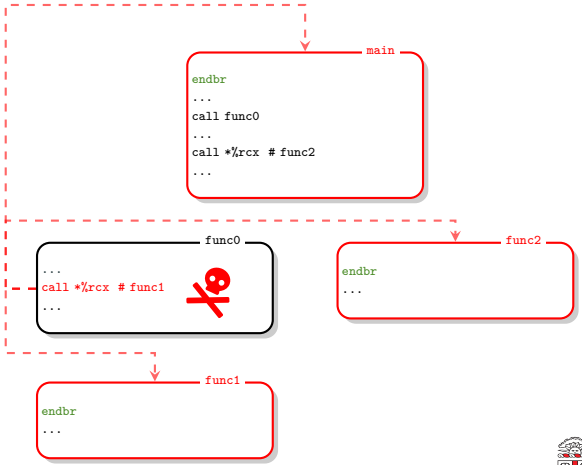

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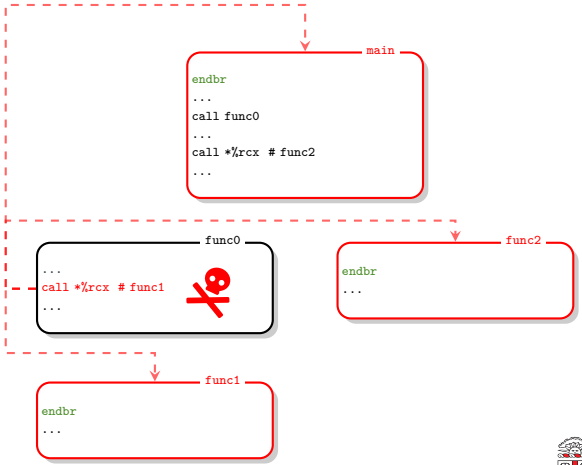
Target Domain: Anywhere HW feature is available

Compatibility: No major requirements (just enable feature and add `endbr`s)

Coverage: Forward-edges

Effectiveness: Coarse-grain



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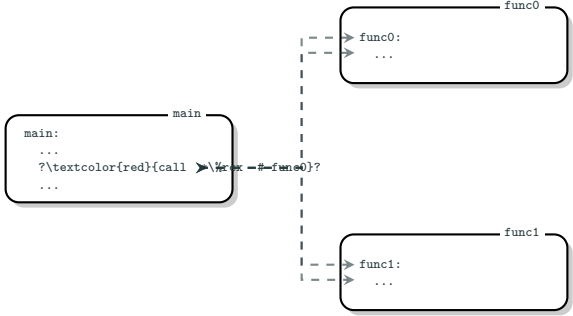

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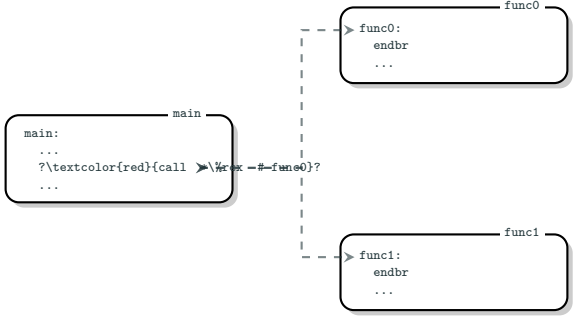

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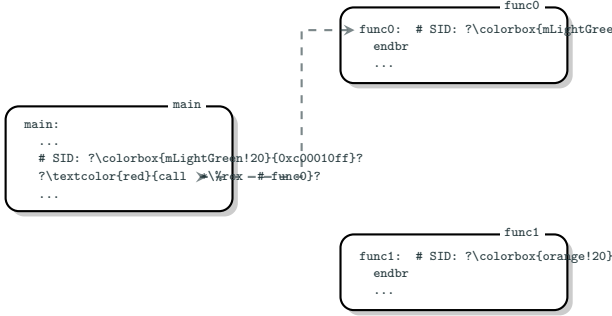

