Binary analysis: Defense Mechanism

Yue Duan

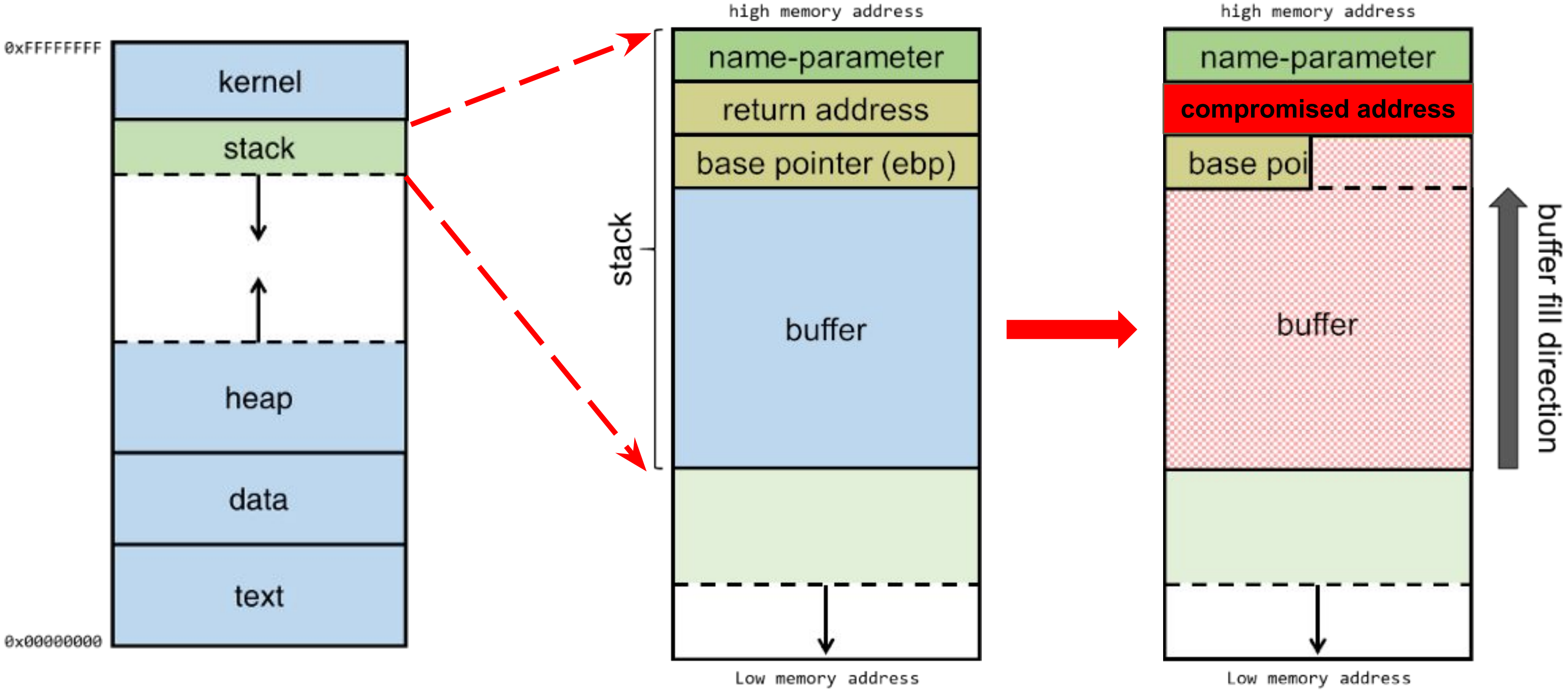
Outline

- Control-flow problems
- Simple defense mechanisms
- Research paper:
    - Control-Flow Integrity

