PennState

CSE543 Computer Security

Module: Return-Oriented Programming

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Anatomy of Control-Flow Exploits

- Two steps in control-flow exploitation
- First -- attacker gets control of program flow (return address, function pointer)
    - Stack (buffer), heap, format string vulnerability, …
- Second -- attacker uses control of program flow to launch attacks
    - E.g., Code injection
        - Adversary injects malicious code into victim
        - E.g., onto stack or into other data region

    - How is code injection done?

Code Injection

- Advantage
  - Adversary can install any code they want
    - What code do adversaries want?
  - Defenses
    - NX bit - set memory as non-executable (stack)
    - W (xor) X - set memory as either writeable or executable, but not both

- What can adversary do to circumvent these defenses and still execute useful code (for them)?

Return-to-libc Attacks

- Method
  - Overwrite target of indirect call/jmp target to a library routine (e.g., system)
    - Return address, function pointer, …
- Advantage
  - Get useful function without code injection
- Defenses
  - Remove unwanted library functions
- How could an adversary run any exploit they want?
  - Topic of today's lecture

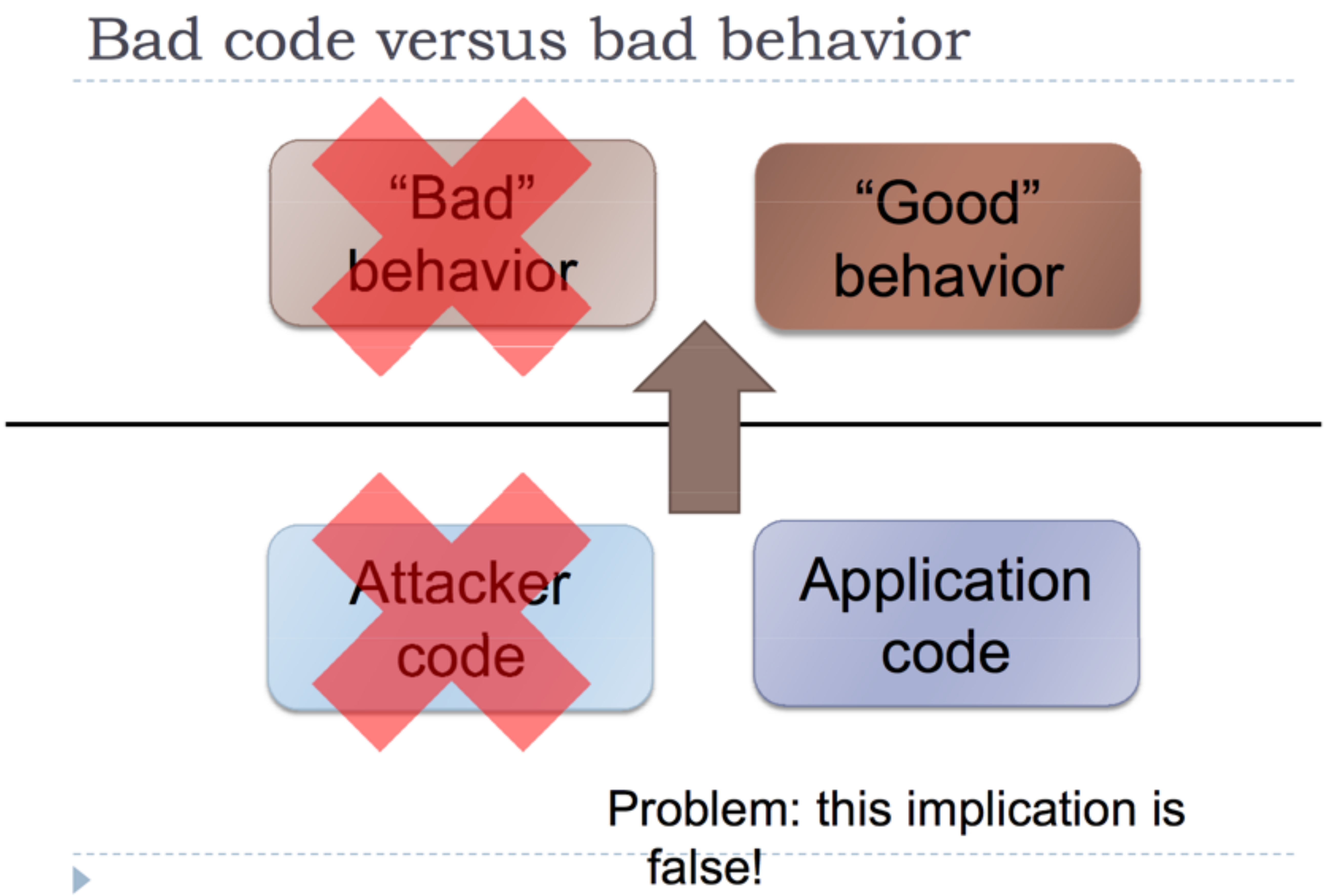
Return-Oriented Programming

- Arbitrary exploitation without code injection

Return-oriented Programming:
Exploitation without Code Injection

Erik Buchanan, Ryan Roemer, Stefan Savage, Hovav Shacham
University of California, San Diego

Return-Oriented Programming



Bad code versus bad behavior

“Bad” behavior

“Good” behavior

Attacker code

Application code

Problem: this implication is false!

ROP Thesis

any sufficiently large program codebase

arbitrary attacker computation and behavior,
without code injection

(in the absence of control-flow integrity)

Return-to-libc

- Divert control flow of exploited program into libc code
  - system(), printf(),
- No code injection required

- Perception of return-into-libc: limited, easy to defeat
  - Attacker cannot execute arbitrary code
  - Attacker relies on contents of libc — remove system()?

- We show: this perception is *false.*

ROP vs return-to-libc

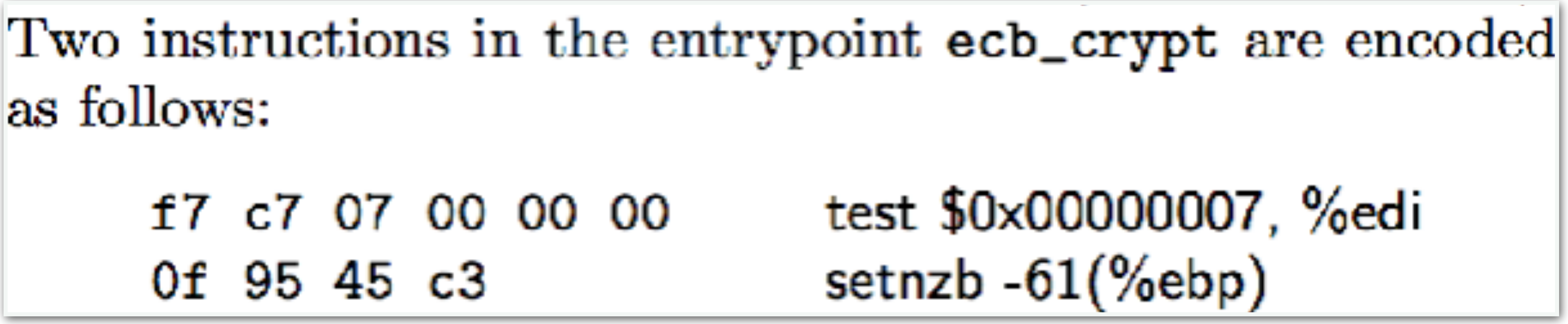
attacker control of stack

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

(given any sufficiently large codebase to draw on)

