Systems and Internet Infrastructure Security

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Advanced Systems Security: Control-Flow Integrity

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Vulnerability

- How do you define computer ‘vulnerability’?

Buffer Overflow

- First and most common way to take control of a process
- Attack code
  - Call the victim with inputs necessary to overflow buffer
  - Overwrites the return address on the stack
- Exploit
  - Jump to attacker chosen code
  - Run that code

Determine what to attack

- Local variable that is a char buffer
  - Called buf

```
...
printf("BEFORE picture of stack\n");
for ( i=((unsigned) buf-8); i<((unsigned) ((char *)&ct)+8); i++ )
  printf("%p: 0x%x\n", (void *)i, *(unsigned char *) i);

/* run overflow */
for ( i=1; i<tmp; i++ ){
  printf("i = %d; tmp= %d; ct = %d; &tmp = %p\n", i, tmp, ct, (void *)&tmp);
   strcpy(p, inputs[i]);

  /* print stack after the fact */
  printf("AFTER iteration %d\n", i);
  for ( j=((unsigned) buf-8); j<((unsigned) ((char *)&ct)+8); j++ )
    printf("%p: 0x%x\n", (void *)j, *(unsigned char *) j);

   p += strlen(inputs[i]);
  if ( i+1 != tmp )
    *p++ = ' ';
 }
printf("buf = %s\n", buf);
printf("victim: %p\n", (void *)&victim);

return 0;
}
```

```
BEFORE picture of stack
0xbfa3b854: 0x3
0xbfa3b855: 0x0
0xbfa3b856: 0x0
0xbfa3b857: 0x0
0xbfa3b858: 0x3
0xbfa3b859: 0x0
0xbfa3b85a: 0x0
0xbfa3b85b: 0x0
0xbfa3b85c: 0x0
0xbfa3b85d: 0x0
0xbfa3b85e: 0x0
0xbfa3b85f: 0x0
0xbfa3b860: 0x0
0xbfa3b861: 0x0
0xbfa3b862: 0x0
0xbfa3b863: 0x0
0xbfa3b864: 0x0
0xbfa3b865: 0x0
0xbfa3b866: 0x0
0xbfa3b867: 0x0
0xbfa3b868: 0xa8
0xbfa3b869: 0xb8
0xbfa3b86a: 0xa3
0xbfa3b86b: 0xbf
0xbfa3b86c: 0x71
0xbfa3b86d: 0x84
0xbfa3b86e: 0x4
0xbfa3b86f: 0x8
0xbfa3b870: 0x3
0xbfa3b871: 0x0
0xbfa3b872: 0x0
0xbfa3b873: 0x0
```

buf

ebp

rtn addr

ct

Configure Attack

- Configure following
  - Distance to return address from buffer
    - Where to write?
  - Location of start of attacker's code
    - Where to take control?
  - What to write on stack
    - How to invoke code (jump-to existing function)?
  - How to launch the attack
    - How to send the malicious buffer to the victim?