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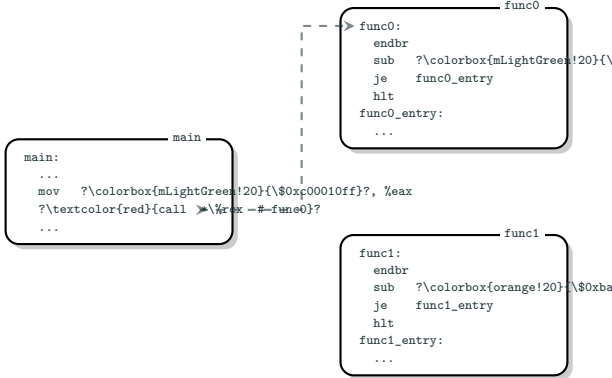

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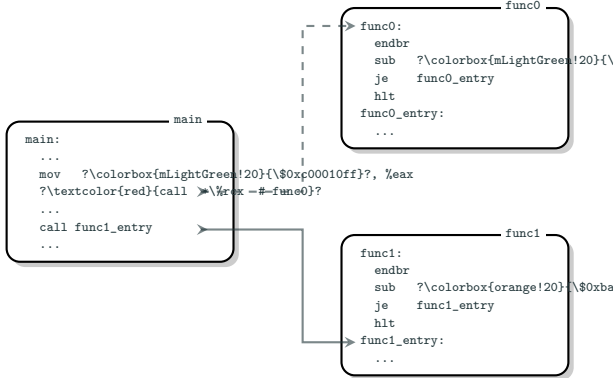
- Extends compile-time instrumentation with fast SID checks
- Direct calls bypass all instrumentation, experiencing no overhead



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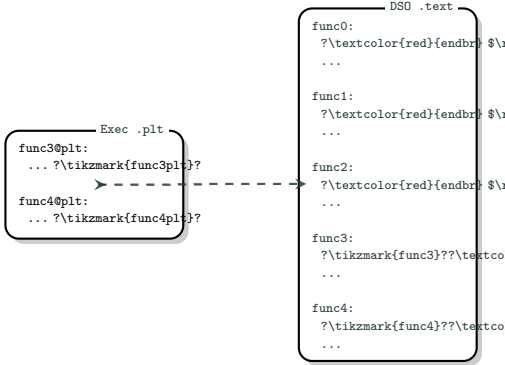

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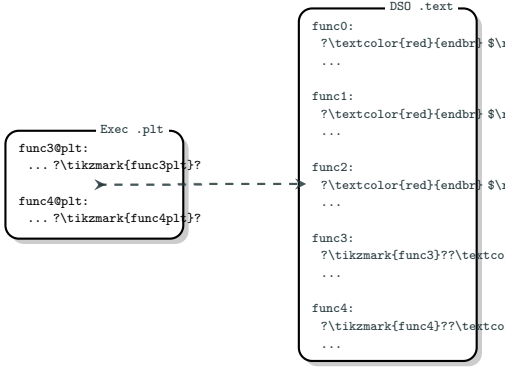

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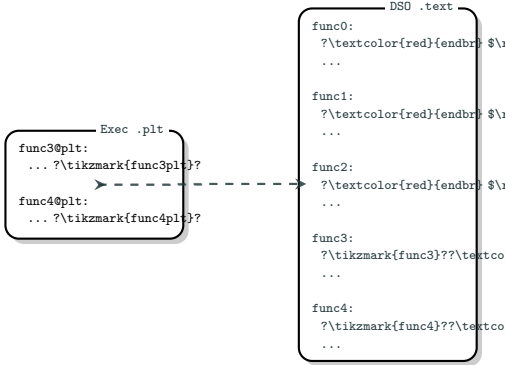
- During compilation, symbols are collected into `.plt.nopout` that are:



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NOPout

- Load-time feature to *elide* `endbr` from unused functions
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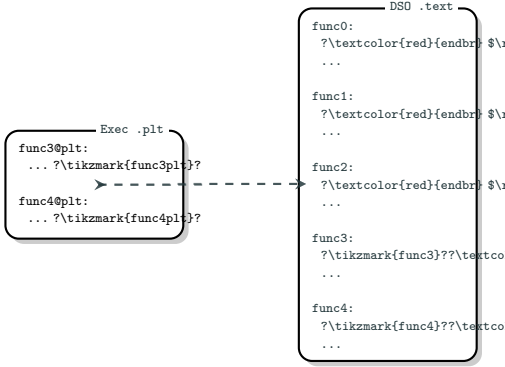