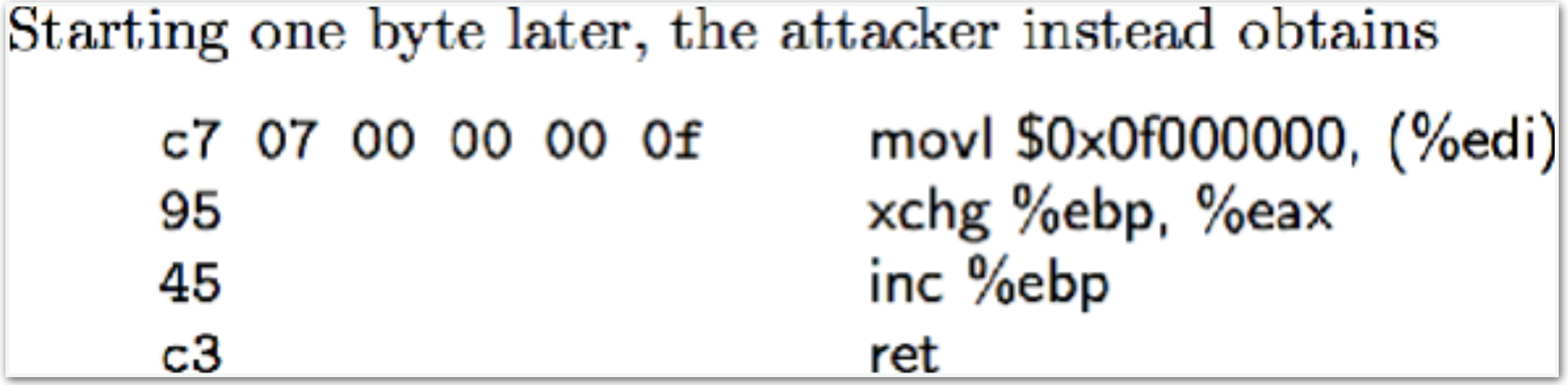
Code Sequence in Libc

Code sequences exist in libc that were not placed there by the compiler



Two instructions in the entrypoint **ecb_crypt** are encoded as follows:

```
f7 c7 07 00 00 00        test $0x00000007, %edi
0f 95 45 c3              setnzb -61(%ebp)
```



Starting one byte later, the attacker instead obtains

```
c7 07 00 00 00 0f        movl $0x0f000000, (%edi)
95                       xchg %ebp, %eax
45                       inc %ebp
c3                       ret
```

Find code sequences by starting at ret's ('0xc3') and looking backwards for valid instructions