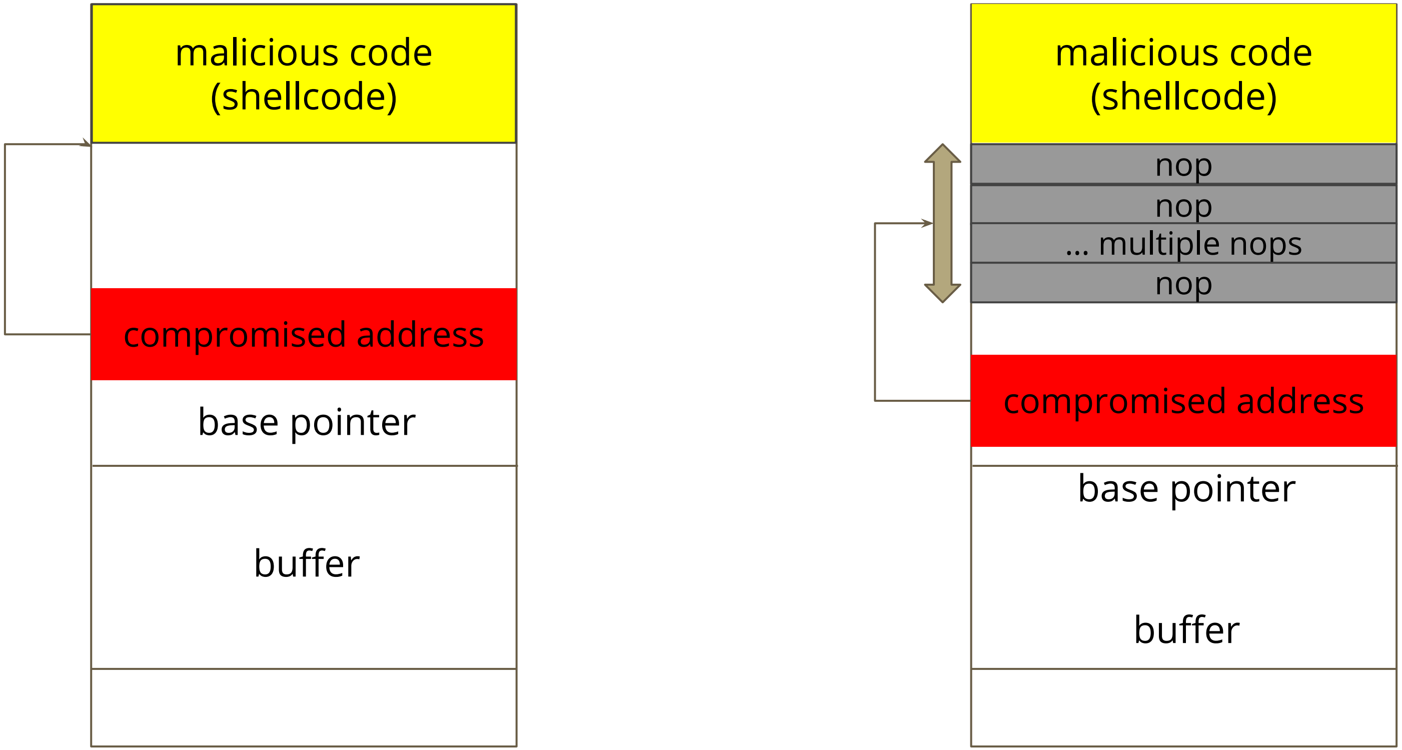
Control-flow Violation

```c
#include <stdio.h>
int main(int argc, char **argv)
{
    char buf[8]; // buffer for eight characters
    gets(buf); // read from stdio (sensitive function!)
    printf("%s\n", buf); // print out data stored in buf
    return 0; // 0 as return value
}
```

Control-flow Violation



Control-flow Violation



Shellcode

```
#include <stdio.h>

int main( ) {
    char *name[2];

    name[0] = ``/bin/sh'';
    name[1] = NULL;
    execve(name[0], name, NULL);
}
```

```
Line 1:  xorl    %eax,%eax
Line 2:  pushl   %eax          # push 0 into stack (end of string)
Line 3:  pushl   $0x68732f2f   # push "//sh" into stack
Line 4:  pushl   $0x6e69622f   # push "/bin" into stack
Line 5:  movl    %esp,%ebx     # %ebx = name[0]
Line 6:  pushl   %eax          # name[1]
Line 7:  pushl   %ebx          # name[0]
Line 8:  movl    %esp,%ecx     # %ecx = name
Line 9:  cdq                   # %edx = 0
Line 10: movb    $0x0b,%al
Line 11: int     $0x80         # invoke execve(name[0], name, 0)
```

Steps

- insert shellcode into somewhere in memory
- overwrite return address with shellcode's address
- when function returns, shellcode will be executed
- a shell will be launched
- if the vulnerable program happens to be root-owned SetUID program

