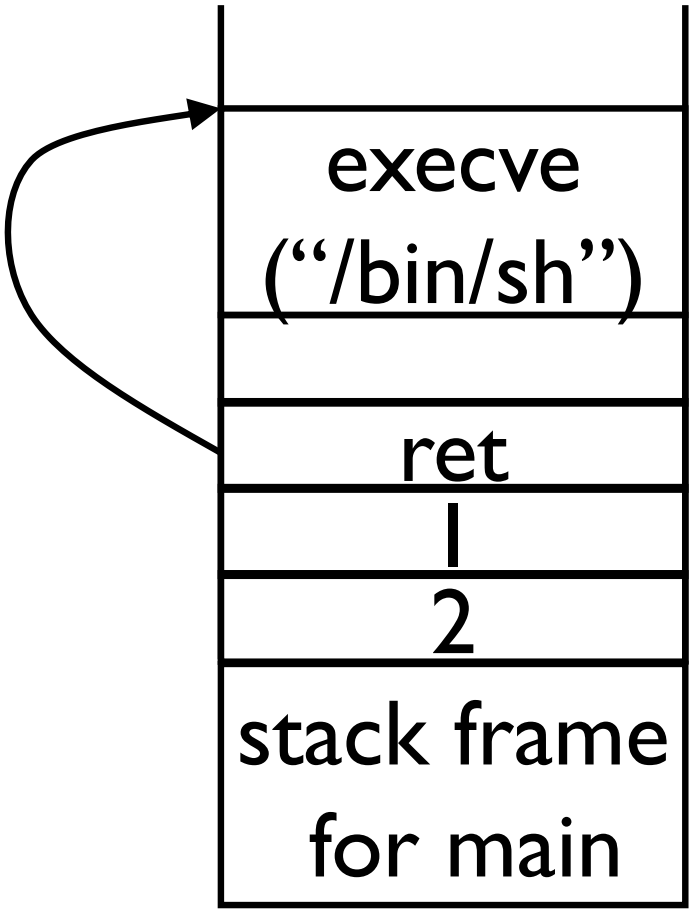
CMPSC 447
Return-oriented Programming

Trent Jaeger
Systems and Internet Infrastructure Security (SIIS) Lab
Computer Science and Engineering Department
Pennsylvania State University

Code Injection



- Remember this exploit
- The adversary's goal is to get execve to run to generate a command shell
- To do this the adversary uses execve from libc – i.e., reuses code that is already there

Injection Requirements

- What is required for a code injection attack?
  - Appreciated by the adversary…
  - That is not expected in practice?

Injection Requirements

- What is required for a code injection attack?
  - Appreciated by the adversary…
  - That is not expected in practice?
- Answer: Execute stack memory
  - Code is injected in stack memory
  - So, we must be able to execute stack memory
- Must all memory be executable?
  - Recall page permissions

Prevent Injection

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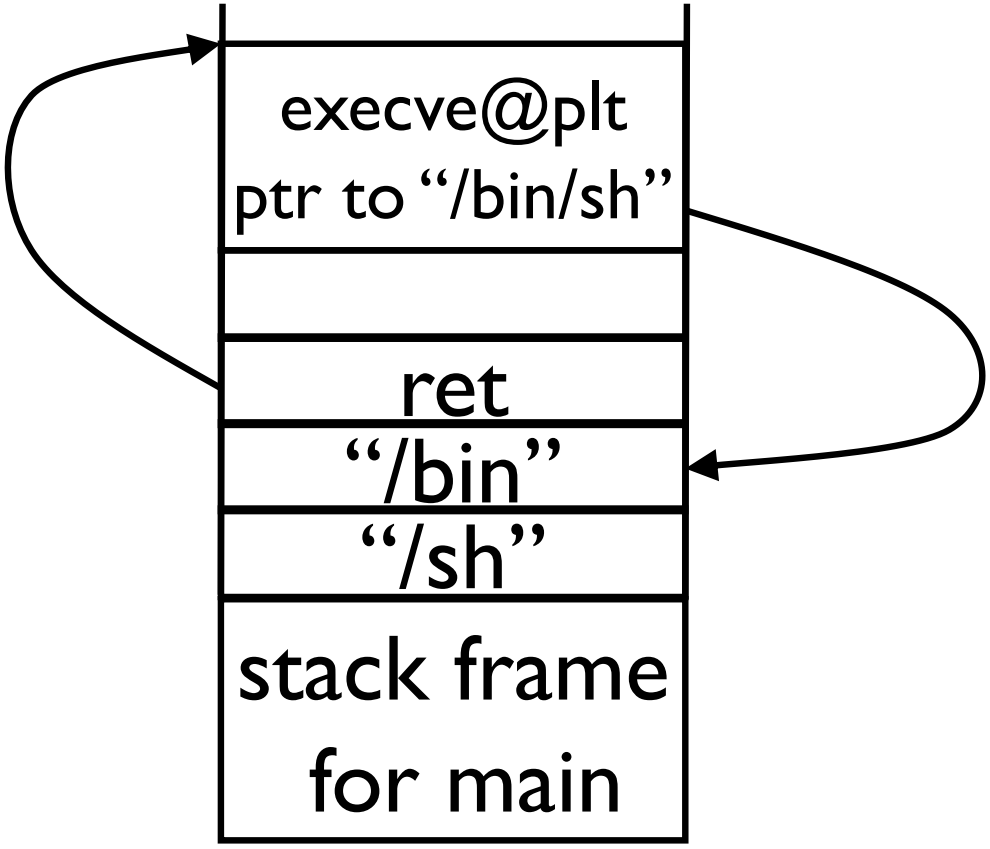
- An available defense can prevent injection
  - DEP or W xor X: Stack memory is not executable
- Set the program memory regions to be either writable or executable, but not both
  - Writable: Stack and heap and global data
  - Executable: Code
  - Of course, some can be read-only and not executable
- Bottom line is that we can remove the execute permission from stack and heap memory pages
  - And prevent writing of code pages