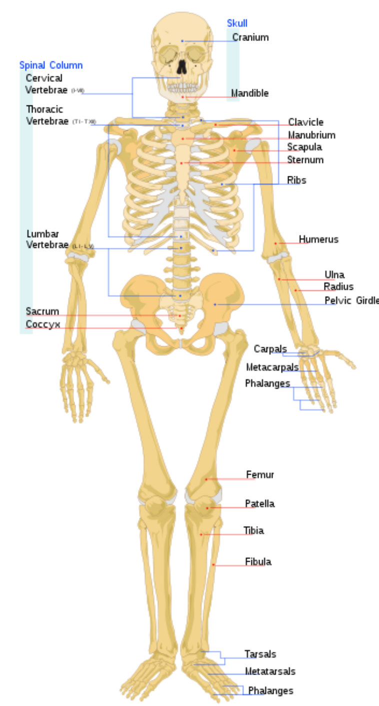
Return Address

- x86 Architecture
  - Build 32-bit code for Linux environment
- Remember integers are represented in "little endian" format
- Take address 0x8048471
  - See trace at right

```
BEFORE picture of stack
0xbfa3b854: 0x3
0xbfa3b855: 0x0
0xbfa3b856: 0x0
0xbfa3b857: 0x0
0xbfa3b858: 0x3      buf
0xbfa3b859: 0x0
0xbfa3b85a: 0x0
0xbfa3b85b: 0x0
0xbfa3b85c: 0x0
0xbfa3b85d: 0x0
0xbfa3b85e: 0x0
0xbfa3b85f: 0x0
0xbfa3b860: 0x0
0xbfa3b861: 0x0
0xbfa3b862: 0x0
0xbfa3b863: 0x0
0xbfa3b864: 0x0
0xbfa3b865: 0x0
0xbfa3b866: 0x0
0xbfa3b867: 0x0
------------------------------
0xbfa3b868: 0xa8
0xbfa3b869: 0xb8
0xbfa3b86a: 0xa3     ebp
0xbfa3b86b: 0xbf
------------------------------
0xbfa3b86c: 0x71
0xbfa3b86d: 0x84     rtn addr
0xbfa3b86e: 0x4
0xbfa3b86f: 0x8
------------------------------
0xbfa3b870: 0x3
0xbfa3b871: 0x0
0xbfa3b872: 0x0      ct
0xbfa3b873: 0x0
```

Anatomy of Control Flow Attacks

- Two steps
- First, the attacker changes the control flow of the program
  - In buffer overflow, overwrite the return address on the stack
  - What are the ways that this can be done?
- Second, the attacker uses this change to run code of their choice
  - In buffer overflow, inject code on stack
  - What are the ways that this can be done?



Return-oriented Programming

- General approach to control flow attacks
- Demonstrates how general the two steps of a control flow attack can be
- First, change program control flow
  - In any way
- Then, run any code of attackers' choosing - code in the existing program
  - From starting address (gadget) to ret

ROP

- Use ESP as program counter
  - E.g., Store 5 at address 0x8048000
    - without introducing new code

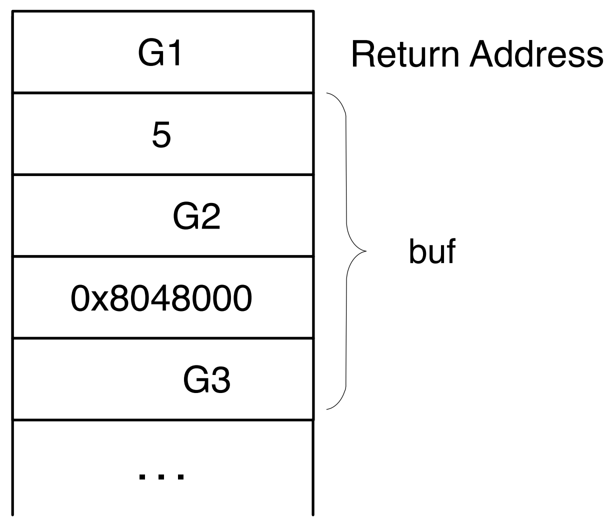
Code

```
pop %eax
ret

pop %ebx
ret

movl %eax, (%ebx)
    ret
```

Stack



Registers

%eax =

%ebx =

Memory

0x8048000 =

ROP

- Use ESP as program counter
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Code

G!: pop %eax
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G2: pop %ebx
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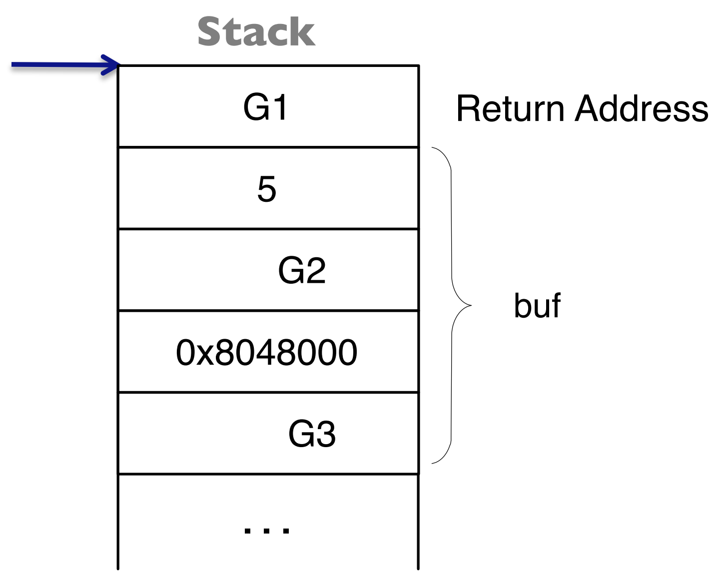
ret