ROP Example

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

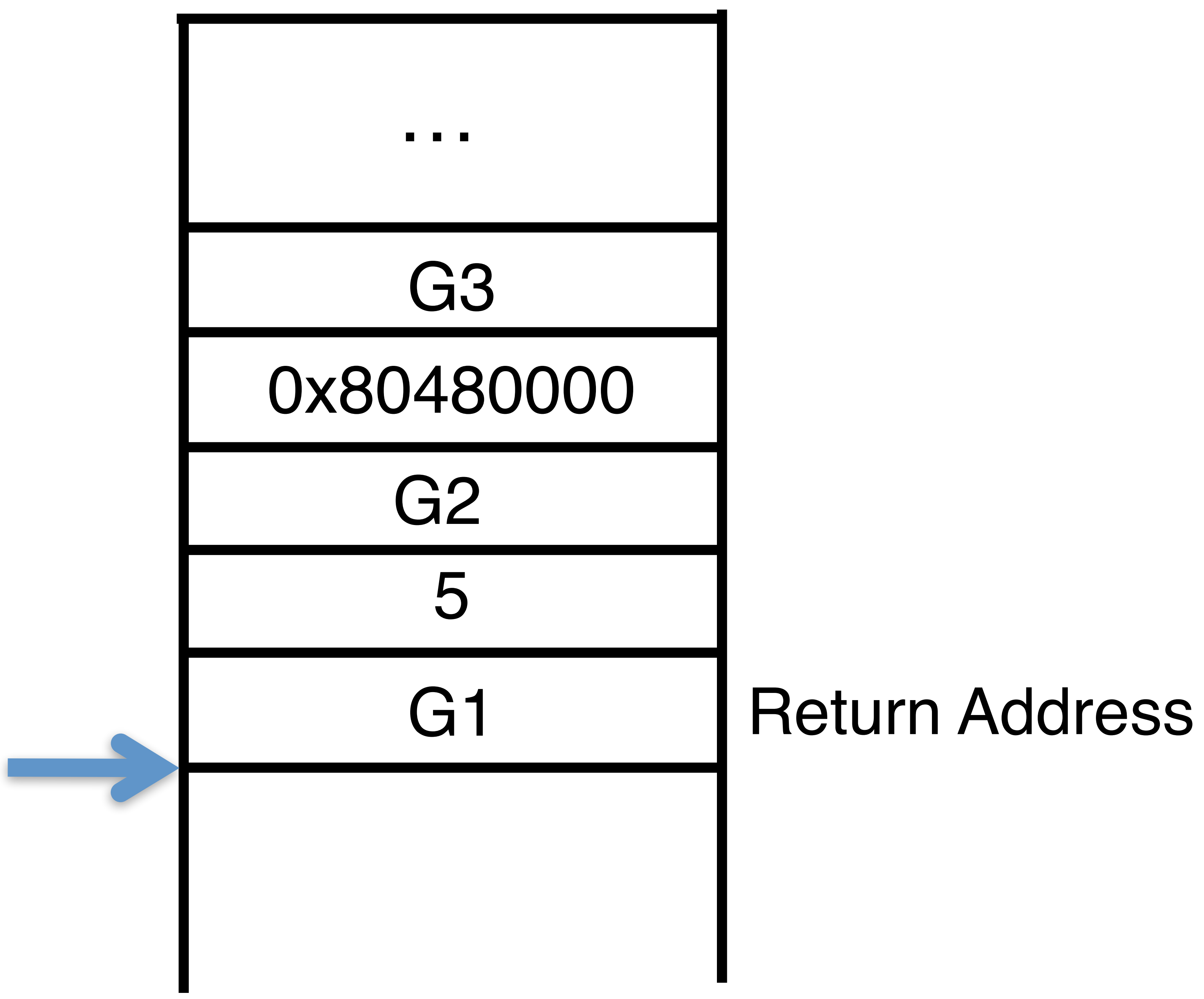
Code

G1: pop %eax
ret

G2: pop %ebx
ret

G3: movl %eax, (%ebx)
ret

Stack



Registers

%eax =

%ebx =

Memory

0x8048000 =

ROP Example

- Use ESP as program counter
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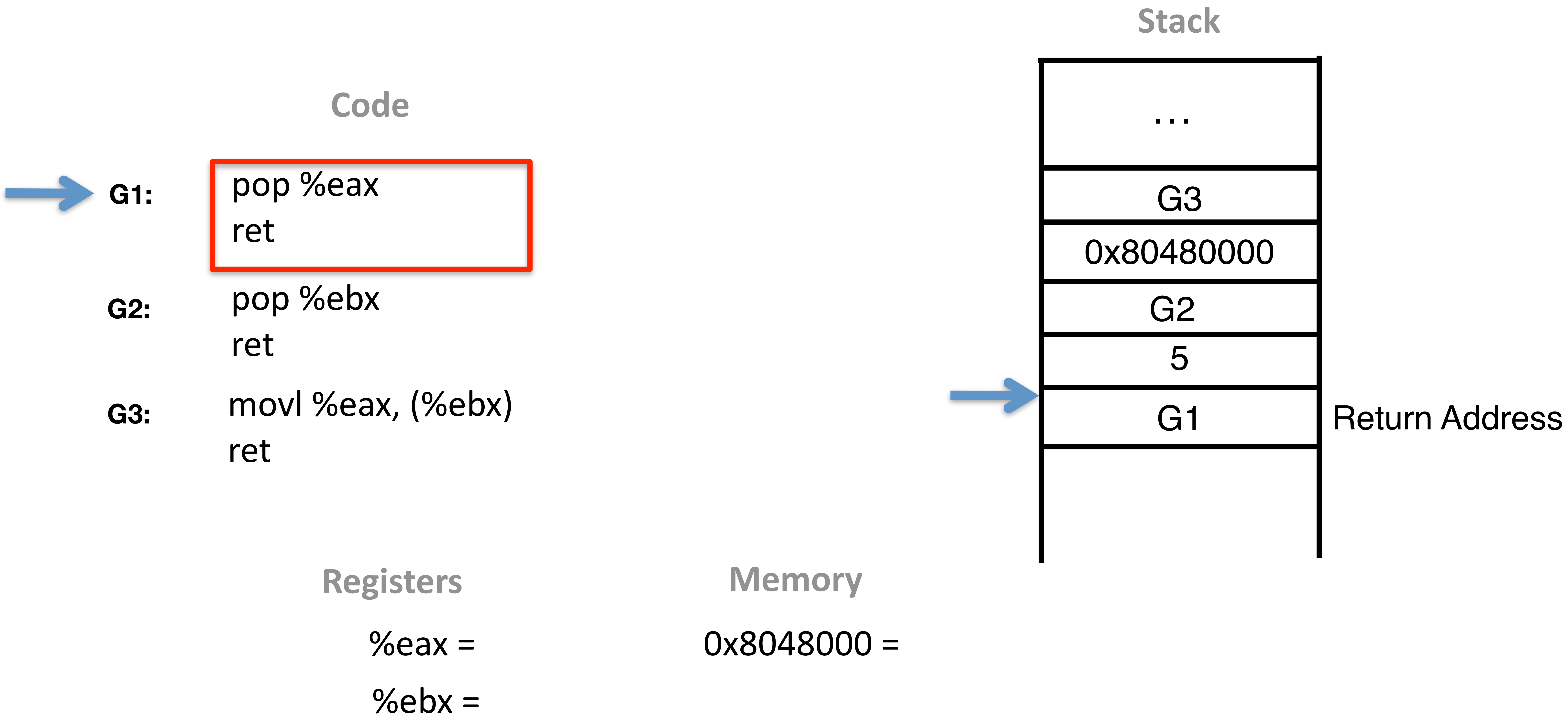
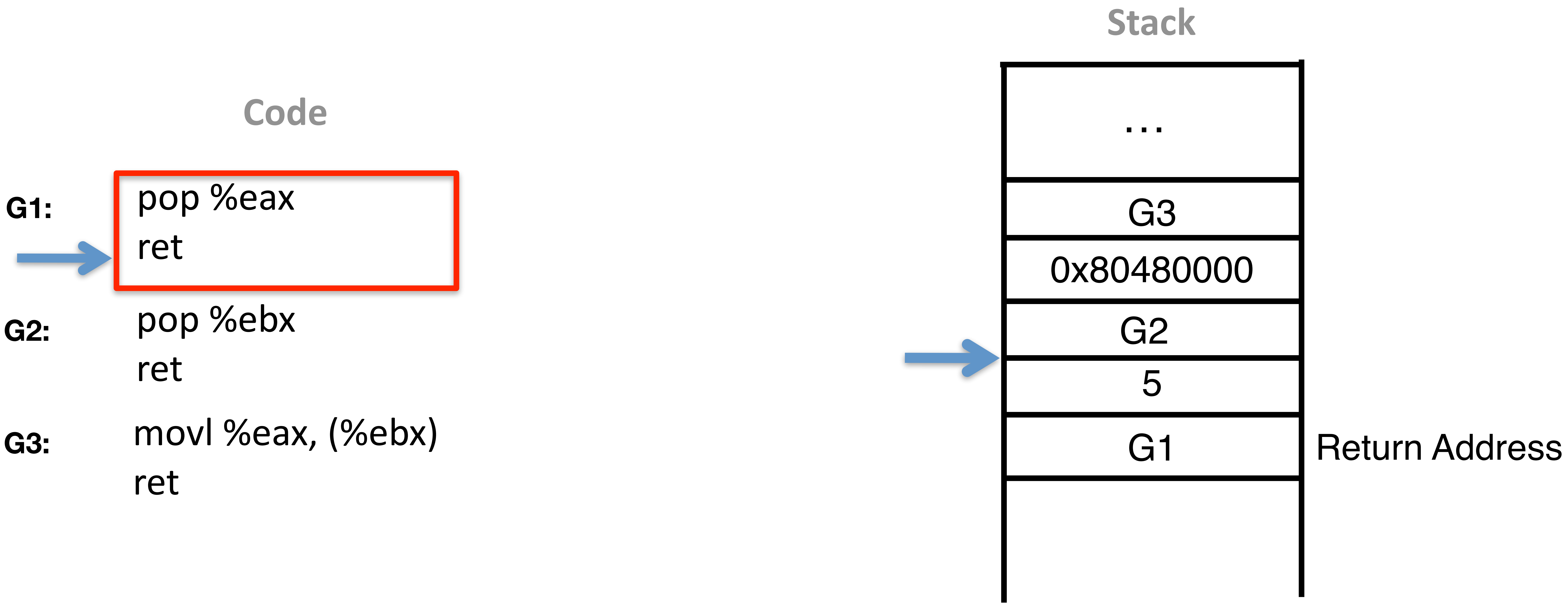