Fundamental Problems

- No distinguishment between code and data
  - data in the process can be interpreted as code
- Attacker can easily redirect control flow to the injected data (code)

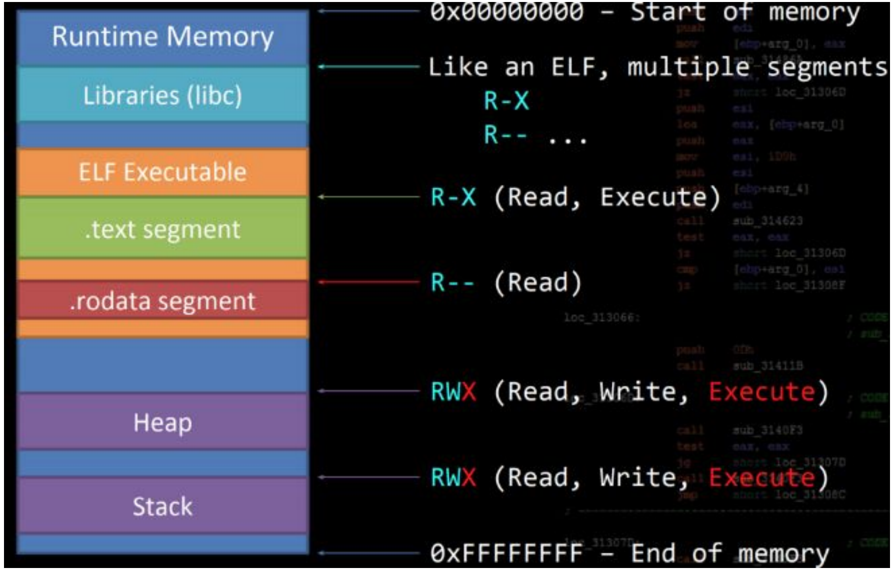
Simple Defense Mechanisms

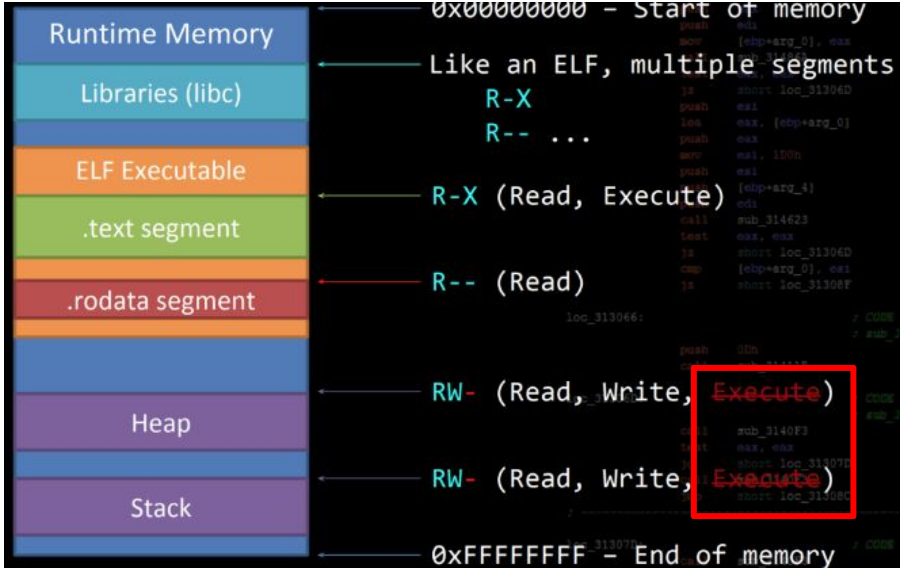
- Data Execution Prevention (DEP)
- Address Space Layout Randomization (ASLR)
- Stack Canary

