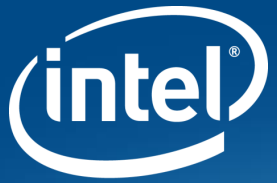

CONTROL-FLOW ENFORCEMENT TECHNOLOGY

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Intel

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Introduction

Control-flow Enforcement Technology (CET)

- An upcoming Intel® processor family feature that blocks return/jump-oriented programming (ROP) attacks
- Two components:
  - Shadow Stack (SHSTK)
  - Indirect Branch Tracking (IBT)

Control-flow Definition

The code execution path, branched by RET, JMP, or CALL.

Op Code	Operand
RET	On program stack
JMP *%rax	In memory (%rax as a pointer)
CALL *%rax	In memory (%rax as a pointer)

Shadow Stack Management

- Most of programs are compatible with SHSTK. No special treatment is needed.
- Exception handling
- Increment shadow stack pointer by the same amount.
- setjmp and longjmp
  - Save shadow stack pointer. Increment shadow stack pointer until the old value is restored.
  - ucontext

  Allocate a new shadow stack for each user provided stack with a restore token.

  Use restore token to switch shadow stack.

Indirect Branch Tracking

- All indirect branch targets must start with ENDBR64/ENDBR32.
  - ENDBR64/ENDBR32 is NOP on non-CET processors.
- The “notrack” prefix before indirect branches disables IBT.
- Optional legacy bitmap to disable IBT on legacy libraries

Mark CET-enabled Applications

- CET enabled binary must be marked.
  - A binary is marked as CET enabled only if all its components are marked as CET enabled.
- CET enabled programs are binary compatible with legacy processors.
  - CET is enabled at run-time only for CET enabled programs on CET processors.
- Linker is updated to:
  - Properly mark programs as CET enabled when all its components are marked as CET enabled.
  - Place ENDBR at all linker generated indirect branch targets.
- Kernel loader and dynamic loader are updated to properly enable CET for CET enabled programs on CET processors.

Enable CET in GCC

- Place ENDBR at all potential indirect branch targets.
- Unwind shadow stack for stack unwind intrinsics.
- Generate CET marker when CET is enabled.
- Provide a header file to generate CET marker in assembly codes.

Enable CET in Run-time Libraries

- Place ENDBR at all indirect branch targets in assembly codes.
- Mark all assembly codes as CET enabled.
- Unwind shadow stack when unwinding normal stack, including C++ exception.
  - Count number of stack frames to unwind. Increment shadow stack pointer by the same amount.
- setjmp and longjmp
  - Save shadow stack pointer. Increment shadow stack pointer until the old value is restored.
- ucontext:
  - Allocate a new shadow stack for each user provided stack with a restore token.
  - Use restore token to switch shadow stack.

Enable CET in Applications

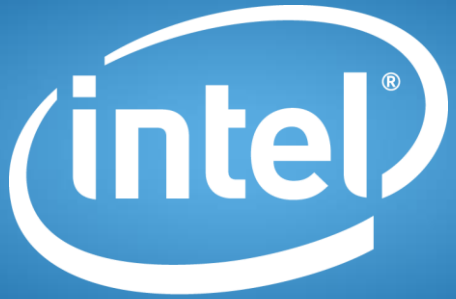
- For C/C++ sources, compile with -fcf-protection.
- For assembly sources:
  - Place ENDBR at all potential indirect branch targets in assembly codes.
  - Mark all assembly codes as CET enabled.

Status

- Specification is available by searching **“Intel CET”** or at:

  https://software.intel.com/sites/default/files/managed/4d/2a/control-flow-enforcement-technology-preview.pdf

- CET has been enabled in
  - GCC 8
  - binutils 2.31
  - glibc 2.28
- CET can be enabled in OS piece by piece
  - Start with GCC, glibc and binutils.
- Linux* kernel patches have been submitted to upstream.
  - https://github.com/yyu168/linux_cet