ROP Example

- 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

…
G3
0x80480000
G2
5
G1 Return Address

Registers

%eax = 5

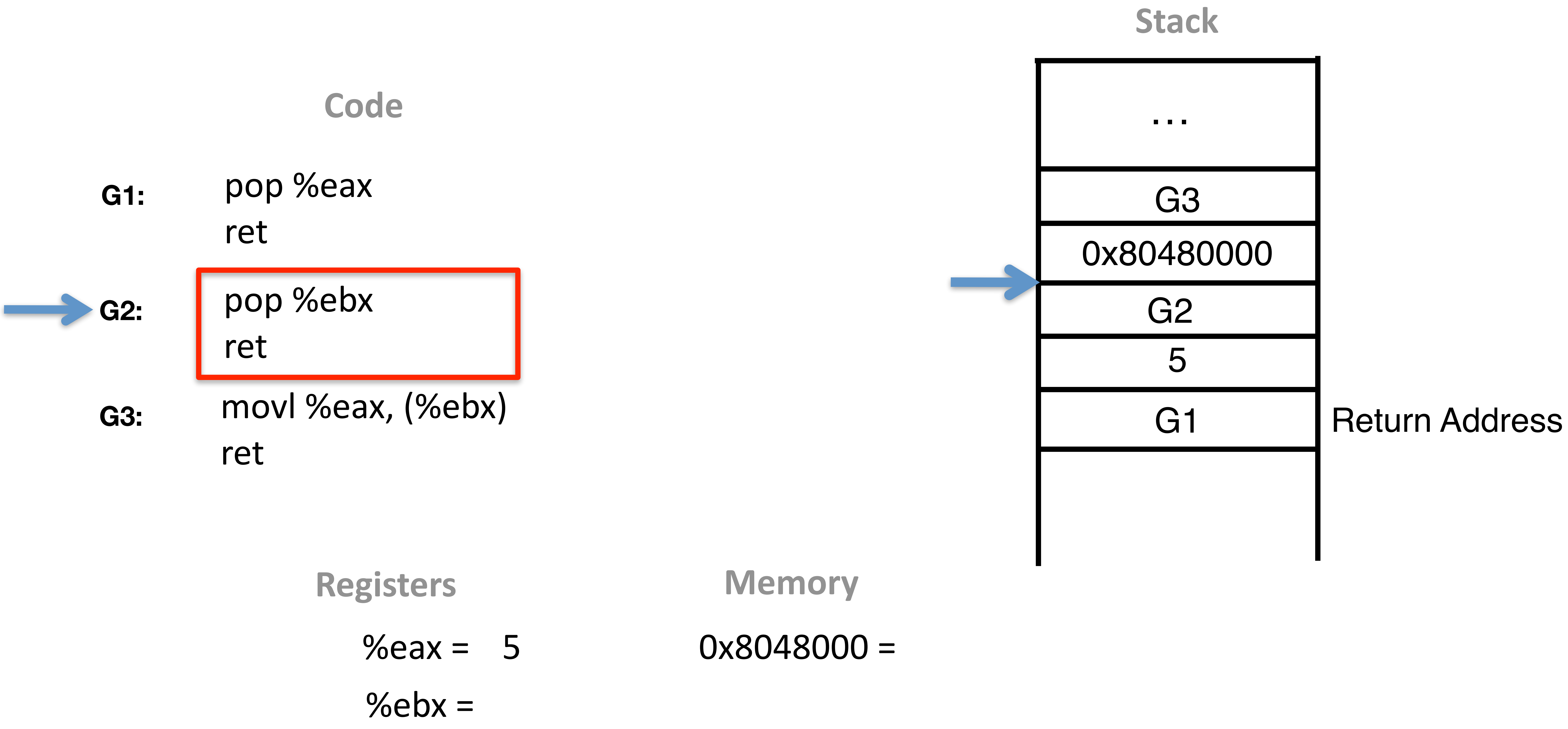
%ebx =

Memory

0x8048000 =

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

…
G3
0x80480000
G2
5
G1 Return Address

Registers

%eax = 5

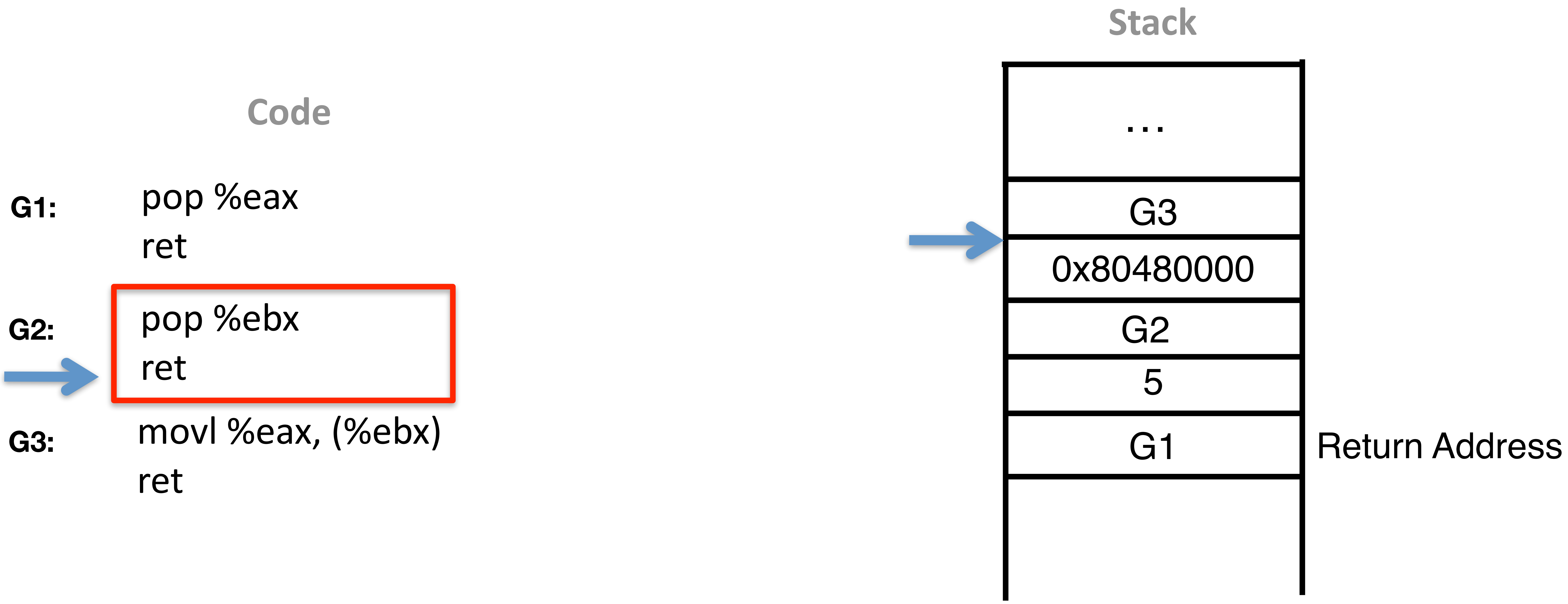
%ebx =

Memory

0x8048000 =

ROP Example

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



Stack

Code

G1: pop %eax
ret

G2: pop %ebx
ret

G3: movl %eax, (%ebx)
ret

Registers

%eax = 5

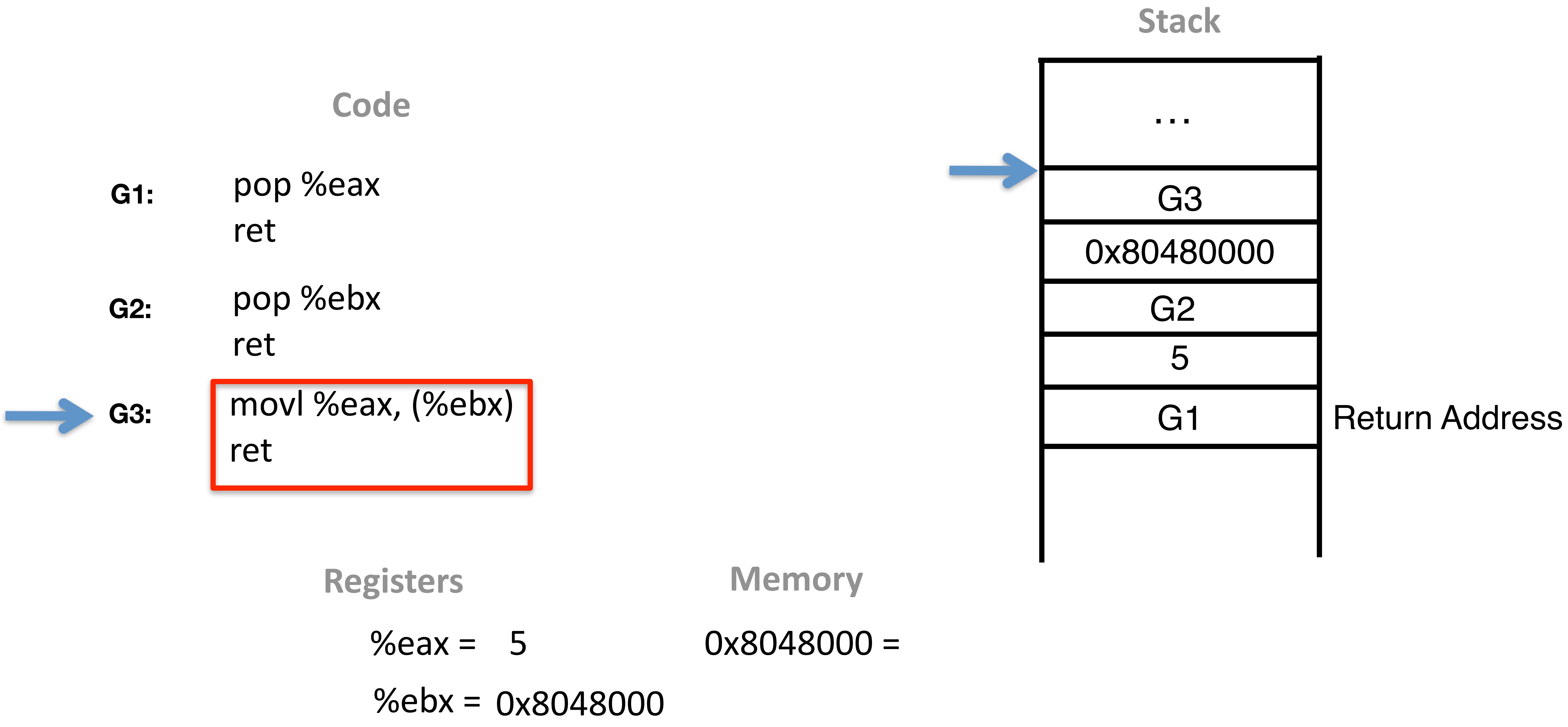
%ebx = 0x8048000

Memory

0x8048000 =

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

…
G3
0x80480000
G2
5
G1 (Return Address)