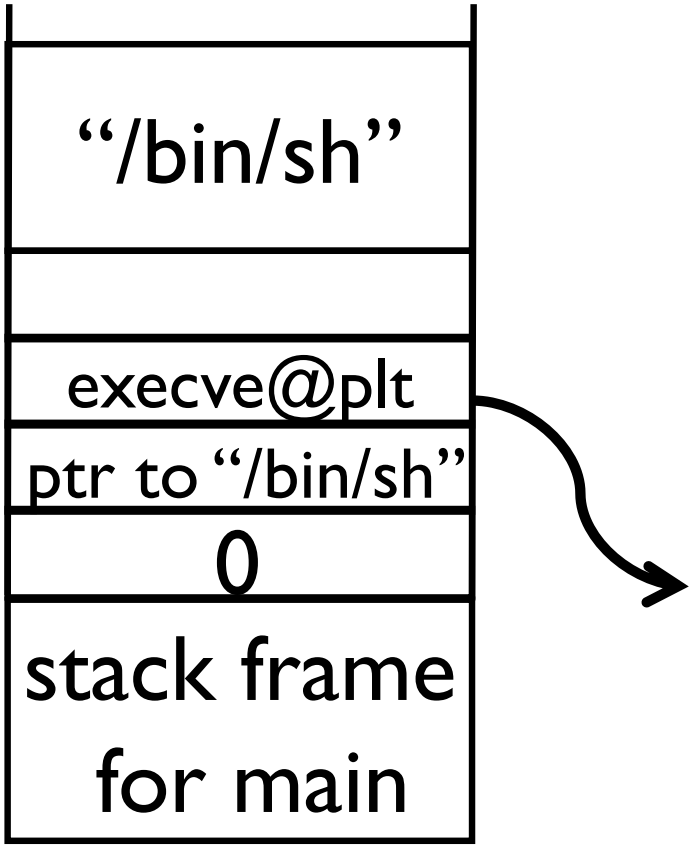
Bypass DEP

- Can we invoke execve without code injection?
  - If so, how?

Return-to-execve

- How can we invoke execve without code injection?
  - Use the code directly
- The difference is subtle, but significant





Return-to-execve

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- How can we invoke execve without code injection?
  - Call execve directly from return value
- The difference is subtle, but significant
  - In the original exploit, we wrote the address of execve into buffer on the stack and modified return address to start executing at buffer
    - I.e., we are executing in the stack memory region
  - Instead, we can modify the return address to point to execve directly, so we continue to execute code
    - Key: Point return address (function pointer) to code memory (PLT to invoke libc function) rather than stack memory

Return-to-Libc

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- Can we invoke any Libc functon without code injection?
  - Well, any that the program uses explicitly from the PLT
  - And any other from Libc code – if you know where it is
- Called "Return-to-Libc" in general
  - Change the return address to refer to a Libc function
  - Gives you access to a lot of valuable code for attacks
- Can you invoke other code like this?

Return-to-X in General

- Return-to-Libc attacks can be employed more generally to enable adversaries to execute existing code under their control
  - Termed "return-oriented attacks"
    - by Hovav Shacham and his colleagues
    - Next few slides are Prof Shacham's

Return-Oriented Programming

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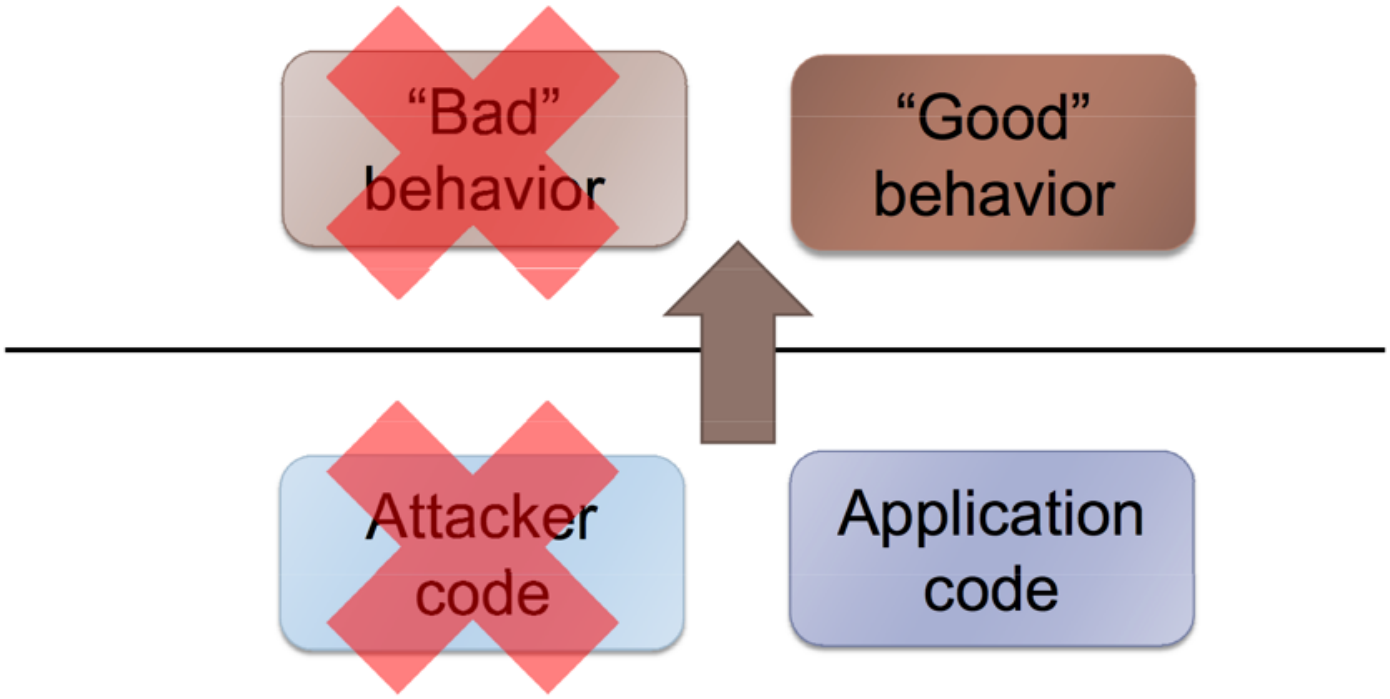
Bad code versus bad behavior



Problem: this implication is false!