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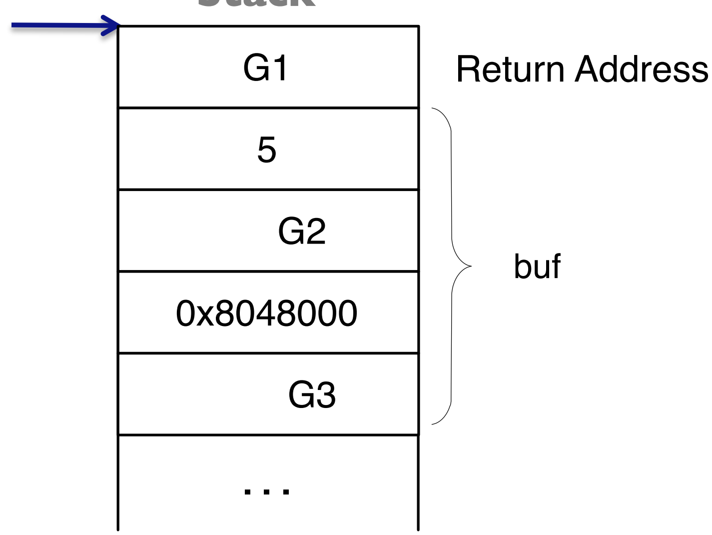

Registers

%eax =

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Memory

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ROP

PENNSTATE 1855

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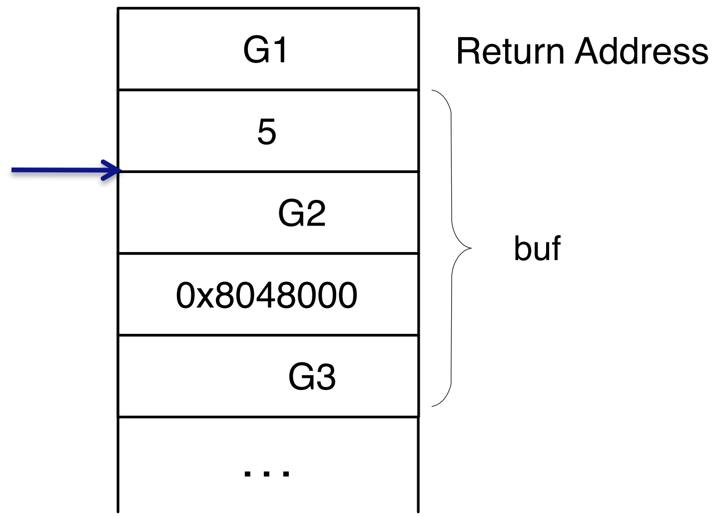

Registers

%eax = 5

%ebx =

Memory

0x8048000 =

ROP

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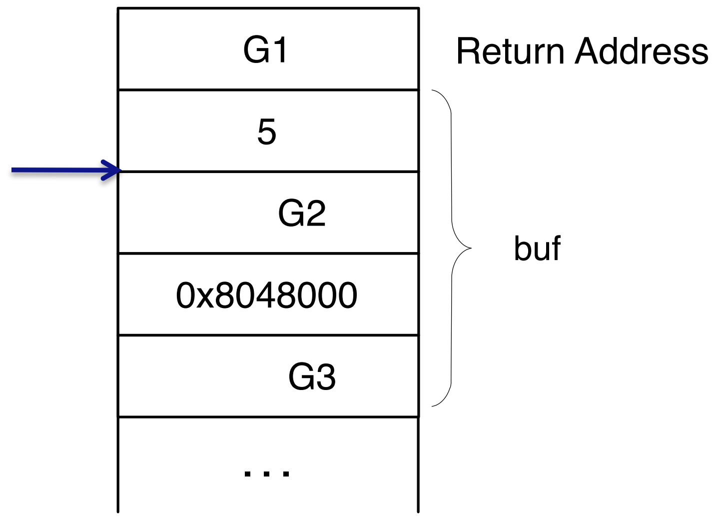