Registers

%eax = 5

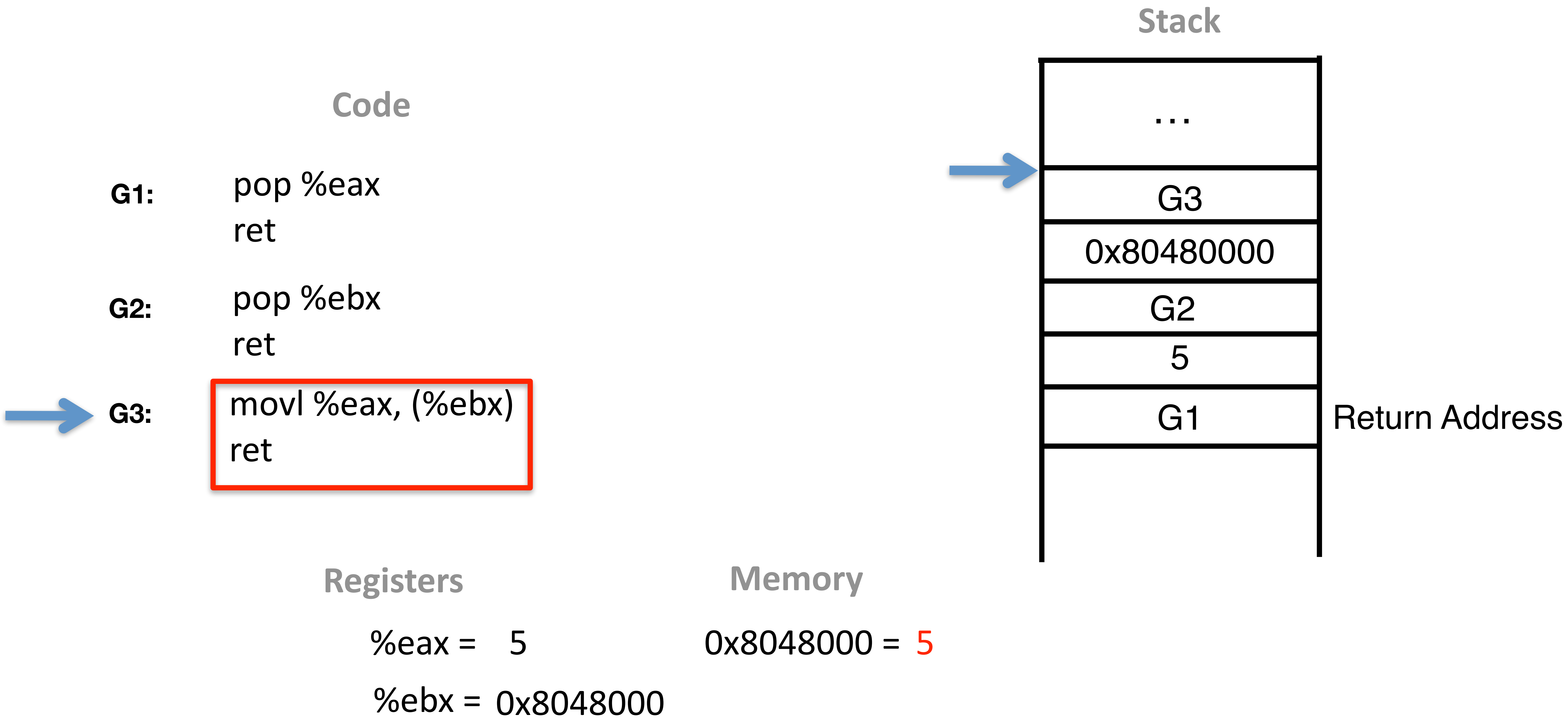
%ebx = 0x8048000

Memory

0x8048000 =

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

…
G3
0x80480000
G2
5
G1

Return Address

Registers

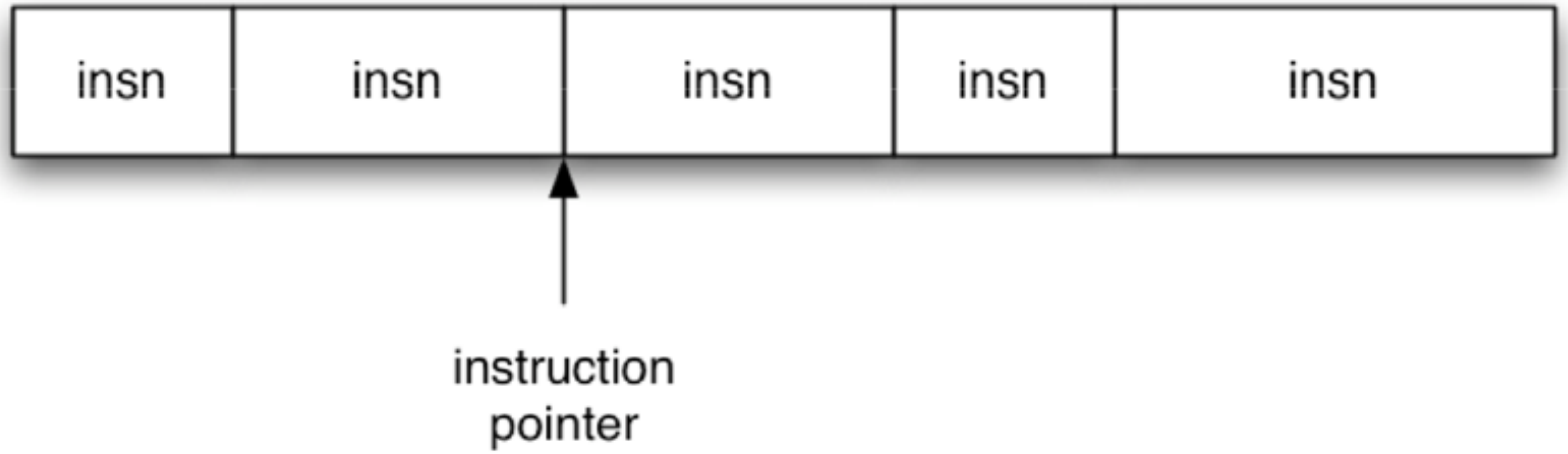
%eax = 5

%ebx = 0x8048000

Memory

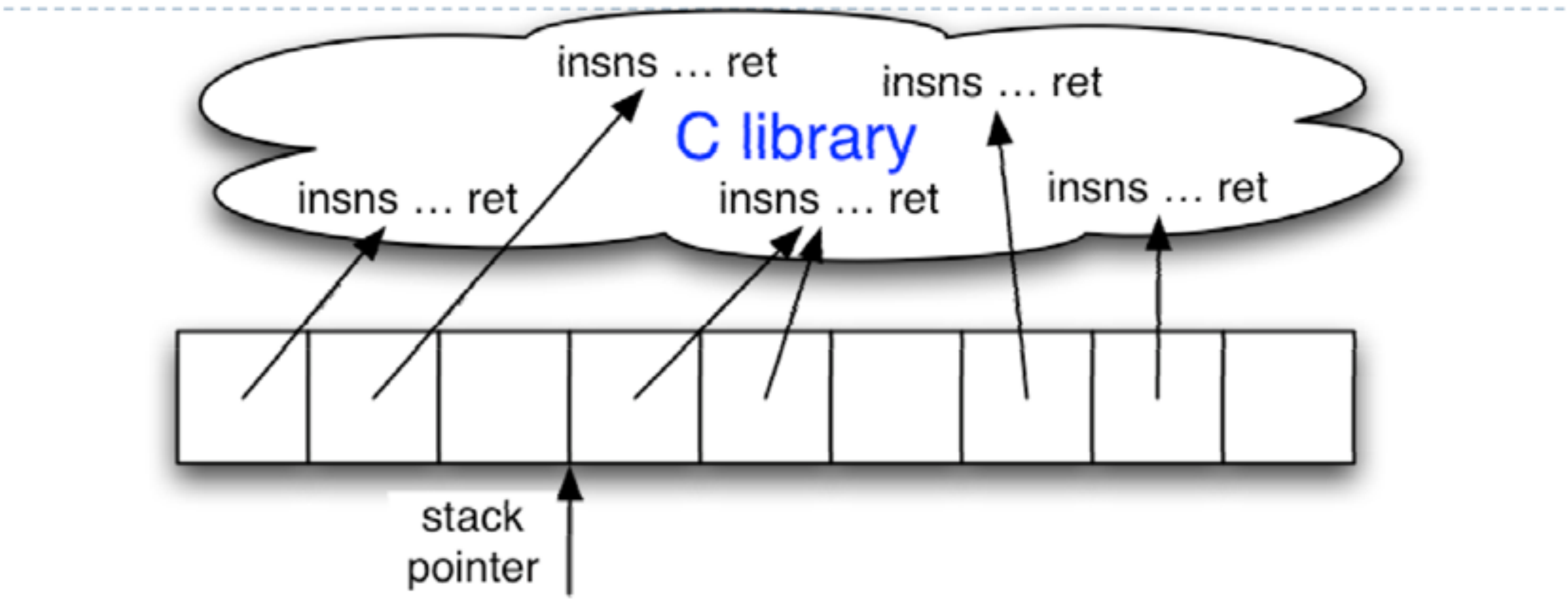