Data Execution Prevention

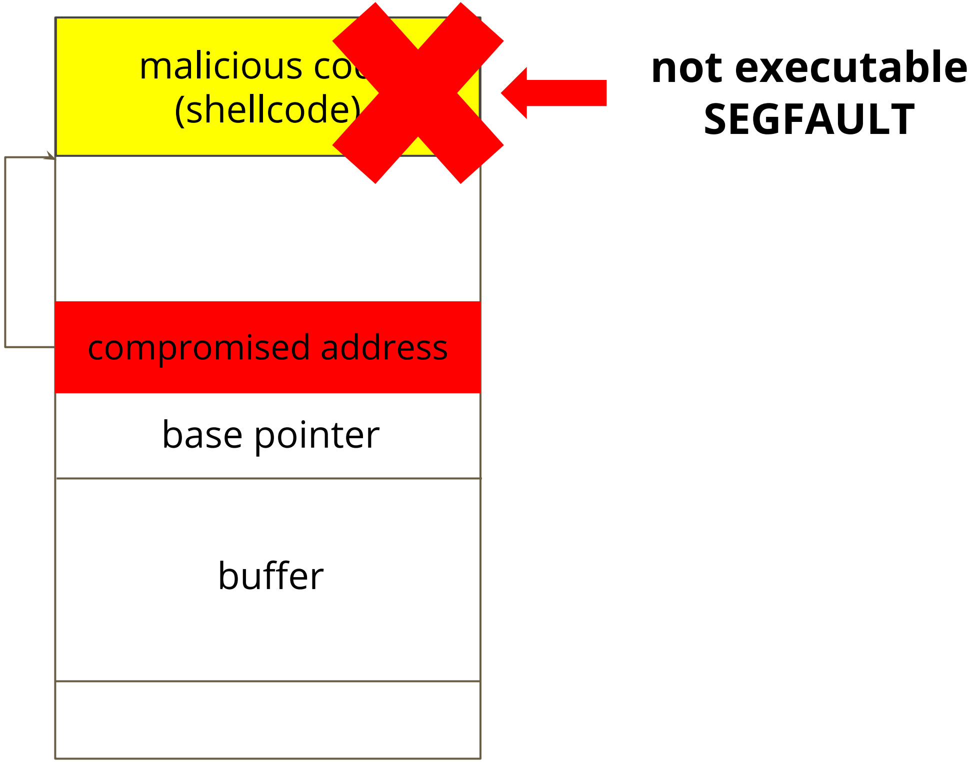
- System-level memory protection feature
- DEP prevents code from being run from data pages
  - heap, stacks, etc
- If an application attempts to run
  - memory access violation exception is raised
  - process is terminated