ROP Thesis

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any sufficiently large program codebase

arbitrary attacker computation and behavior,
without code injection

(in the absence of control-flow integrity)

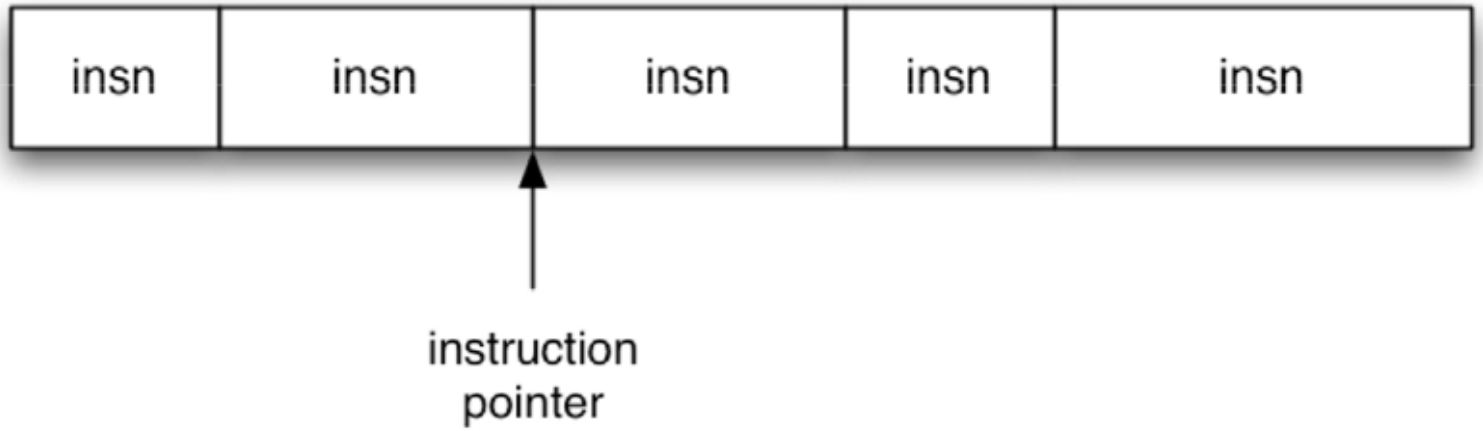
ROP vs return-to-libc

attacker control of stack

arbitrary attacker computation and behavior
via return-into-libc techniques

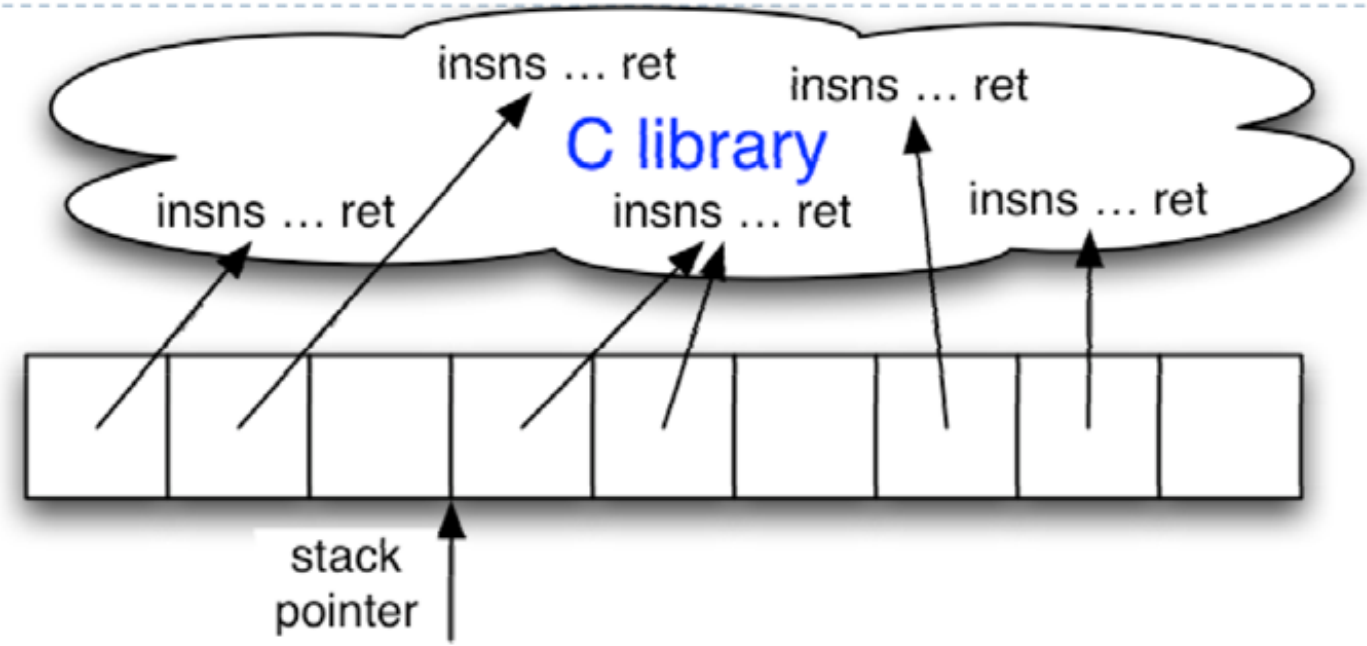
(given any sufficiently large codebase to draw on)

Machine Instructions



- Instruction pointer (%eip) determines which instruction to fetch & execute
- Once processor has executed the instruction, it automatically increments %eip to next instruction
- Control flow by changing value of %eip

ROP Execution



- *Stack pointer* (%esp) determines which instruction sequence to fetch & execute
- Processor doesn't automatically increment %esp; — but the "ret" at end of each instruction sequence does