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Memory

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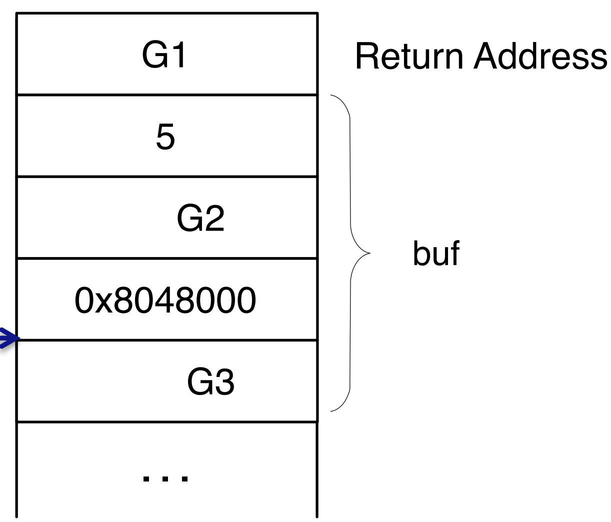
Stack



Registers

%eax = 5

%ebx = 0x8048000

Memory

0x8048000 =

ROP

PENNSTATE

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Code

G!: pop %eax
ret

G2: pop %ebx
ret

G3: movl %eax, (%ebx)
ret

Stack

G1
5
G2
0x8048000
G3
. . .

Return Address

buf

Registers

%eax = 5

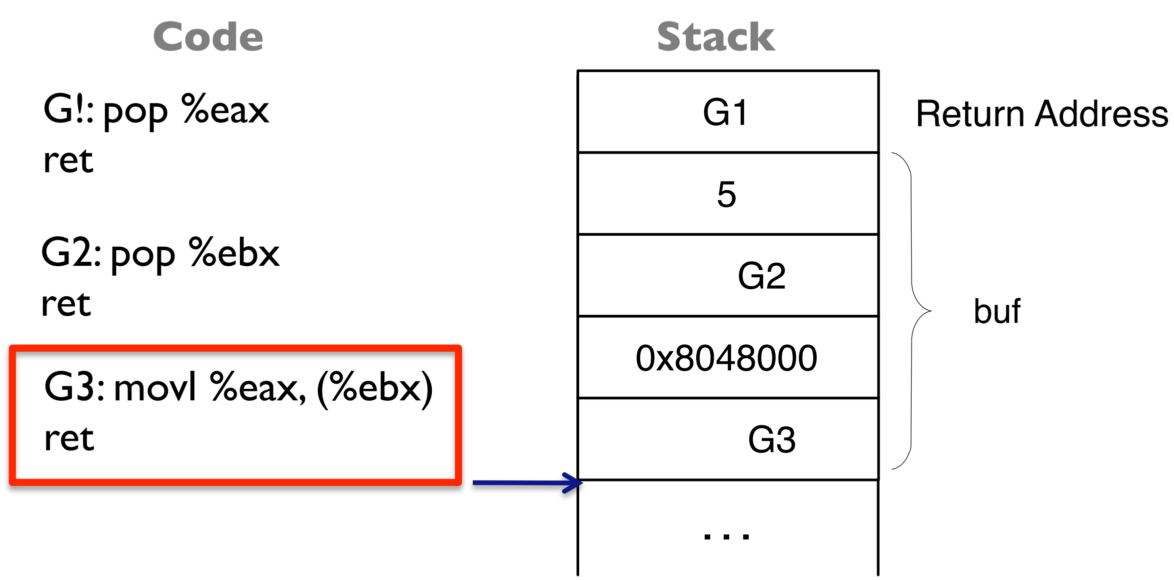
%ebx = 0x8048000

Memory

0x8048000 =

ROP

- Use ESP as program counter
  - E.g., Store 5 at address 0x8048000
    - without introducing new code