Data Execution Prevention





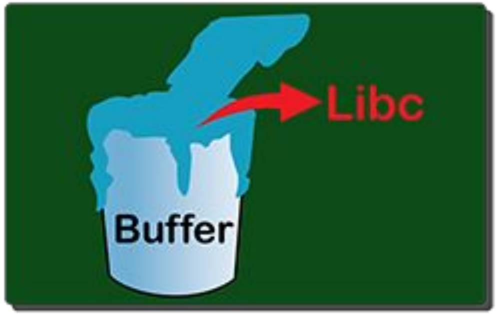
Data Execution Prevention



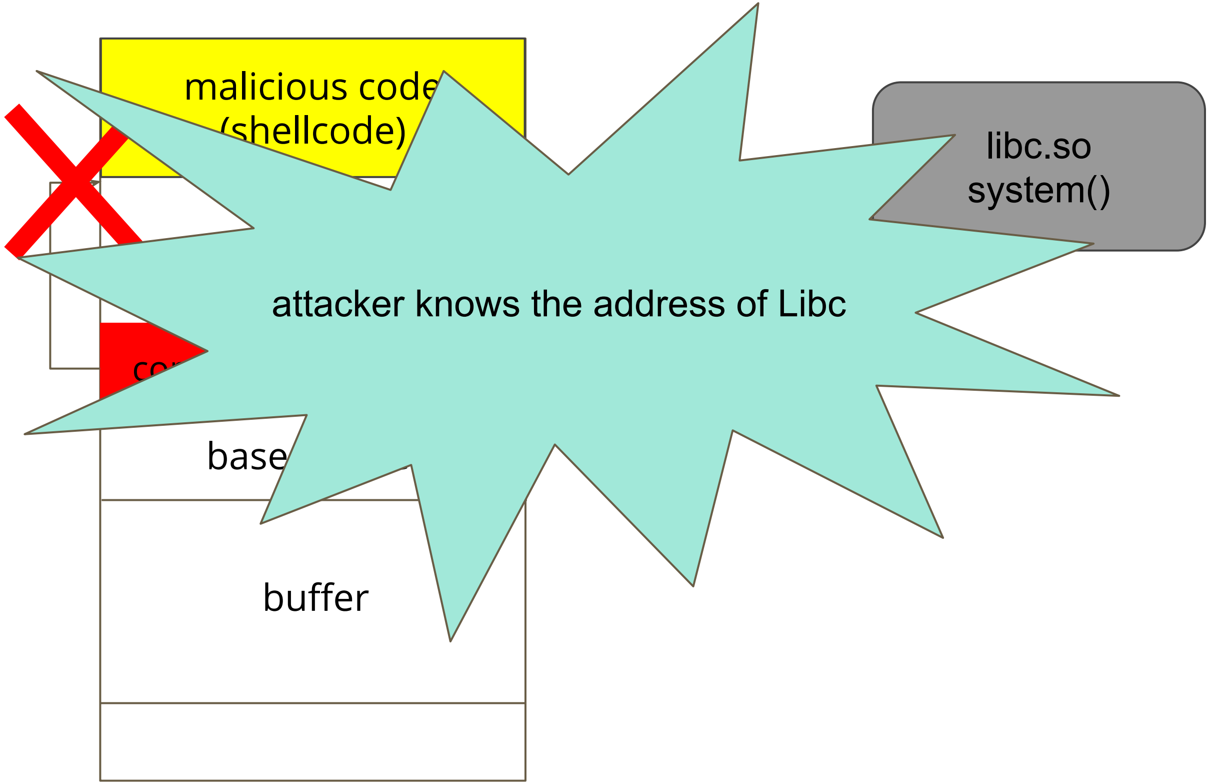
Evasion

- What if ...
  - attacker does not inject code
  - in stead, he reuses existing code

Return-to-libc attack : reuse code in Libc



Return-to-Libc



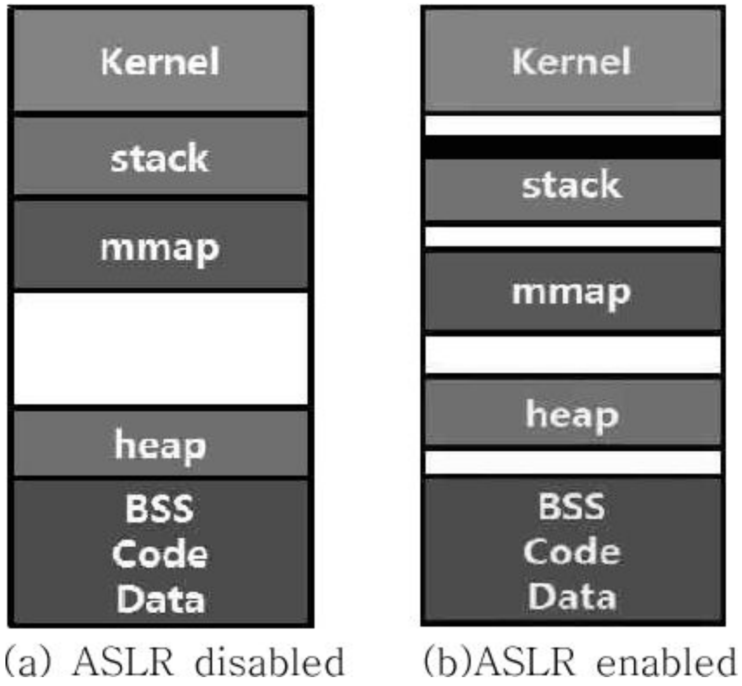
Address Space Layout Randomization (ASLR)

- Multiple attacks rely on guessing addresses
  - inject shellcode
  - return-to-libc

- Key idea:
  - Can we make the guessing practically impossible?

Address Space Layout Randomization (ASLR)

- Randomize the address space positions
  - base of the executable
  - stack
  - heap
  - libraries
- Possible evasions
  - bruteforce
  - information leakage
  - return-oriented programming (ROP)