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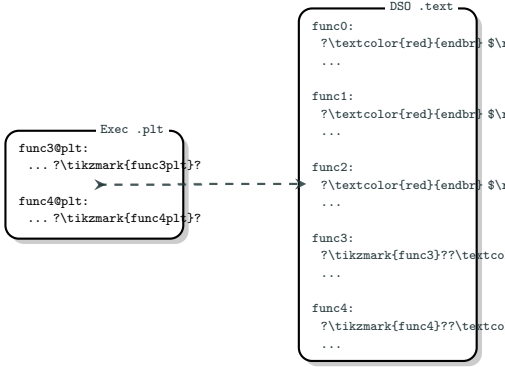

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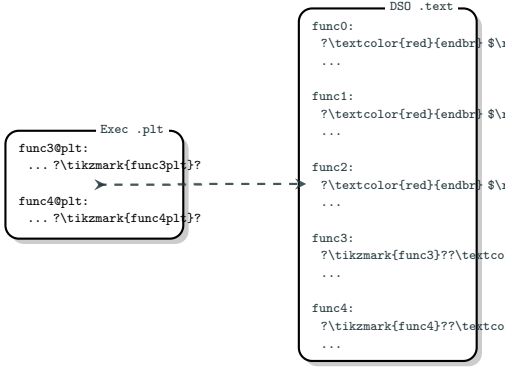

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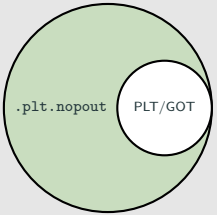
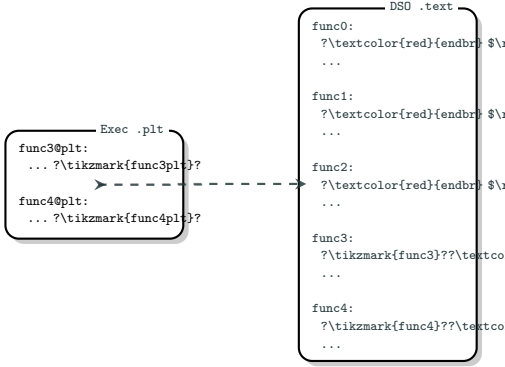
  - Non-local (i.e., will be visible to other object files)
  - Functions (i.e., `STT_FUNC`s)
- At load-time, `libnopout.so` compares `.plt.nopout` to PLT/GOT slots
- If an entry is in `.plt.nopout` but not in a PLT/GOT slot, its 4-byte `endbr` is replaced with a 4-byte `nop`





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NOPout Problems

1. Order of Operations: `s/endbr/nop/` at runtime

NOPoutNG Solutions

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NOPout Problems

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NOPout vs. NOPoutNG

NOPout Problems

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NOPoutNG Solutions

1. Order of Operations: `s/nop/endbr/` at runtime
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   - Minimized CoW effects

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NOPout vs. NOPoutNG

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2. Extraneous Metadata: Requires new ELF section

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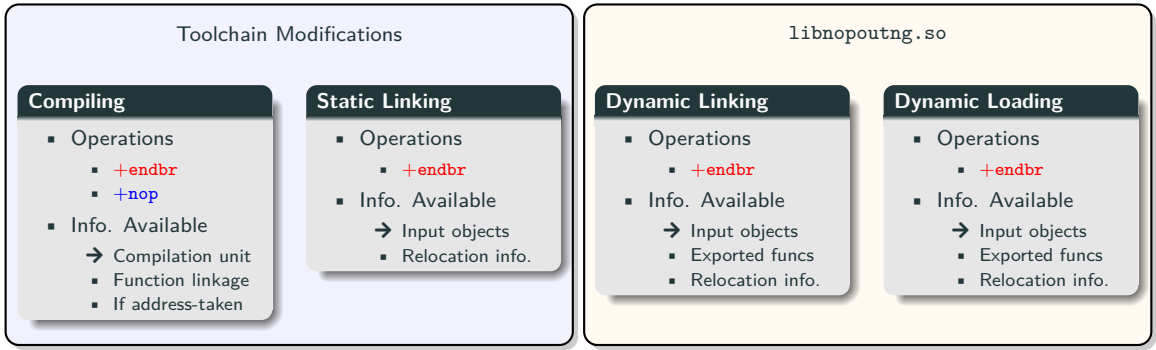
Toolchain Modifications
Compiling
Operations
+endbr
+nop
Info. Available
Compilation unit
Function linkage
If address-taken
Static Linking
Operations
+endbr
Info. Available
Input objects
Relocation info.
libnopoutng.so
Dynamic Linking
Operations
+endbr
Info. Available
Input objects
Exported funcs
Relocation info.
Dynamic Loading
Operations
+endbr
Info. Available
Input objects
Exported funcs
Relocation info.