ROP Example

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

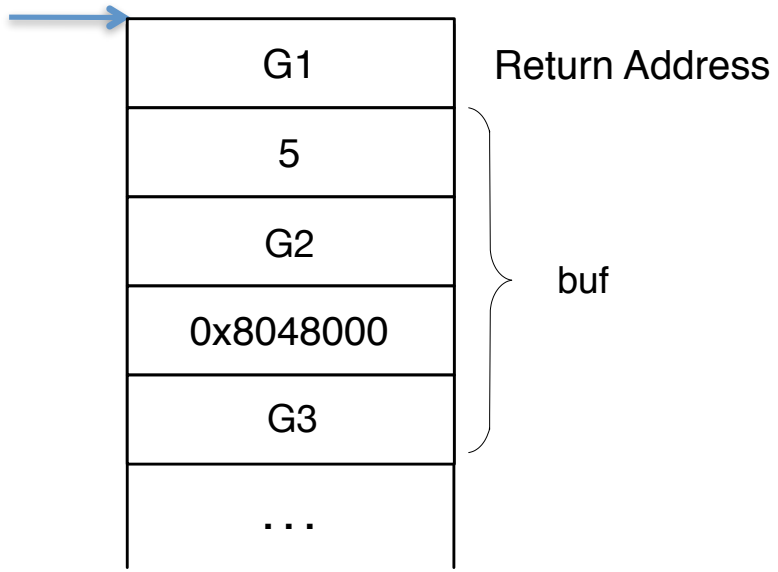
Code

G1: pop %eax
ret

G2: pop %ebx
ret

G3: movl %eax, (%ebx)
ret

Stack



Registers

%eax =

%ebx =

Memory

0x8048000 =

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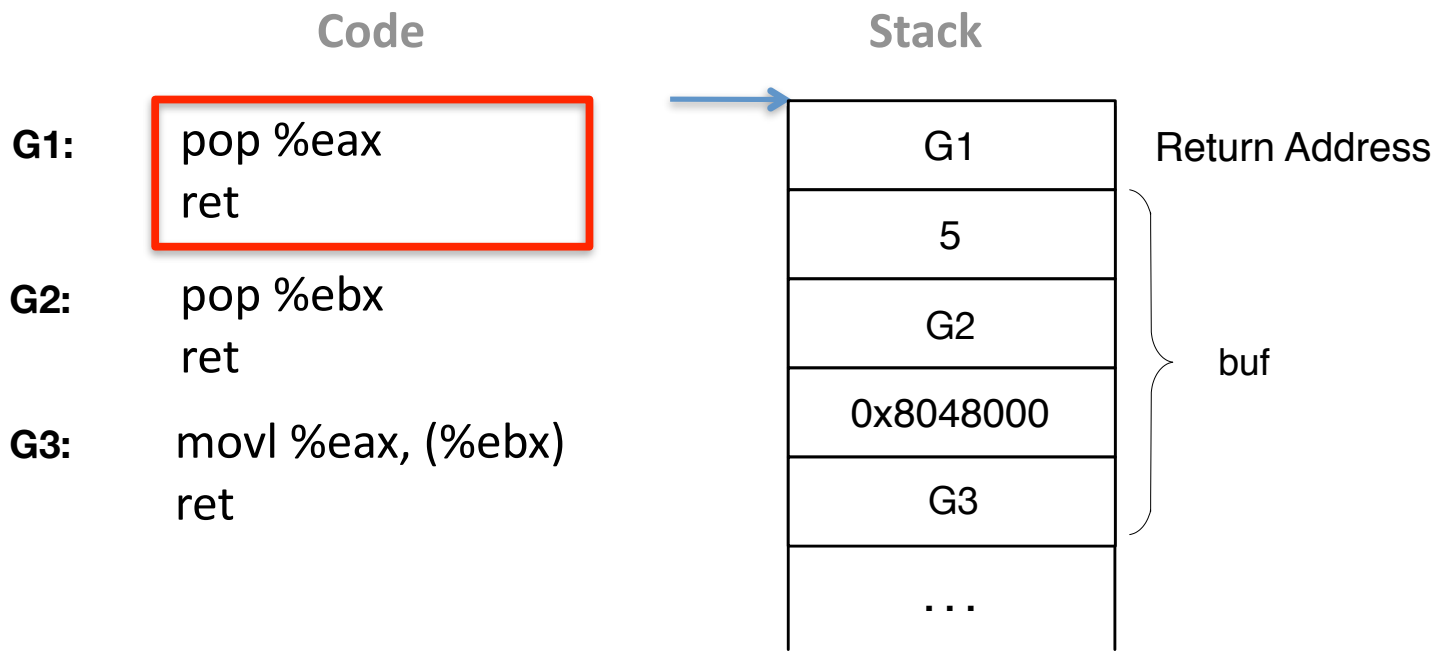

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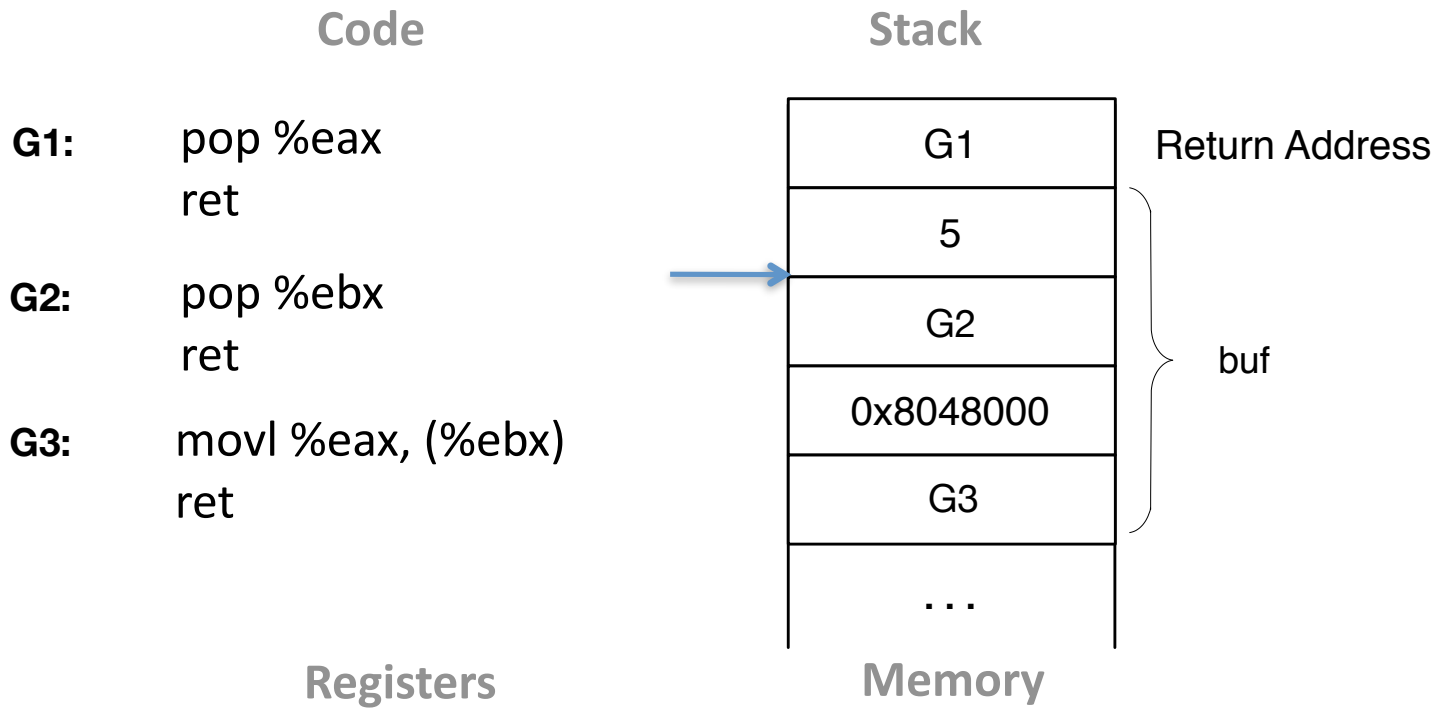