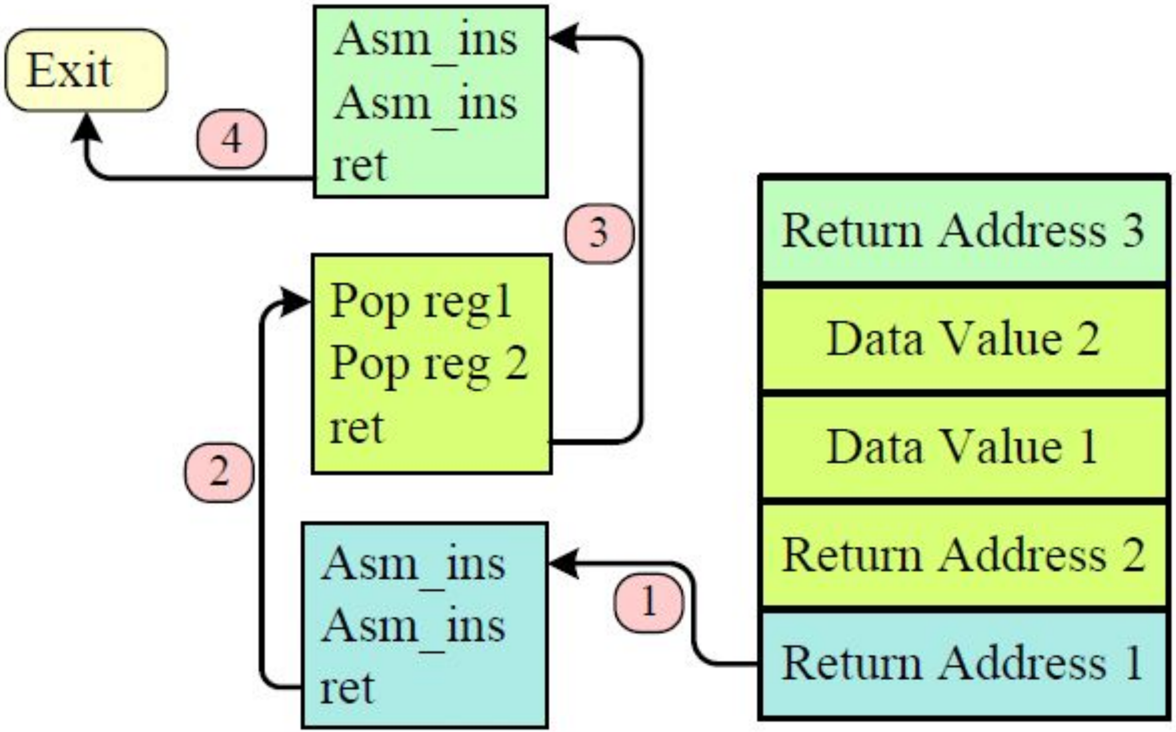


Return-Oriented Programming (ROP)

- Key idea:
  - reuse existing code without knowing the exact addresses
  - find meaningful code ‘gadgets’
  - chain ‘gadgets’ together with return to complete a malicious action

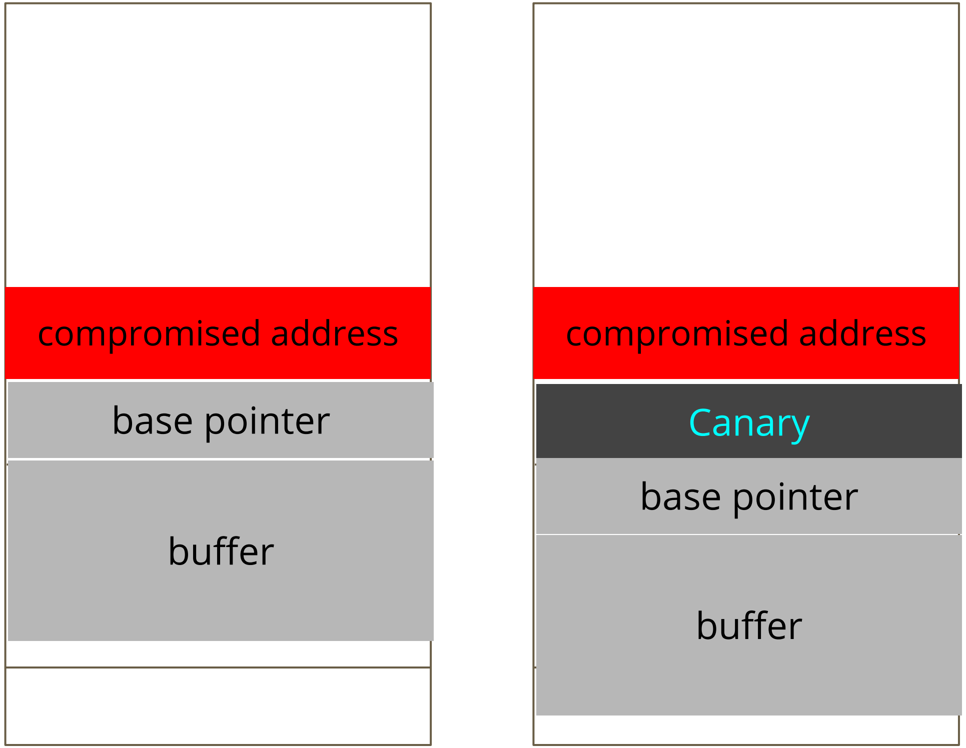
```
xor eax, eax
ret

pop ebx
pop eax
ret

add eax, ebx
ret
```