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Information Available

- Linkage and partial address-taken property of functions within compilation unit

Inserting `endbrs`

- `NOPoutNG` inserts `endbr` into functions that:
  - Are address-taken

Inserting `nops`

- `NOPoutNG` inserts `nops` into functions that:
  - Aren't local (i.e., `STB_BIND != STB_LOCAL`)
  - Aren't address-taken locally

a.c

```
1  int main(int c, char **v) {
2    ((c > 1) ? &f1 : &f2)();
3    f3();
4  }
```

Compile
+endbr
+nop

a.o

```
?<?main?>:?
   ?0:? ?\textcolor{\nopcolor}{nopl   (\%ra
   ?\minteddots?
   ?c:? mov  0x0(%rip),%rax  # ?<?f2?>?
     # -> R_X86_64_REX_GOTPCRELX
   ?13:? mov  0x0(%rip),%rcx  # ?<?f1?>?
     # -> R_X86_64_REX_GOTPCRELX
   ?\minteddots?
   ?2b:? callq  *%rax
   ?2d:? callq  32  # ?<?f3?>?
     # -> R_X86_64_PLT32
   ?\minteddots?
```

b.c

```
1  void f1() { puts("f1\n"); }
2  void f2() { puts("f2\n"); }
3  void f3() {
4    void (*fp)() = &f2;
5    fp();
6  }
```

Compile
+endbr
+nop

b.o

```
?<?f1?>:?
   ?0:? ?\textcolor{\nopcolor}{nopl   (\%ra
   ?\minteddots?
   ?f:? callq  14  # ?<?puts?>?
     # -> R_X86_64_PLT32
   ?\minteddots?
?<?f2?>:?
   ?20:? ?\textcolor{\endbrcolor}{endbr64}?
   ?\minteddots?
   ?2f:? callq  34  # ?<?puts?>?
     # -> R_X86_64_PLT32
   ?\minteddots?
?<?f3?>:?
   ?40:? ?\textcolor{\nopcolor}{nopl   (\%ra
   ?\minteddots?
   ?4c:? mov  0x0(%rip),%rax  # ?<?f2?>?
     # -> R_X86_64_REX_GOTPCRELX
   ?\minteddots?
   ?59:? callq  *-0x8(%rbp)
   ?\minteddots?
```

Information Available

- Relocation info. for all input object files

Inserting `endbrs`

- Exported functions address-taken locally already have `endbrs`
- `R_X86_64_REX_GOTPCRELX` relocations for `f1` and `f2` so we add `endbrs`

Maintaining `nop`s

- The call to `f3` is relaxed and doesn't turn into a call via the PLT → `nop` stays

Information Available

- Exported functions in all loaded binaries
- Dynamic relocations from all loaded binaries

Metadata Collection

- `NOPoutNG` searches the `.dynsym` of all loaded objects, collecting:
  - All functions required (i.e., `SHN_UNDEF`, `STT_FUNC`)
  - All functions provided (i.e., defined, `STT_FUNC`)

Inserting `endbrs`

- Required functions provided get `endbrs`

Maintaining `nops`

- Provided functions **not** required keep `nops`

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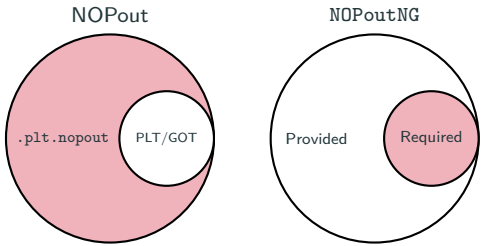