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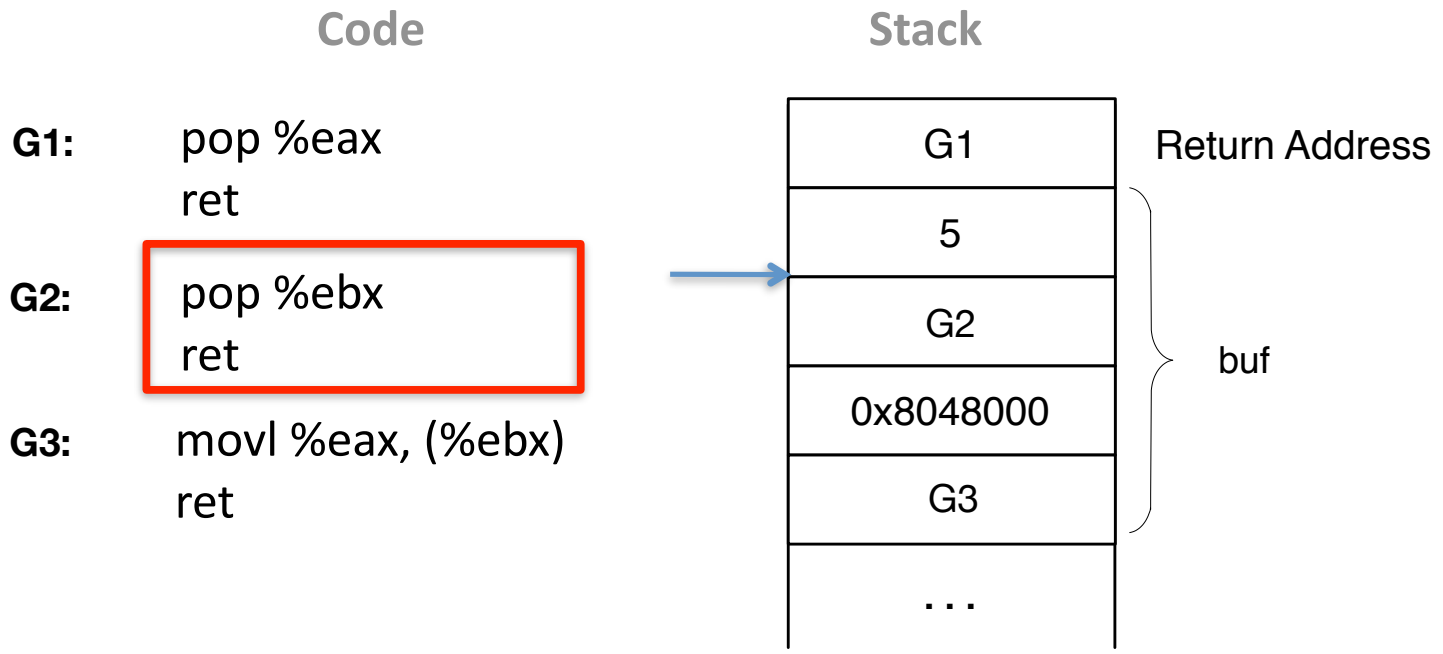

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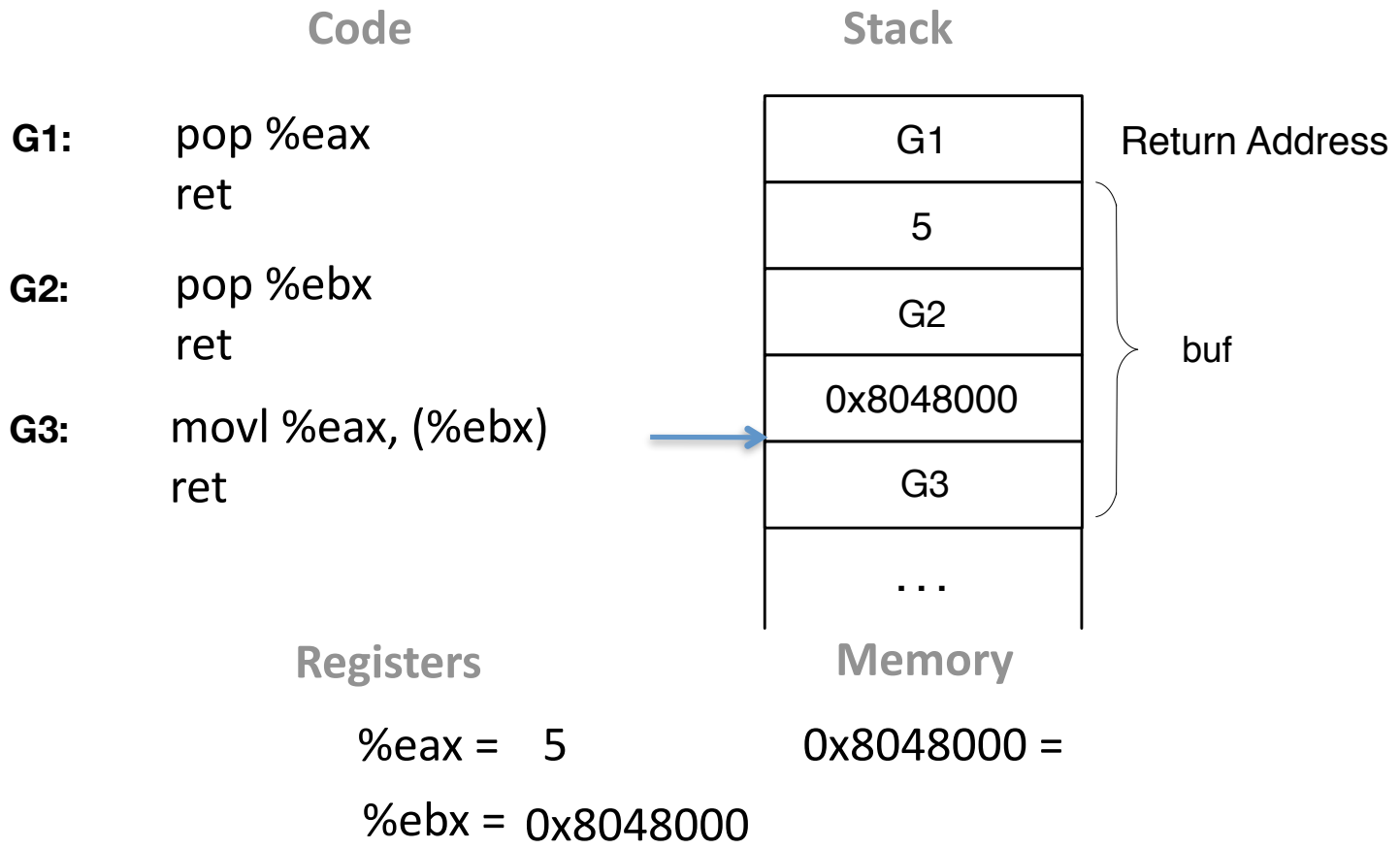