0x8048000 = 5

Machine Instructions



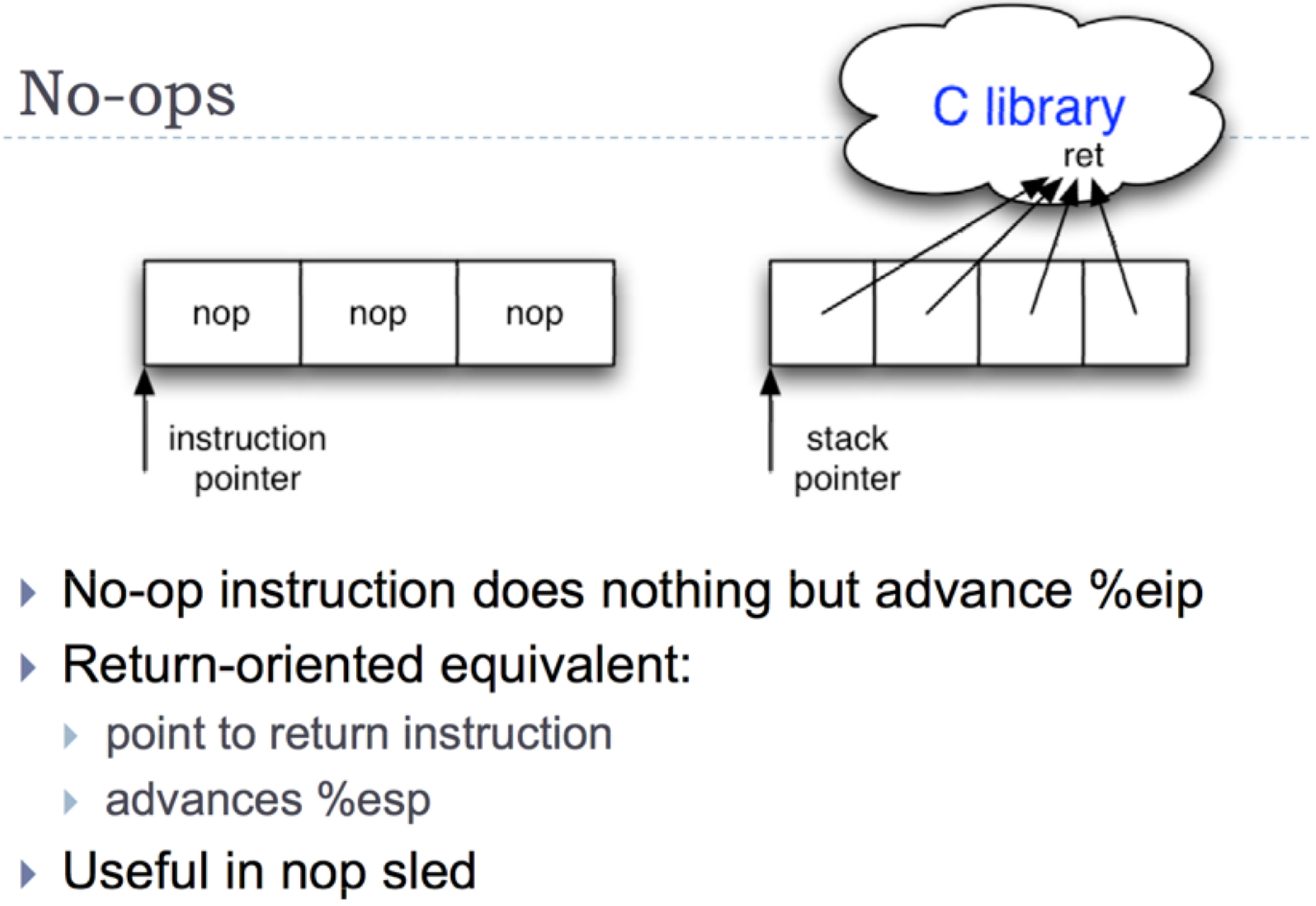
- Instruction pointer (%eip) determines which instruction to fetch & execute
- Once processor has executed the instruction, it automatically increments %eip to next instruction
- Control flow by changing value of %eip