⚓ Hooking `dlopen` and `dlsym`

- Record the addresses of `dlopen` and `dlsym` in `libc.so` while iterating through its symbols
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Live-Patching Scheme

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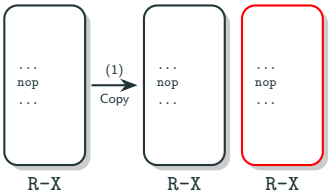

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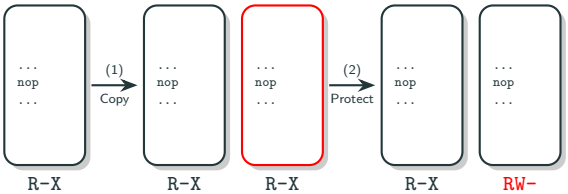

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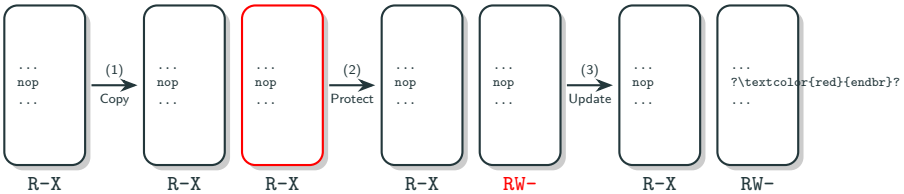

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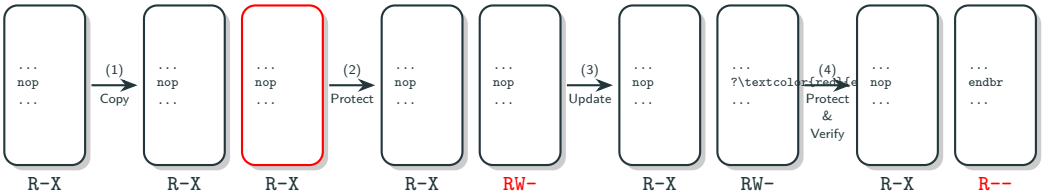

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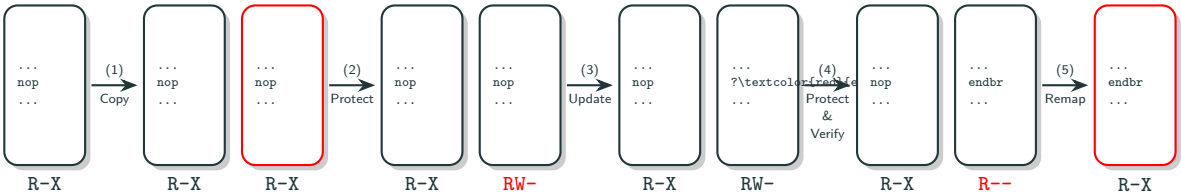

Toolchain Modifications

- Modified LLVM v12
  - Adds ≈100 C++ LoC to compiler
  - Adds ≈100 C++ LoC to (static) linker

Runtime Library

- Self-contained shared library, `libnopoutng.so`, ≈1250 C LoC
- File-system footprint ≈42KB
- Memory footprint ≈19KB
- `LD_PRELOAD` library to activate protection

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Machine Description

- CPU: Intel Core i7-11800H @ 2.3GHz
- Memory: 16GB of DDR4 RAM
- OS: Debian v11 with Linux kernel v5.13 (patched to support user-space IBT)
- DVFS disabled
- Forced C-state to be `C0`
- Single user mode enabled for "quiet" system

Software Description

- Hardened *all* benchmark applications and their dependencies
- Software built:
  - position independent
  - `-O2` optimization
  - full `RELRO` (incl. eager binding)
- `musl libc` used

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SPEC CPU 2017

- Motivation
  - Industry standard benchmark
  - Runtime reports include program startup time
- Setup
  - 8 C benchmarks from SPECspeed Int/FP suites
  - 5 runs of the `ref` workload
- Results
  - IBT overhead is minimal, ranging from ≈0%–5.03%
  - `NOPoutNG` adds negligible overhead to IBT