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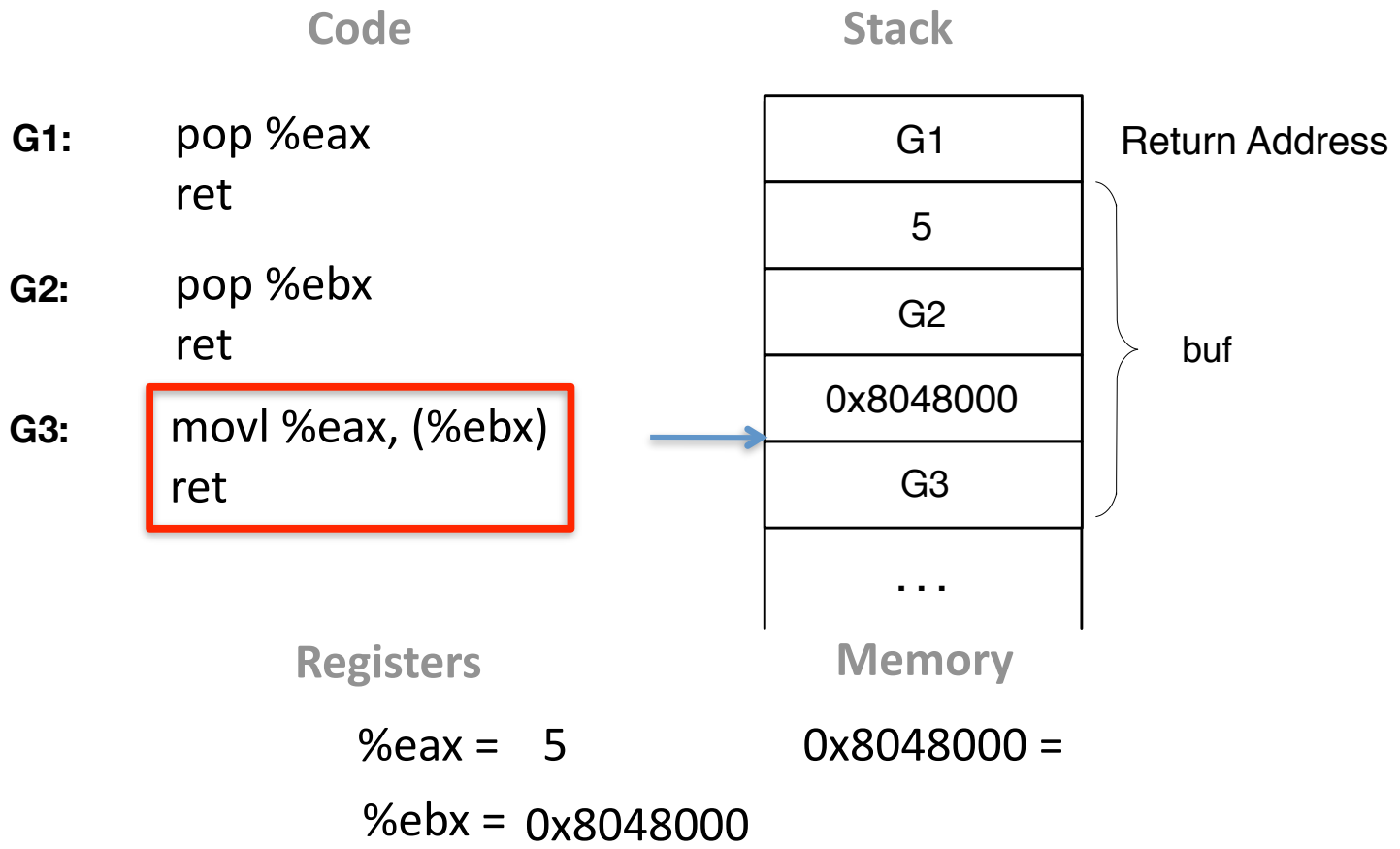

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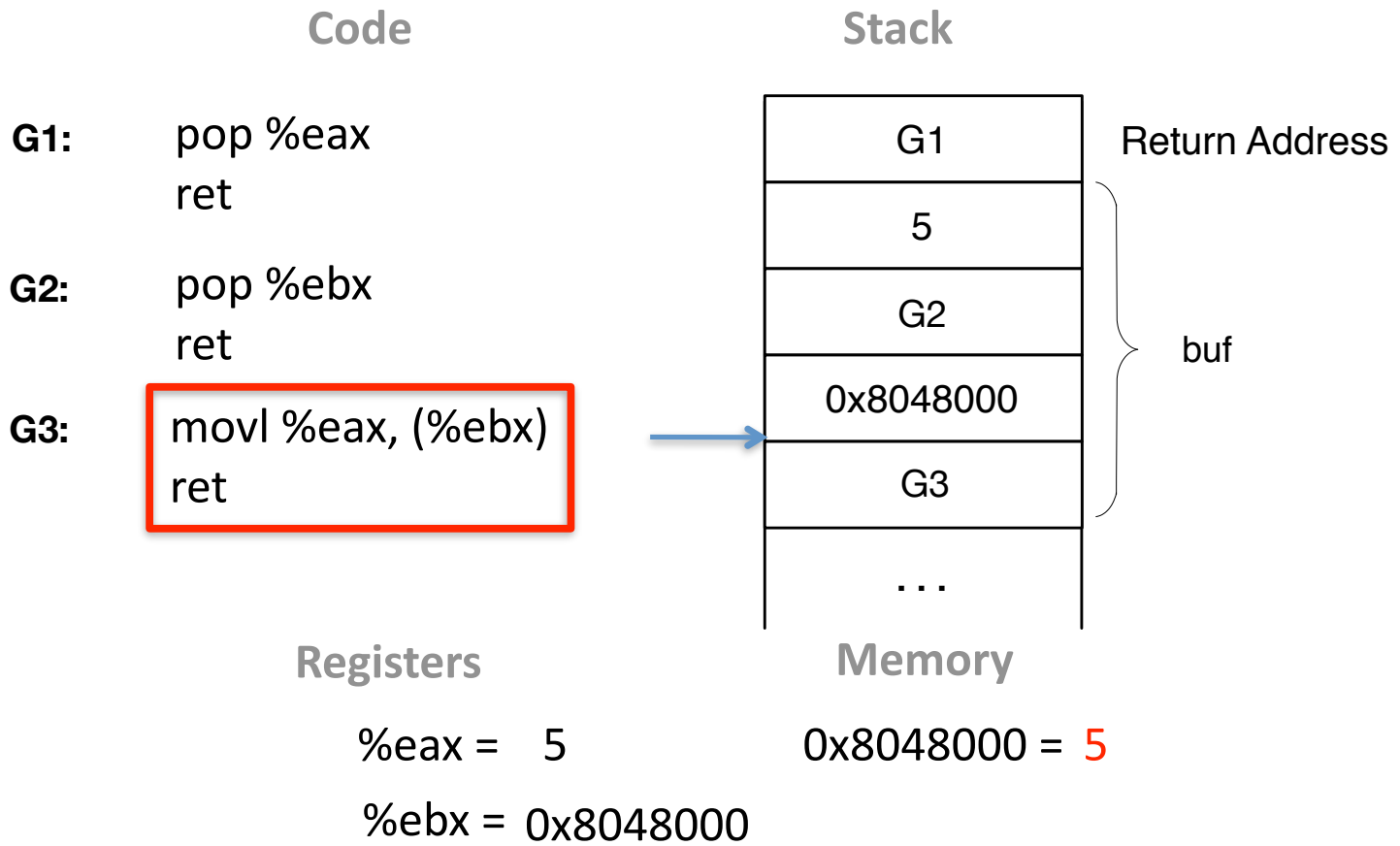