Registers

%eax = 5

%ebx = 0x8048000

Memory

0x8048000 = 5

Prevent ROP Attacks

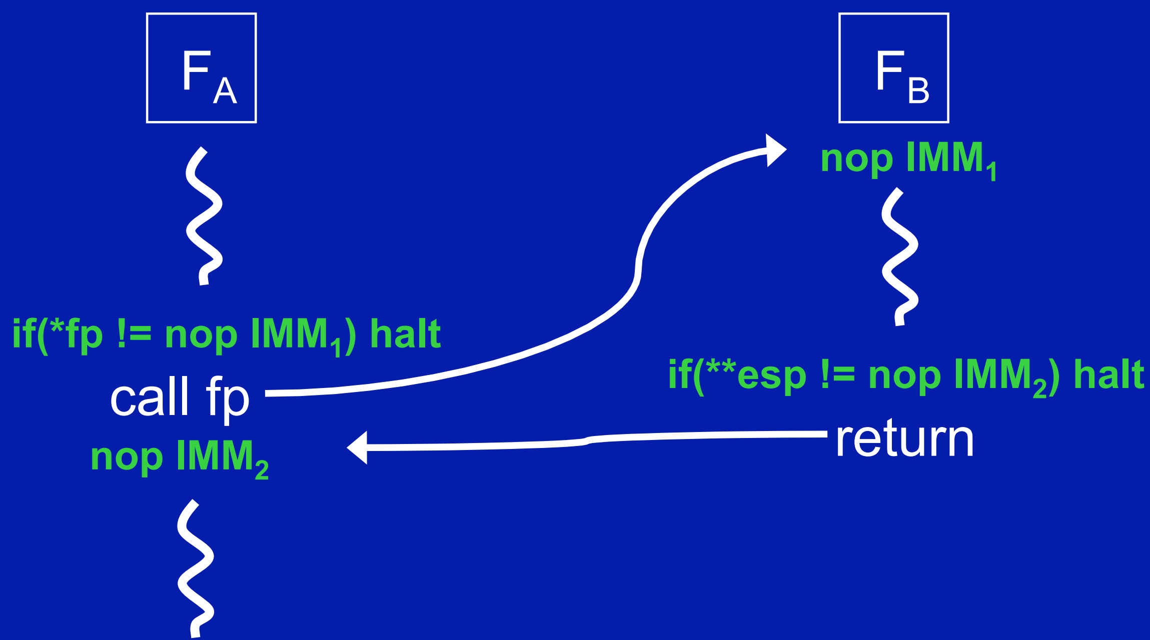
- How would you prevent a program from executing gadgets rather than the expected code?

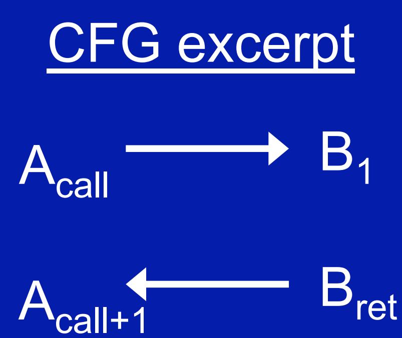
Prevent ROP Attacks

- How would you prevent a program from executing gadgets rather than the expected code?
  - Control-flow integrity
    - Force the program to execute according to an expected CFG

Control-Flow Integrity

Our Mechanism





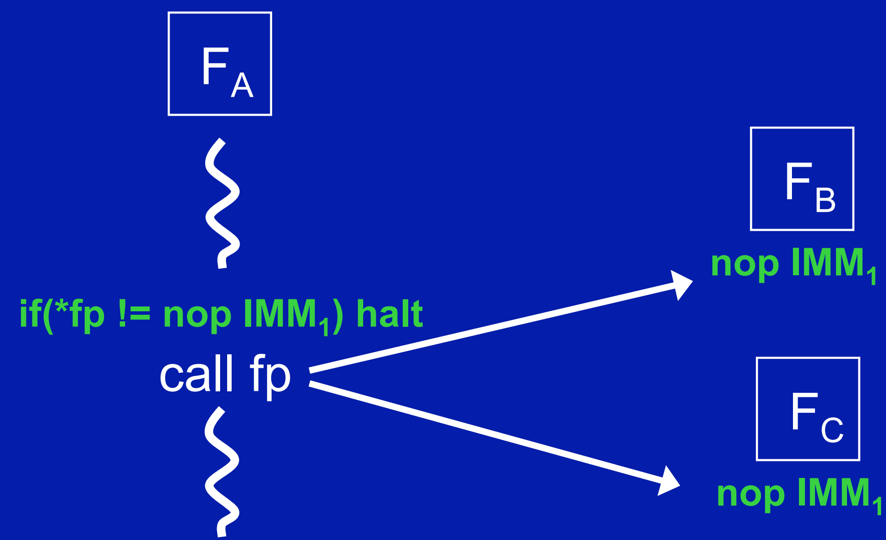
NB: Need to ensure bit patterns for nops appear nowhere else in code memory

Control-Flow Integrity

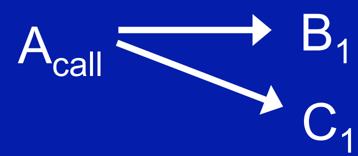
PENNSTATE

More Complex CFGs

Maybe statically all we know is that F_A can call any int→ int function



CFG excerpt



$succ(A_{call}) = \{B_1, C_1\}$

Construction: All targets of a computed jump must have the same destination id (IMM) in their nop instruction

Control-Flow Integrity

Imprecise Return Information

Q: What if F_B can return to many functions ?