Return-Oriented Programming (ROP)



Stack Canary

- Also called StackGuard
- random integer
    - next to the return address
- before return, always check if
    - canary has been changed
- Built-in feature for most of the modern compilers
- Can be guessed



Control-Flow Integrity

M Abadi, M Budiu, Ú Erlingsson, J Ligatti

ACM CCS 2005

Motivation

- Many attacks involve control-flow hijacking
- Existing defense mechanisms
  - either impractical
  - or need hardware support
- Fundamental limitations
  - lack of a realistic attack model
  - reliance on informal reasoning and hidden assumptions

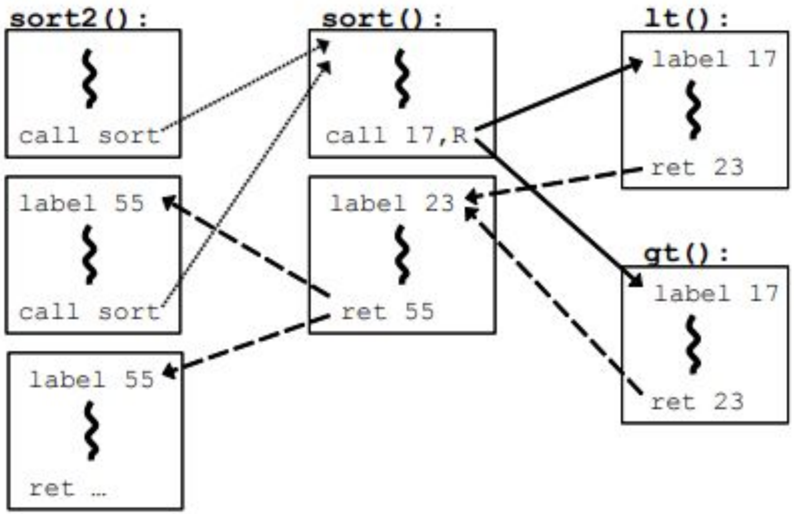
- Major challenge: How to protect control-flow from being hijacked?

Control-Flow Integrity

- Key idea:
    - execution should always follow the pre-defined control flow (CFI security policy)!
- CFI policy
    - extracted from Control-flow graph (CFG)
    - enforced at runtime with checks

Example

```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
}

sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```



CFI Enforcement

- For each control transfer, such as a function call
  - statically determine its possible destinations
- Insert a unique bit pattern at every destination
  - two destinations are considered equivalent if CFG contains edges to each from the same source
- Insert codes that
  - enforce runtime check
  - whether the bit pattern of the target instruction matches the pattern of possible destinations
- Done by binary instrumentation technique

CFI Enforcement - jmp

original code

Opcode bytes	Instructions		Opcode bytes	Instructions	
FF E1	jmp ecx	; computed jump	8B 44 24 04	mov eax, [esp+4]	; dst
			...		

instrumentation (a)

```
81 39 78 56 34 12   cmp   [ecx], 12345678h   ; comp ID & dst      78 56 34 12   ; data 12345678h   ; ID
75 13               jne   error_label        ; if != fail         8B 44 24 04   mov  eax, [esp+4]  ; dst
8D 49 04            lea   ecx, [ecx+4]       ; skip ID at dst     ...
FF E1               jmp   ecx                ; jump to dst
```

instrumentation (b)