Building ROP Functionality

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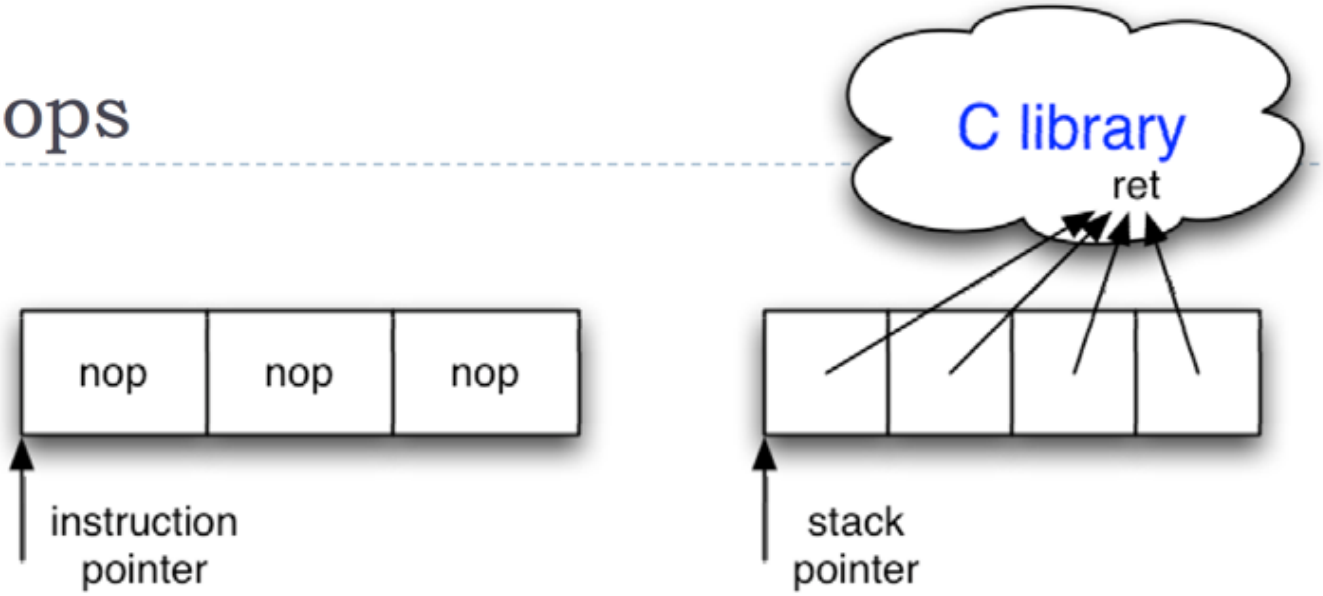
No-ops



- No-op instruction does nothing but advance %eip
- Return-oriented equivalent:
  - point to return instruction
  - advances %esp
- Useful in nop sled

Building ROP Functionality

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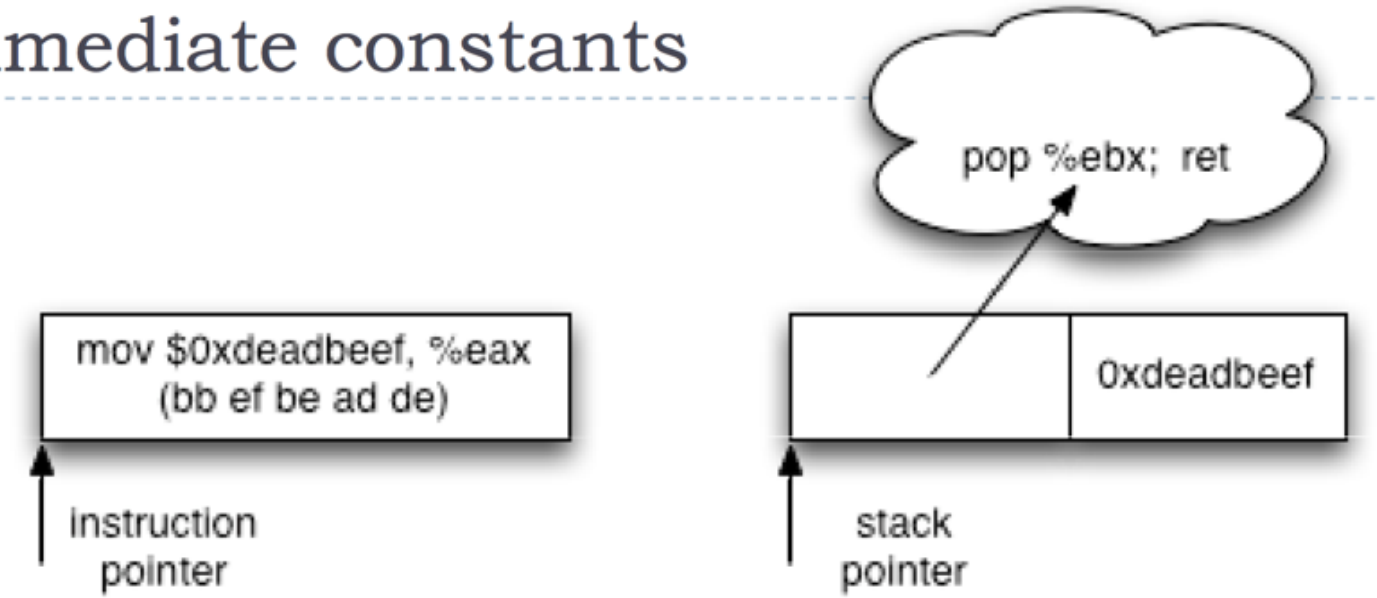
Immediate constants