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

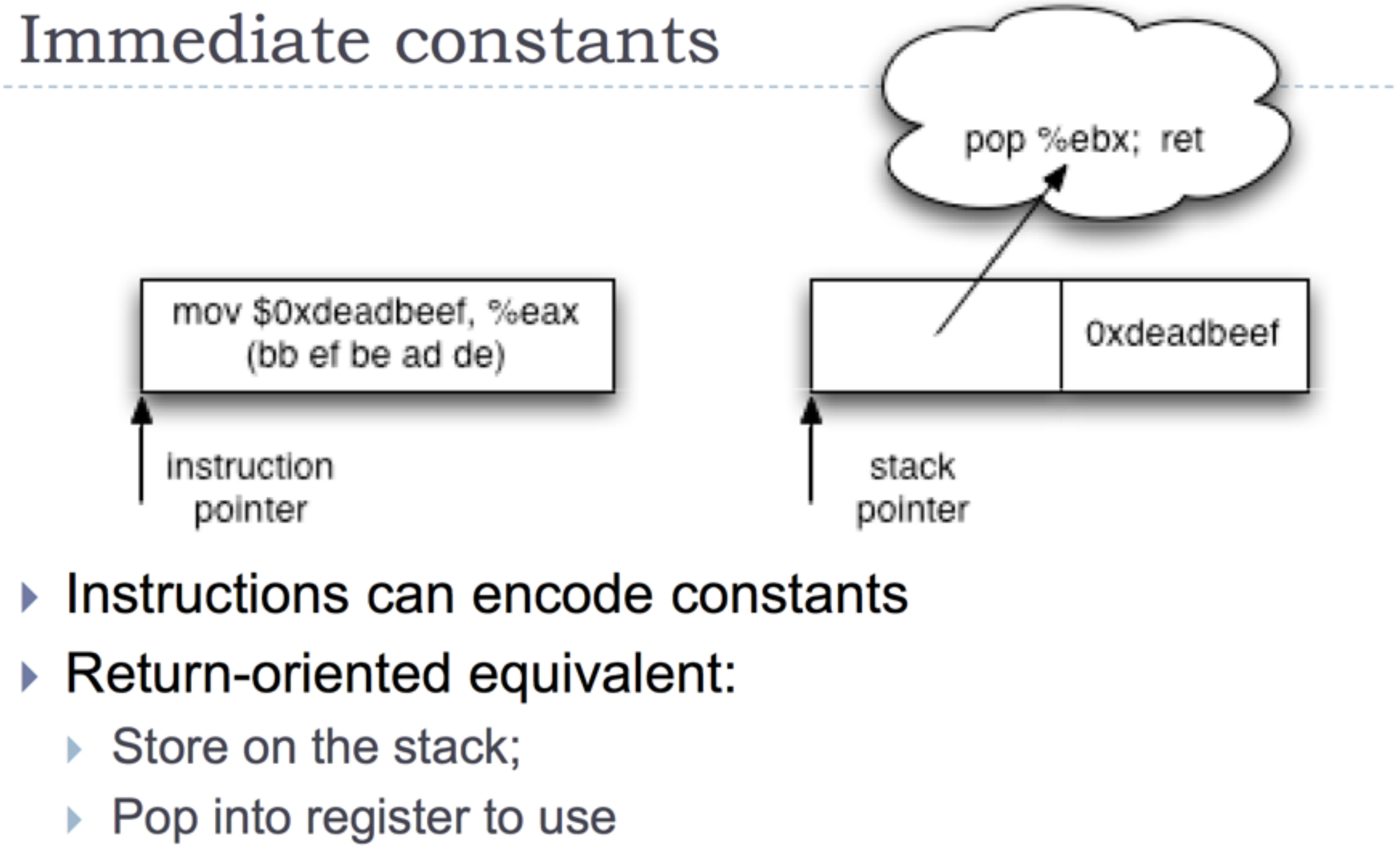
Building ROP Functionality



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

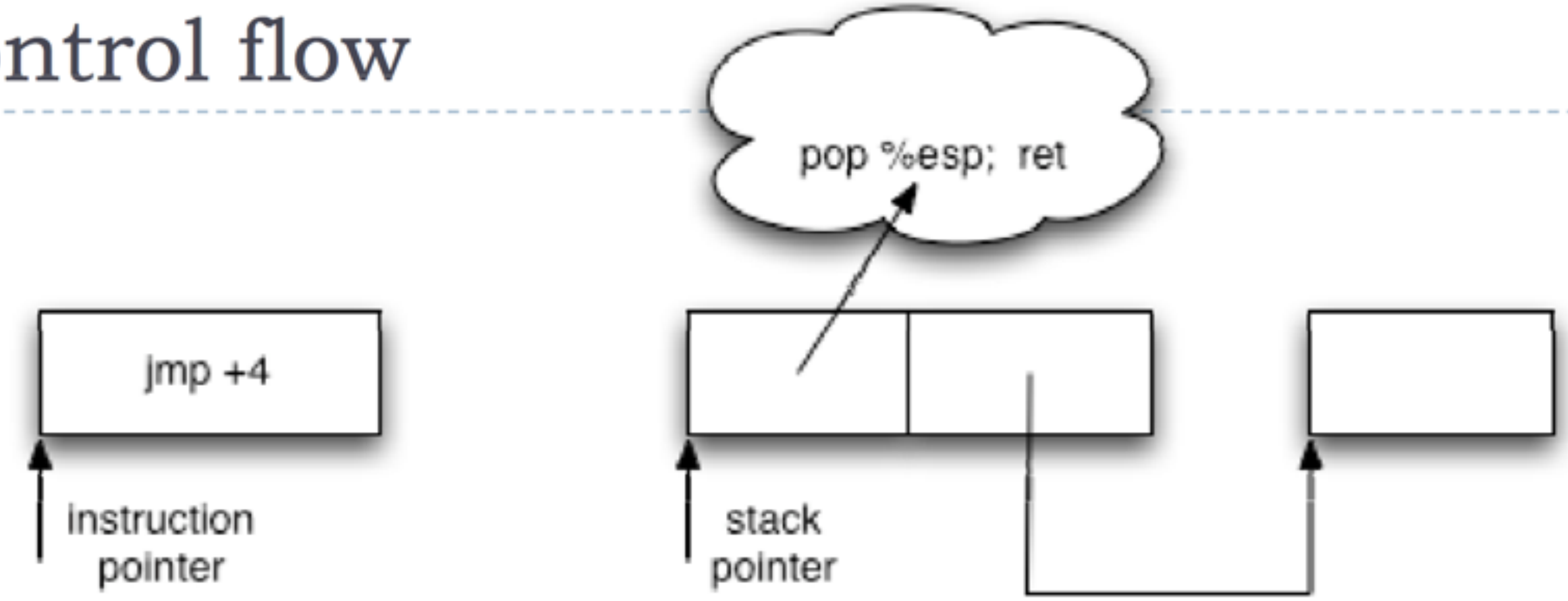


Immediate constants

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

Building ROP Functionality

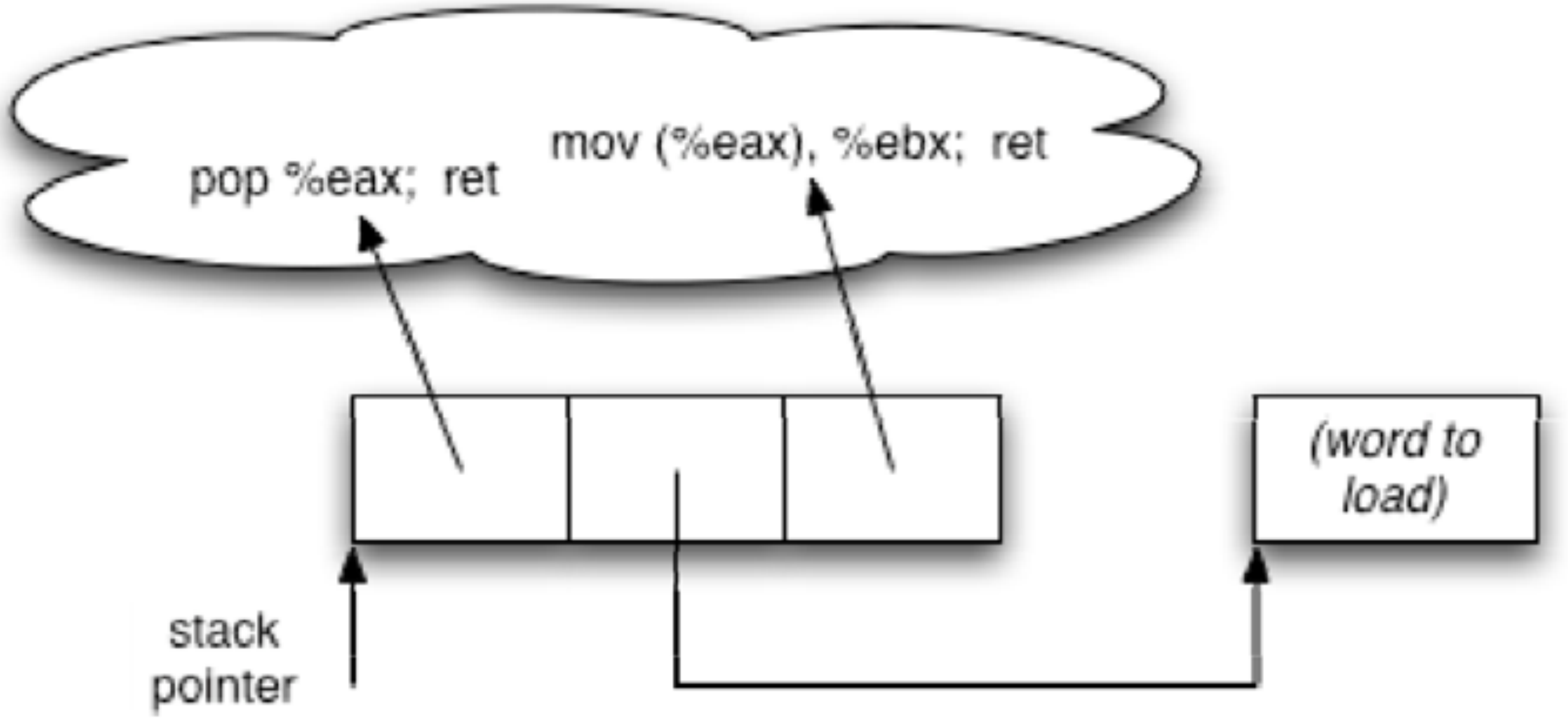
Control flow