A: Imprecise CFG

F_A

call F_B

nop IMM_2

F_B

if(esp != nop IMM_2) halt**

return

F_D

call F_B

nop IMM_2

CFG excerpt

A_{call+1} ← B_{ret}

D_{call+1} ← B_{ret}

$succ(B_{ret}) = \{A_{call+1}, D_{call+1}\}$

CFG Integrity: Changes to the PC are only to valid successor PCs, per succ().

Destination Equivalence

- Eliminate impossible return targets
  - Two *destinations* are said to be *equivalent* if connect to a common source in the CFG.

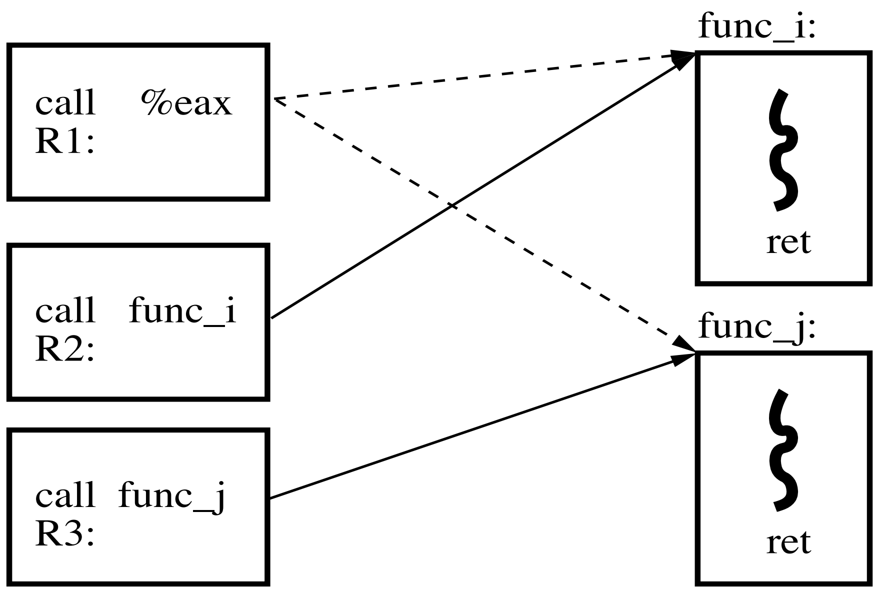


Figure 4. Destination equivalence effect on *ret* instructions (a dashed line represents an indirect *call* while a solid line stands for a direct *call*)

Destination Equivalence

- Eliminate impossible return targets
  - Can *R2* be a return target of *function_j*?