Benchmark	IBT	IBT + `NOPoutNG`
`600.perlbench`	5.03%	5.03%
`602.gcc`	0.77%	0.77%
`605.mcf`	0.06%	0.06%
`625.x264`	0.08%	0.15%
`657.xz`	0.43%	0.43%
`619.lbm`	≈0%	3.67%
`638.imagick`	0.08%	0.08%
`644.nab`	0.45%	0.45%

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Real-world Applications

- Motivation
  - Variety of real-world use-cases
- Setup
  - Networking performed over `lo`
  - Benchmarks were tuned to maximize CPU utilization
  - 10 runs of each benchmark
- Results
  - `NOPoutNG` adds negligible overhead

Benchmark	IBT	IBT + `NOPoutNG`
Nginx (1KB)	0.07%	0.07%
Nginx (100KB)	0.25%	0.25%
Nginx (1MB)	0.30%	1.56%
Redis (`GET`)	≈0%	≈0%
Redis (`SET`)	≈0%	≈0%
SQLite	≈0%	0.06%

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Dynamic Loading μBenchmark

- Motivation
  - Study the performance of our `dlopen`/`dlsym` implementation
- Setup
  - Compression sizes derived from the Calgary corpus*
  - Data was non-uniform and constant across runs
  - 100 benchmark iterations
- Results
  - `NOPoutNG` yields an average overhead of 13.23%

Dynamic Loading μBenchmark Design

- Allocate buffers *etc.*
- Start timing
  - `dlopen zlib`
  - `dlsym compress, uncompress, and crc32`
  - Checksum, compress, and uncompress 4 buffers
- Stop timing
- Free buffers *etc.*

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*T. Bell, I. H. Witten, and J. G. Cleary, "Modeling for Text Compression," ACM Computing Surveys (CSUR), vol. 21, no. 4, pp. 557–591, 1989.

Effectiveness

endbr Reduction

- Larger reduction equates to more security and a reduced attack surface.
- Across the board, we are able to reduce the number of endbr dynamically by 33.49%–86.40%.

Application	# endbr	
	IBT	NOPoutNG
Nginx	3244	1466 (-54.47%)
Redis	5413	3600 (-33.49%)
SQLite	2366	1111 (-53.04%)
600.perlbench	3758	1341 (-64.32%)
602.gcc	11512	4505 (-60.87%)
605.mcf	1746	403 (-76.92%)
625.x264	2141	646 (-69.83%)
657.xz	2057	519 (-74.77%)
619.lbm	1726	397 (-77.00%)
638.imagick	3639	495 (-86.40%)
644.nab	1891	429 (-77.31%)

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Comparison with NOPout

- The order of operations in `NOPoutNG` significantly reduces the amount of CoW work that needs to be performed.
- This increases the "shareability" of libraries.

Application	NOPout	NOPoutNG	
	+nop	+endbr	Pages
Nginx	1602 (92.44%)	131 (7.56%)	42 (172KB)
Redis	1656 (91.34%)	157 (8.66%)	53 (217KB)
SQLite	1101 (94.67%)	62 (5.33%)	25 (102KB)
`600.perlbench`	1089 (93.56%)	75 (6.44%)	27 (111KB)
`602.gcc`	1115 (95.46%)	53 (4.54%)	20 (82KB)
`605.mcf`	1156 (99.40%)	7 (0.60%)	5 (20KB)
`625.x264`	1158 (99.40%)	7 (0.60%)	4 (16KB)
`657.xz`	1150 (98.88%)	13 (1.12%)	9 (37KB)
`619.lbm`	1158 (99.57%)	5 (0.43%)	4 (16KB)
`638.imagick`	1156 (99.40%)	7 (0.60%)	4 (16KB)
`644.nab`	1138 (97.51%)	29 (2.49%)	18 (74KB)

Conclusion

! NOPout Problems

1. Order of Operations: `s/endbr/nop/` at runtime
2. Extraneous Metadata: Requires new ELF section
3. Dynamic Loading: Loose description, no evaluation
4. Limited Evaluation: No performance measurements