- Instructions can encode constants
- Return-oriented equivalent:
  - Store on the stack;
  - Pop into register to use

Building ROP Functionality

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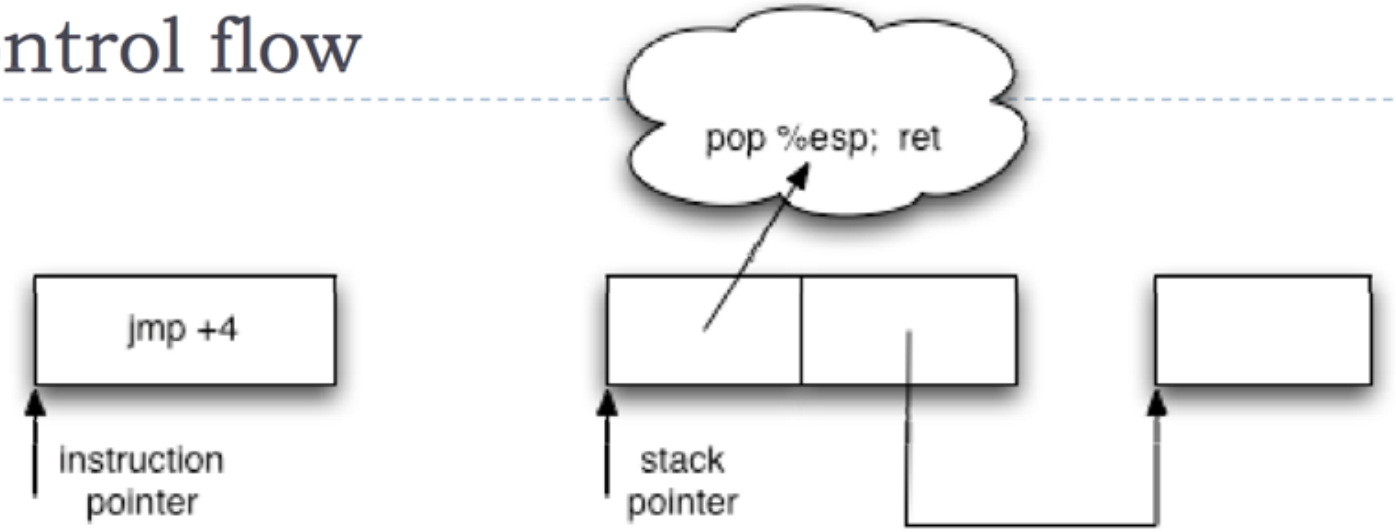
Control flow



- Ordinary programming:
  - (Conditionally) set %eip to new value
- Return-oriented equivalent:
  - (Conditionally) set %esp to new value

Return-oriented Programming

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- What can we do with return-oriented programming?
  - Anything any other program can do
  - How do we know?

Return-oriented Programming

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- What can we do with return-oriented programming?
  - Anything any other program can do
  - How do we know? Turing completeness
- A language is Turing complete if it has (loosely)
  - Conditional branching
  - Can change memory arbitrarily
- Both are possible with ROP

Finding Gadgets

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- Snippets of code ending in "ret" are called gadgets
- How do we build a complete exploit from available code?
  - Must find the gadgets that are available in that code
- How do you think one finds all the gadgets in a code region?

Finding Gadgets

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- Snippets of code ending in "ret" are called gadgets
- How do we build a complete exploit from available code?
  - Must find the gadgets that are available in that code
- How do you think one finds all the gadgets in a code region?
  - From each byte offset in the code region, see what sequence of instructions are encoded until a "ret" is reached
    - Find "a, b, c, ret" – where a, b, and c are other instructions

Finding Gadgets

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- Snippets of code ending in "ret" are called gadgets
- How do we build a complete exploit from available code?
  - Must find the gadgets that are available in that code
- How do you think one finds all the gadgets in a code region?
  - Start from a "ret" byte "0xc3" at any memory location and work backwards to find the longest useful sequence of instructions for a gadget
    - Find "a, b, c, ret" – find "c, ret", then "b, c, ret", then…

Gadgets and Returns

- Must all useful gadgets end with "ret"?

Gadgets and Returns

- Must all useful gadgets end with "ret"?
  - No, several control transfer functions can be employed to chain gadgets together
- Some examples
  - Jump-oriented programming
  - Call-oriented programming
  - Basic idea – transition to the next gadget through a jump or call rather than using a return
- So, such attacks are more generally called "code-reuse attacks"

ROP in the Wild

- Do adversaries really employ such attacks?

Gadgets and Returns

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- 2010: ROP attacks contained in "exploit packs"
  - Exploit packs are exploits used in penetration testing
- 2013: First ROP-only attack detected
  - Against Adobe Reader XI
  - i.e., no shell code – entire attack within process
- But often there are easier ways to exploit your software flaws
  - Be careful with JIT code – if adversary can modify
  - Why?

Is Code Injection Dead?

- Code Injection Is Still Desirable for Adversaries
  - Add new code for additional attack functionality
    - Could add a new code file and execute
    - But, may still want to use the hijacked process (evade detection)
- But, given DEP is code injection no longer possible?

Disable DEP

- How would we use code reuse to disable DEP?
- Goal is to allow execution of writable memory (i.e., change page permissions)
  - There's a system call for that

```
int mprotect(void *addr, size_t len, int prot);
```

  - Sets protection for region of memory starting at address
  - Invoke this system call to allow execution on stack and then start executing from the injected code

Take Away

- Code injection attacks are prevented by DEP
  - Also called W xor X (write XOR execute)
- But, adversaries can reuse available code in return-oriented programming attacks
  - Generalized to code-reuse attacks
- We examined the ROP mechanism today
  - That is the one you must know
- Note that ROP (code-reuse) attacks can re-enable the possibility of code injection attacks