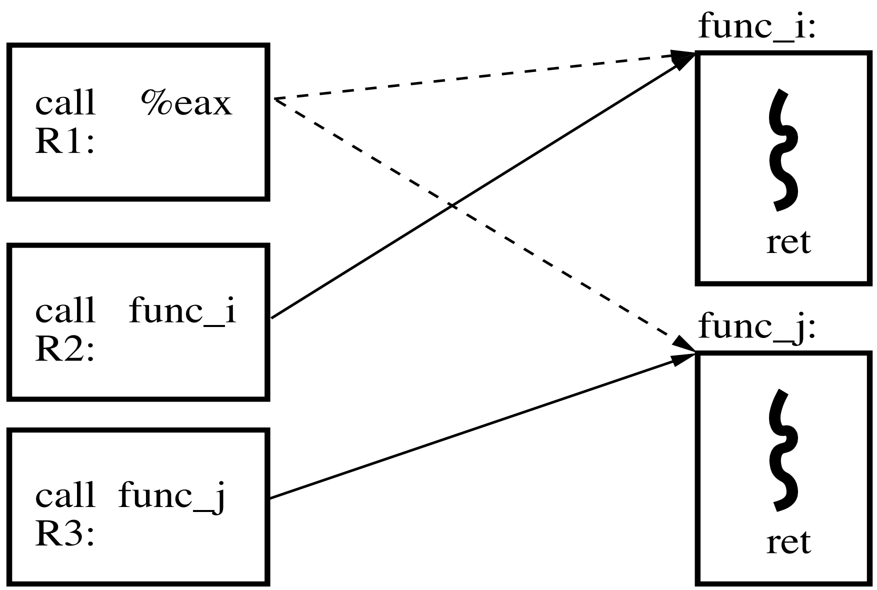


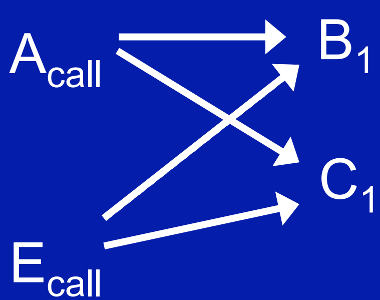
Figure 4. Destination equivalence effect on *ret* instructions (a dashed line represents an indirect *call* while a solid line stands for a direct *call*)

Control-Flow Integrity

No “Zig-Zag” Imprecision

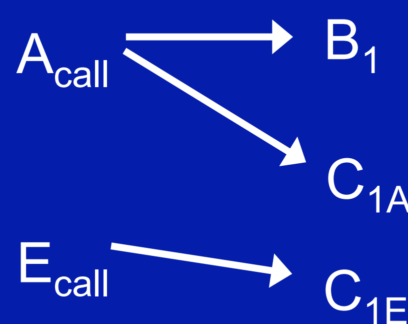
Solution I: Allow the imprecision

CFG excerpt



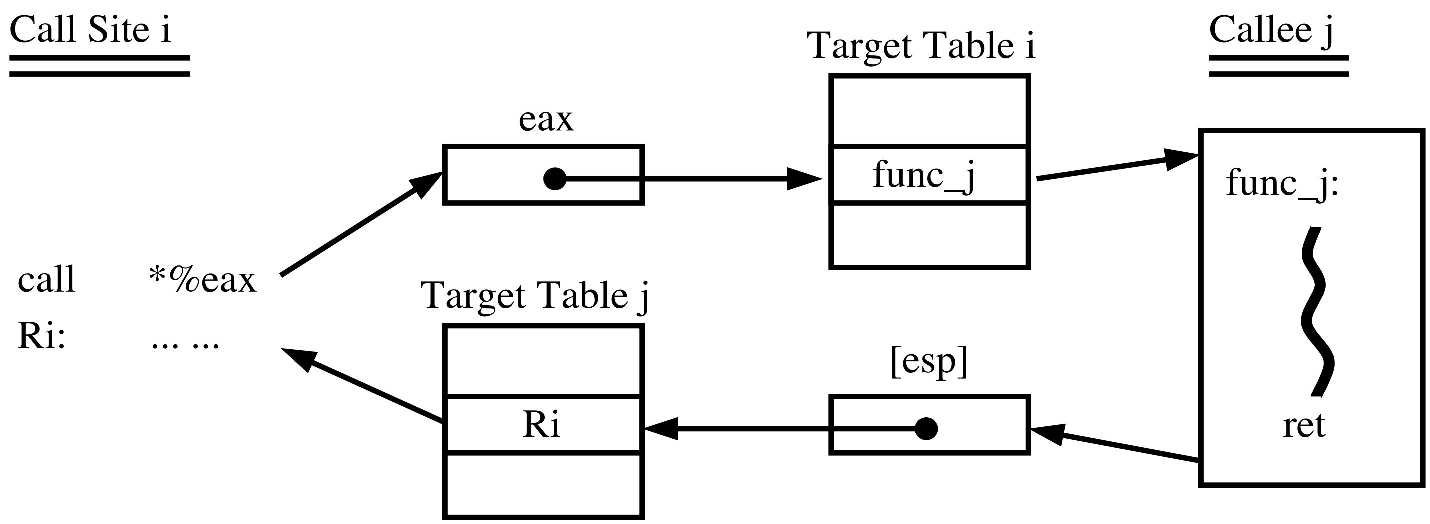
Solution II: Duplicate code to remove zig-zags

CFG excerpt



Restricted Pointer Indexing

- One table for call and return for each function



- Why can't *function_j* return to *R2* with this approach?