✓ `NOPoutNG` Solutions

1. Order of Operations: `s/nop/endbr/` at runtime
2. No Extra Metadata: Leverages existing data
3. Dynamic Loading: Implementation and evaluation
4. Thorough Evaluation: Performance measurements

Prototype Repository
https://gitlab.com/brown-ssl/nopoutng

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Backup

- Programs written in memory unsafe languages (e.g., C/C++, ASM) are prone to memory errors

Example

```
 1 int
 2 main(int argc, char *argv[])
 3 {
 4   int (*fptr)(void) = &foo;
 5   char arr[10];
 6   ...
 7   strcpy(arr, argv[1]);
 8   ...
 9   fptr();
10   ...
11 }
```

Repercussions

- Attackers can corrupt memory to perform control-flow hijacking
- Control-flow hijacking can be escalated to achieve arbitrary code execution

CFI Support

Toolchain Support

- Microsoft Visual C++ (MSVC)
  - Control Flow Guard (CFG) → forward-edge scheme that validates control-flow transfers via a bitmap
  - Extended Flow Guard (XFG) → forward-edge scheme that builds on CFG with a type-based policy
  - Intel CET (Shadow Stacks)
- LLVM/Clang
  - Clang CFI → forward-edge scheme with a type-based policy
  - ShadowCallStack (SCS) → backward-edge scheme to isolate return addresses
  - SafeStack → backward-edge scheme that splits the stack into safe and unsafe parts
  - Intel CET (Shadow Stacks and IBT)
- GCC
  - Virtual Table Verification (VTV) → for C++, verifies at runtime that vtable pointer and vtable object types match
  - Intel CET (Shadow Stacks and IBT)

Hardware Support

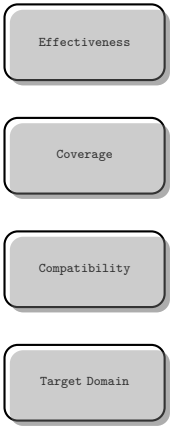
- Intel CET starting with "Tiger Lake" CPUs
- ARM BTI starting with ARMv8.5-A

Operating System Support

- Linux Kernel
  - kCFI → forward-edge scheme implemented in software that uses a type-based policy
  - IBT → HW-assisted, coarse-grain, forward-edge scheme
  - FineIBT → HW-assisted, fine-grain, forward-edge scheme
  - Userspace Shadow Stacks
- Windows Kernel
  - KCFG (Kernel Control Flow Guard) → kernel implementation of CFG

Control-flow Integrity Scheme Classifications

- CFI schemes can be classified according to 4 properties:



Control-flow Integrity Scheme Classifications

- CFI schemes can be classified according to 4 properties:

Effectiveness

Coverage

Compatibility

Target Domain

Effectiveness

- How many (code) locations an indirect branch can target

Coarse-grain schemes are overly permissive

Fine-grain schemes refine the set of allowed targets

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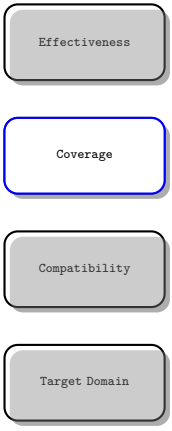
Control-flow Integrity Scheme Classifications

- CFI schemes can be classified according to 4 properties:



Coverage

- The type of control-flow transfers covered
  - Forward edges
    e.g., indirect calls/jumps
  - Backward edges
    e.g., returns

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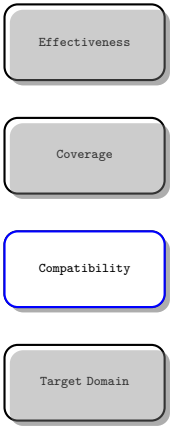
Control-flow Integrity Scheme Classifications

- CFI schemes can be classified according to 4 properties:



Compatibility

- What the scheme requires
  - Source code provides useful information
  - Binary data avoids recompilation
  - Different languages require different considerations

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- CFI schemes can be classified according to 4 properties:

Target Domain

- Where the scheme is applicable
  - User space
  - Kernel space
  - Embedded systems