Software

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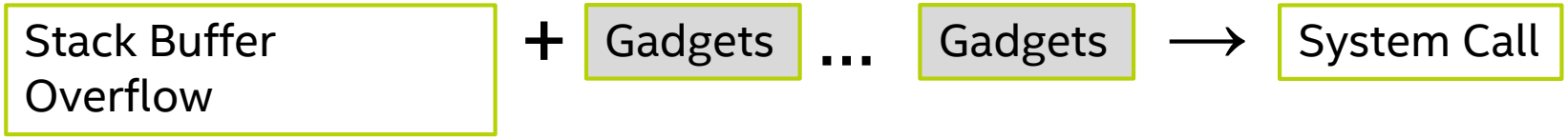
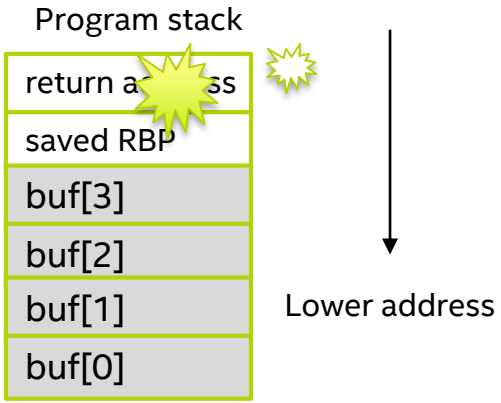
Return/Jump Oriented Programming (ROP) Attacks



No code injection is needed!

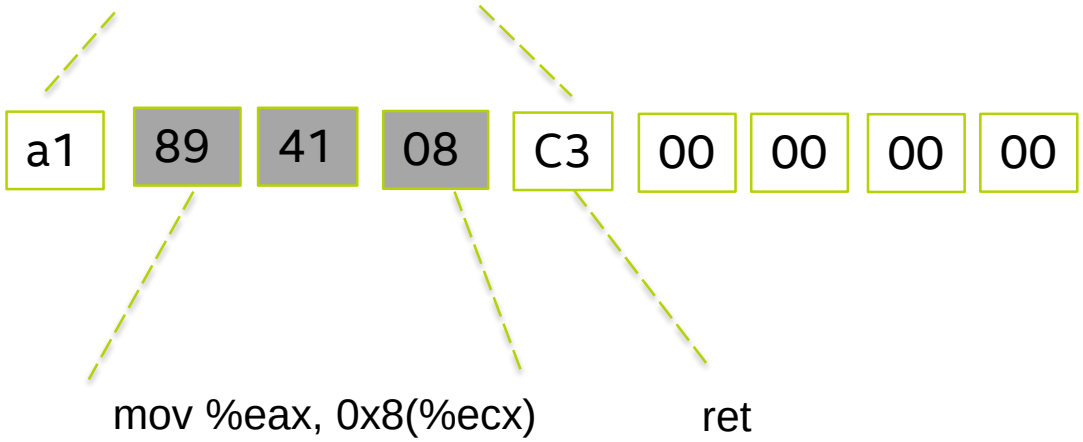
The Stack Buffer Overflow

```
void copy_string(char *input)
{
  char buf[4];
  memcpy(buf, input, strlen(input));
}
```