```
B8 77 56 34 12   mov   eax, 12345677h   ; load ID-1        3E 0F 18 05   prefetchnta        ; label
40               inc   eax              ; add 1 for ID     78 56 34 12       [12345678h]    ;    ID
39 41 04         cmp   [ecx+4], eax     ; compare w/dst    8B 44 24 04   mov  eax, [esp+4]  ; dst
75 13            jne   error_label      ; if != fail       ...
FF E1            jmp   ecx              ; jump to label
```

CFI Enforcement - ret

original code

Opcode bytes	Instructions	
FF 53 08	call [ebx+8]	; call fptr

Opcode bytes	Instructions	
C2 10 00	ret 10h	; return

instrumentation

```
8B 43 08                 mov   eax, [ebx+8]            ; load fptr
3E 81 78 04 78 56 34 12  cmp   [eax+4], 12345678h      ; comp w/ID
75 13                    jne   error_label             ; if != fail
FF D0                    call  eax                     ; call fptr
3E 0F 18 05 DD CC BB AA  prefetchnta [AABBCCDDh]       ; label ID
```

```
8B 0C 24      mov   ecx, [esp]       ; load ret
83 C4 14      add   esp, 14h         ; pop 20
3E 81 79 04   cmp   [ecx+4],         ; compare
DD CC BB AA         AABBCCDDh        ;      w/ID
75 13         jne   error_label      ; if!=fail
FF E1         jmp   ecx              ; jump ret
```

CFI Precision

- Assume that:
  - A() calls C()
  - B() calls C() or D() (When can this happen?)
- CFI will use the same tag for C and D
  - allow A to call D
- Possible solutions:
  - duplicate code or inlining
  - multiple tags

CFI Precision

- function F() is called twice from A() and B()
  - CFI uses the same tag for both call sites
  - allow F() to return to B() after being called from A()
- Solution: shadow call stack
  - always guarantee the return to the latest call site

```
call  eax                ; call func ptr              ret                 ; return
```

with a CFI-based implementation of a protected shadow call stack using hardware segments, can become:

```
add   gs:[0h], 4h        ; inc stack by 4             mov   ecx, gs:[0h]    ; get top offset
mov   ecx, gs:[0h]       ; get top offset             mov   ecx, gs:[ecx]   ; pop return dst
mov   gs:[ecx], LRET     ; push ret dst               sub   gs:[0h], 4h     ; dec stack by 4
cmp   [eax+4], ID        ; comp fptr w/ID             add   esp, 4h         ; skip extra ret
jne   error_label        ; if != fail                 jmp   ecx             ; jump return dst
call  eax                ; call func ptr
```

Evaluation: performance overhead

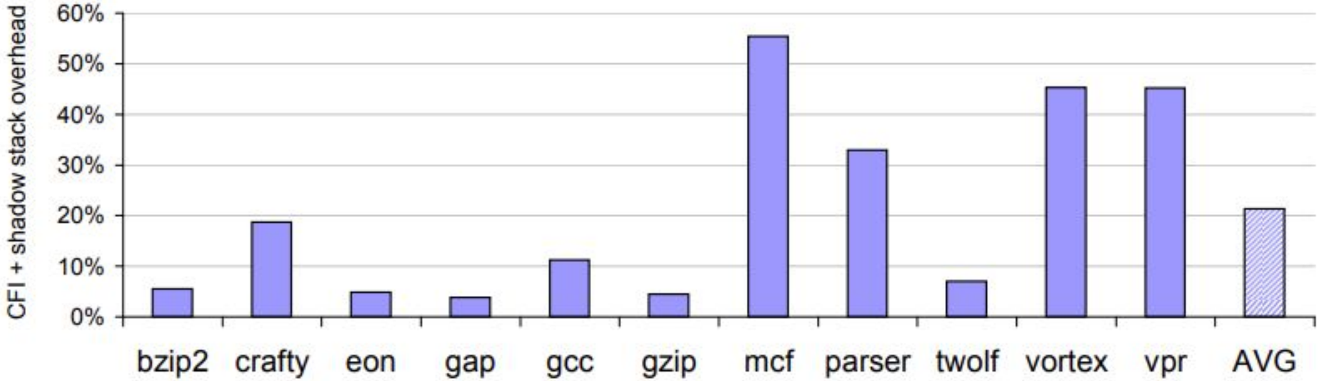


Figure 8: Enforcement overhead for CFI with a protected shadow call stack on SPEC2000 benchmarks.

- modest performance overhead
  - on average 21%
  - 5% for gzip and 11% for gcc

Thank you!

Question?