Control-Flow Graph

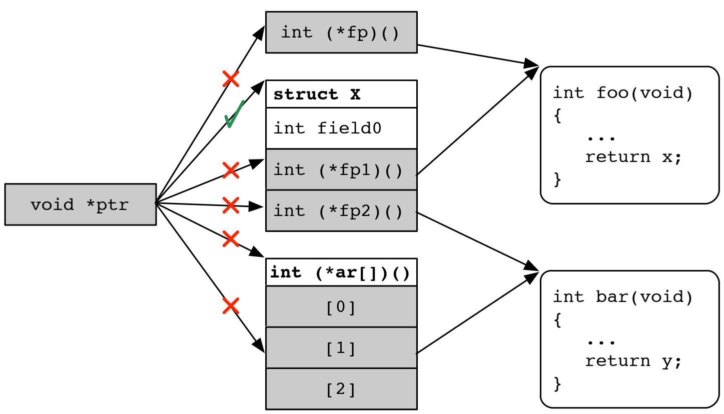
- CFI enforces an expected CFG
  - Each call-site transfers to expected instruction
  - Each return transfers back to expected call-site
- Direct calls
  - Call instructions targeted for specific instruction – no problem
- Indirect calls
  - Function pointers – what are the possible targets?
- Returns
  - Determine return target dynamically – can be overwritten
- Can we compute an accurate CFG?

Enforce CFG

- Challenge in computing an enforceable CFG
  - Targets computed dynamically, so how can we
    - predict in advance and without generating any false positives
- Coarse-grained CFG
  - Any function is a legal *indirect call target (ICT)*
  - Any call-site is a legal *return target*
- Signature-based
  - Function with same signature as call-site is a valid ICT
- Taint-based
  - Track function symbols that can reach a ICT

Taint-based CFG

- If function pointers are used in a restricted way, we can predict the indirect call targets using taint analysis
  - Assumption 1: The only allowed operations on a function pointer variable are assignment and dereferencing (for call)
  - Assumption 2: There exist no data pointer to a function pointer



- *FreeBSD and MINIX largely follow these assumptions*

Shadow Stack

- Method for maintaining return targets for each function call reliably
- On call
  - Push return address on the regular stack
  - Also, push the return address on the shadow stack
- On return
  - Validate the return address on the regular stack with the return address on the shadow stack
- Why might this work? Normal program code cannot modify the shadow stack memory directly

Other Problems with CFI

- CFI enforcement can be expensive
- Idea: only check CFI lazily
  - kBouncer inspects the last 16 indirect branches taken each time the program invokes a system call
    - Why 16? Uses Intel's Last Branch Record (LBR), which can store 16 records
  - ROPecker also checks forward for future gadget sequences (short sequences ending in indirection)
- These hacks do not work – See papers in USENIX Security 2014 for attacks against
- Bottom line – no shortcuts

Control-Flow Bending

- Do we need a shadow stack?
  - After applying coarse-grained CFG

	AIR	Gadget red.	Targets	Gadgets
No CFI	0%	0%	1850580	128929
CFI	99.06%	98.86%	19611	1462

Table 1: Basic metrics for the minimal vulnerable program under no CFI and our coarse-grained CFI policy.

- Still lots of choices and gadgets

Control-Flow Bending

- Do we need a shadow stack?
  - After applying precise CFG
- Problem: Dispatcher functions
  - A function that can overwrite its return address when given adversary controlled input argument values
  - Even with buffer overflow protection (stackguard)
  - E.g., consider memcpy
- How would you use a dispatcher function to control execution while evading CFI?

Control-Flow Bending

- Do we need a shadow stack?
  - After applying precise CFG
- Problem: Dispatcher functions
  - A function that can overwrite its return address when given adversary controlled input argument values
  - Even with buffer overflow protection (stackguard)
  - E.g., consider memcpy
- How would you block a dispatcher function from launching an ROP?

Control-Flow Bending

- If we have a fine-grained CFG and a shadow stack are we safe from control-flow bending?

Control-Flow Bending

- If we have a fine-grained CFG and a shadow stack are we safe from control-flow bending?
- Unfortunately, no.
  - Turing-complete functions
    - A function that has a memory read and memory write
    - A conditional jumps and loops
  - Examples of these functions
    - printf
    - fputs

Take Away

- Memory errors are the classic vulnerabilities in C programs (buffer overflow)
  - Despite years of exploration into defenses, a Turing-complete approach to exploitation remains given an appropriate memory error (return-oriented programming)
- Control-flow integrity has been suggested as the way to block ROP attacks
  - Not as easy as it sounds
  - CFI enforcement requires a fine-grained CFG and shadow stack (or equivalent)
- Yet, still some ROP attacks are possible (bending)