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Notable Relocation Types

Relocation	Calculation
`R_X86_64_64`	$value + addend$
`R_X86_64_PC32`	$value + addend - offset$
`R_X86_64_PC64`	$value + addend - offset$
`R_X86_64_GOTPCREL`	$GOT.offset + \&GOT + addend - offset$
`R_X86_64_GOTPCRELX`	$GOT.offset + \&GOT + addend - offset$
`R_X86_64_REX_GOTPCRELX`	$GOT.offset + \&GOT + addend - offset$

Non-IBT PLT

```
1  PLT0: pushq    GOT?+?8(%rip)         /*  GOT[1]  */
2        jmp      *GOT?+?16(%rip)       /*  GOT[2]  */
3        nopl     0x0(%rax)           /*   PAD    */
4  ...
5  PLT3: jmp      *fsym3@GOT(%rip)    /*  GOT[5]  */
6        pushq    $0x2
7        jmp      PLT0
8  PLT4: jmp      *fsym4@GOT(%rip)    /*  GOT[6]  */
9        pushq    $0x3
10       jmp      PLT0
11 ...
12 PLTn: jmp      *fsymn@GOT(%rip)    /* GOT[n+2] */
13       pushq    $0xn-1
14       jmp      PLT0
```

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IBT PLT

```
1  PLT0: pushq    GOT?+?8(%rip)         /*  GOT[1]  */
2        jmp      *GOT?+?16(%rip)       /*  GOT[2]  */
3        nopl     0x0(%rax)             /*   PAD    */
4  ...
5  PLT3: endbr64
6        pushq    $0x2
7        jmp      PLT0
8        xchg     %ax,%ax               /*   PAD    */
9  PLT4: endbr64
10       pushq    $0x3
11       jmp      PLT0
12       xchg     %ax,%ax               /*   PAD    */
13 ...
14 PLTn: endbr64
15       pushq    $0xn-1
16       jmp      PLT0
17       xchg     %ax,%ax               /*   PAD    */
18
19 ...
20 SPLT3: endbr64
21        jmp      *fsym3@GOT(%rip)    /*  GOT[5]  */
22        nopw     0x0(%rax,%rax,1)    /*   PAD    */
23 SPLT4: endbr64
24        jmp      *fsym4@GOT(%rip)    /*  GOT[6]  */
25        nopw     0x0(%rax,%rax,1)    /*   PAD    */
26 ...
27 SPLTn: endbr64
28        jmp      *fsymn@GOT(%rip)    /* GOT[n+2] */
29        nopw     0x0(%rax,%rax,1)    /*   PAD    */
```

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FineIBT PLT

```
1  PLT0:    shl    $0x20, %rax
2           or     $SID, %rax
3           pushq  GOT?+?8(%rip)          /* GOT[1] */
4           jmp    *GOT?+?16(%rip)        /* GOT[2] */
5           nopw   %cs:0x0(%rax,%rax,1) /*  PAD   */
6  ...
7  PLT4:    endbr64
8           cmp    $SID, %eax
9           pushq  $0x3
10          xchg   %ax, %ax              /*  PAD   */
11          je     PLT0
12          hlt
13          nopw   0x0(%rax,%rax,1)      /*  PAD   */
14 ...
15 FPLT4:   mov    $SID, %eax
16          jmp    *fsym4@GOT(%rip)      /* GOT[6] */
17          nopl   0x0(%rax,%rax,1)      /*  PAD   */
18 ...
19 ATFPLT4: endbr64
20          sub    $SID, %eax
21          je     FPLT4
22          hlt
23          data16 nopw %cs:0x0(%rax,%rax,1) /*PAD*/
24          nopl   (%rax)                /*  PAD   */
```

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ARM Instrumentation (FineBTI)

```
1  main:                        /* caller */
2    ...
3    movz w9, #0x3a, lsl #16    /* SID = 0x3a0000 */
4    blr  x0                    /* x0 = &func */
5    ...
6    bl   func_entry
7    ...
8  .func_finebti_coldpath:
9    ...                        /* arg0, ..., argn */
10   bl   __finebti_chk_fail@PLT
11 func:                        /* callee */
12   bti  c
13   subs w9, w9, #0x3a0, lsl #12 /* SID=0x3a0000 */
14   bne  .func_finebti_coldpath
15 func_entry:
16   ...
```

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