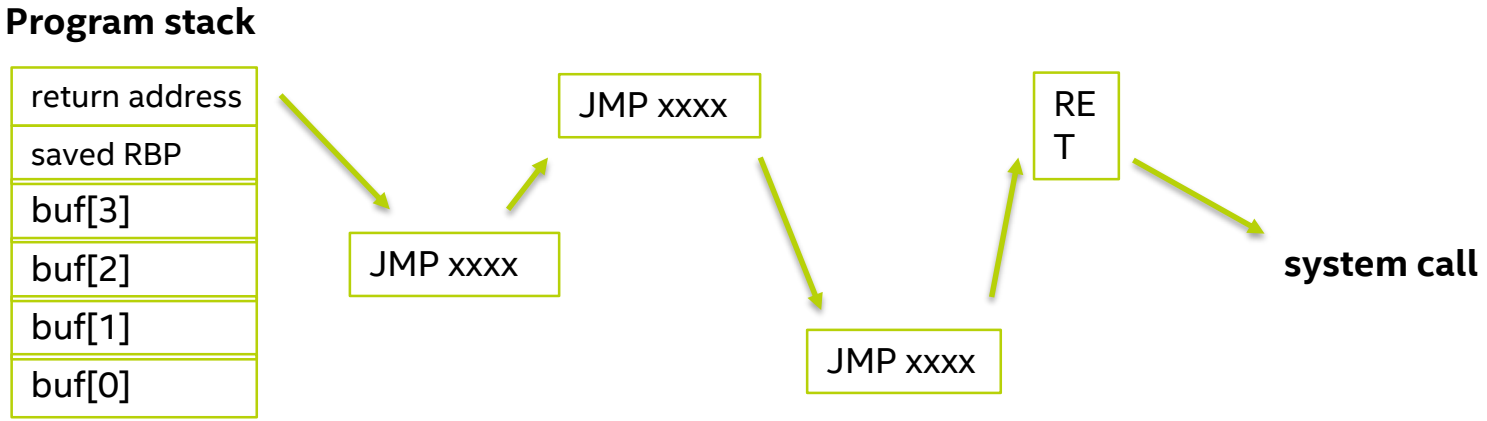


A Code Gadget Example

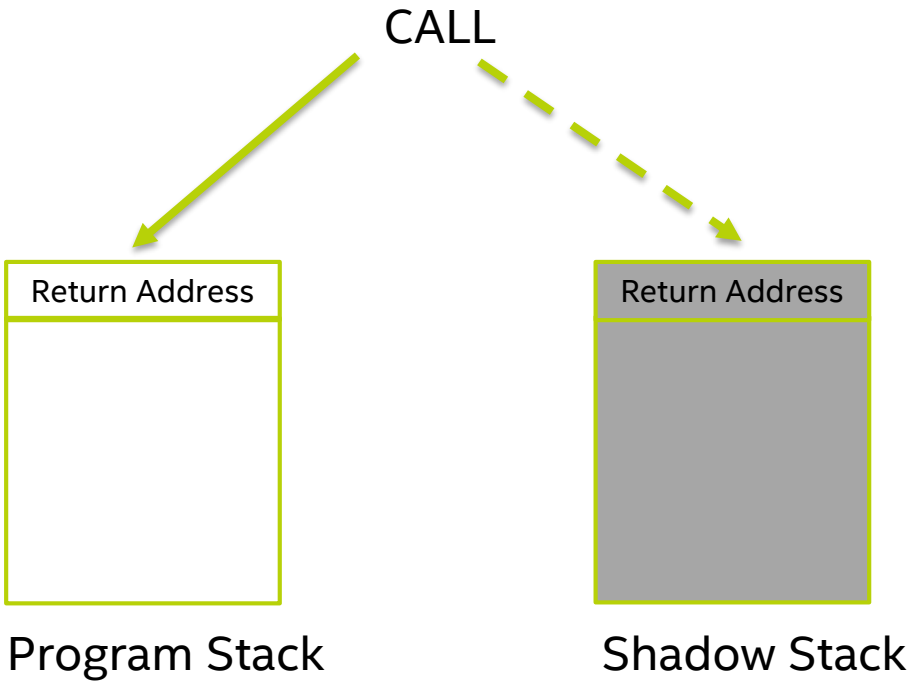
mov 0xc3084189, %eax



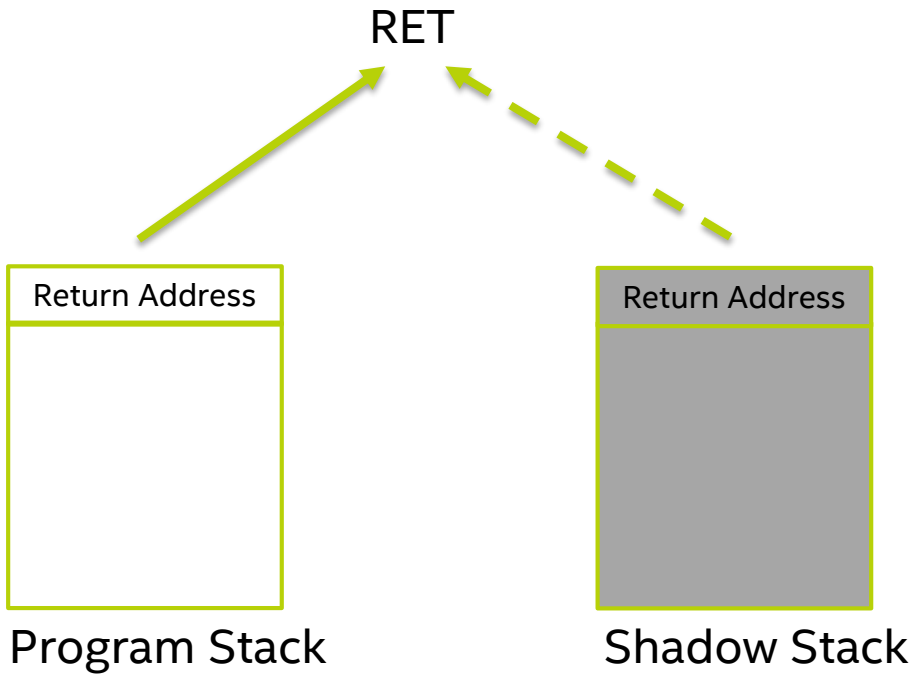
The ROP Attack



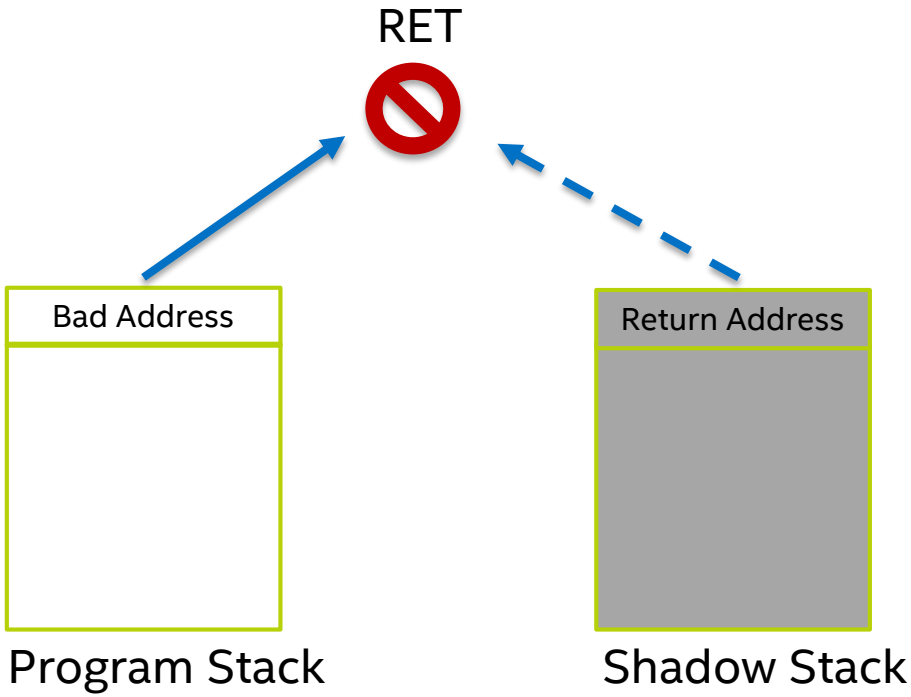
Shadow Stack Concept



Shadow Stack -- Return Address Matching



Shadow Stack Exception



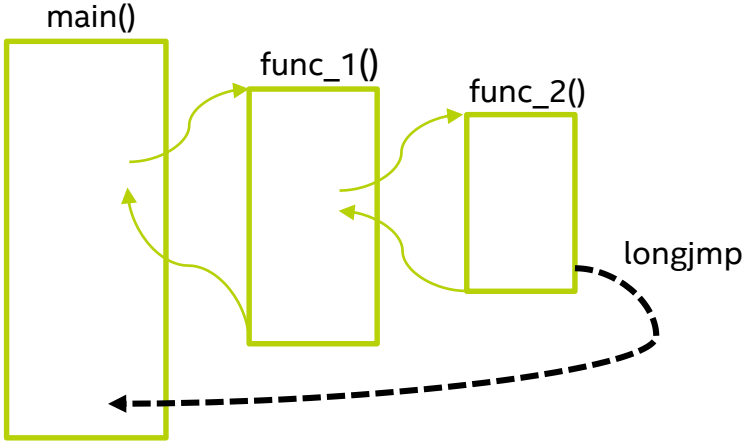
New CET Instructions

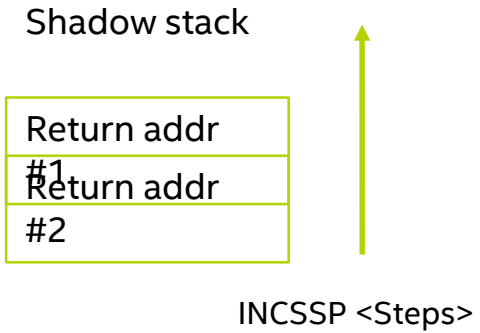
- RDSSP – Read shadow stack pointer
- INCSSP – Shadow stack unwinding

- RSTORSSP, SAVEPREVSSP – Shadow stack context switching
- SETSSBSY, CLRSSBSY – Mark shadow stack in-use

- ENDBR, No-Track – Indirect branch tracking

Shadow Stack Unwinding





Indirect Branch Tracking (IBT)

```
main() {
     int (*f)();
     f = test;
     f();
}

int test() {
     return
}
```

```
<main>:
ENDBR
:
movq    $0x4004fb, -8(%rbp)
mov     -8(%rbp), %rdx
call    *%rdx
:
retq

<test>:
ENDBR
:
add rax, rbx
:
retq
```