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

Creating Programs

Gadgets: multiple instruction sequences



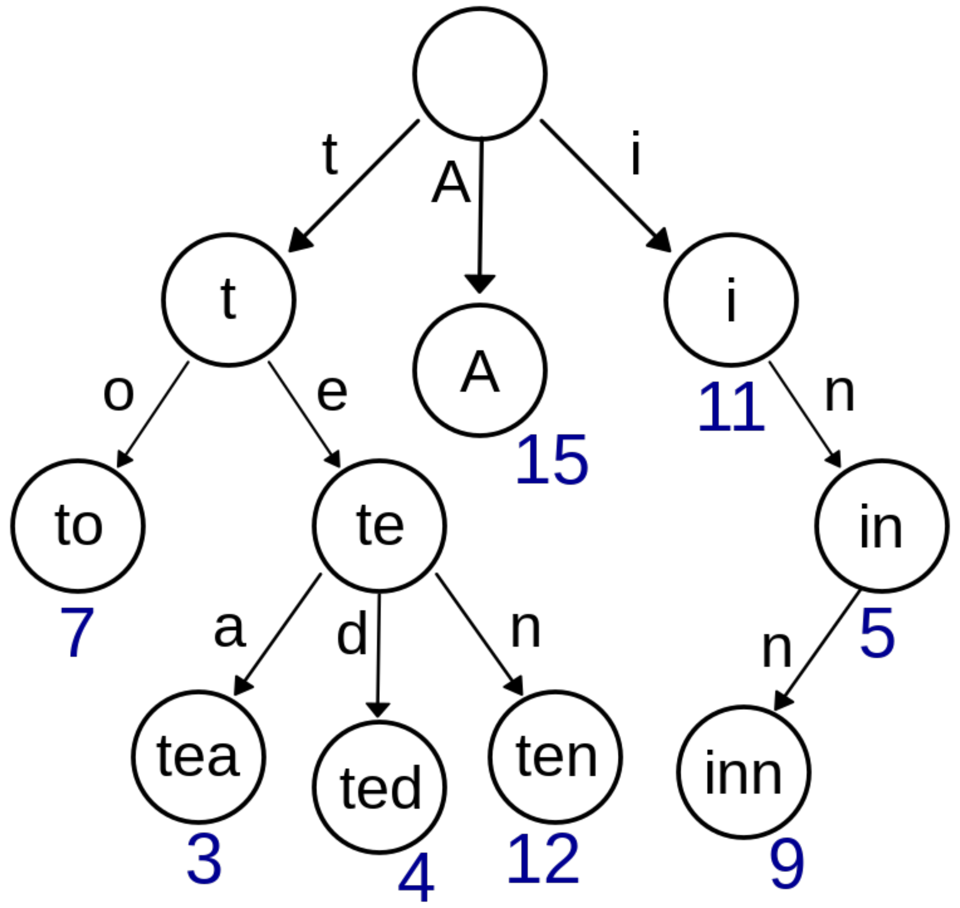
- Sometimes more than one instruction sequence needed to encode logical unit
- Example: load from memory into register:
  - Load address of source word into %eax
  - Load memory at (%eax) into %ebx

Finding Gadgets

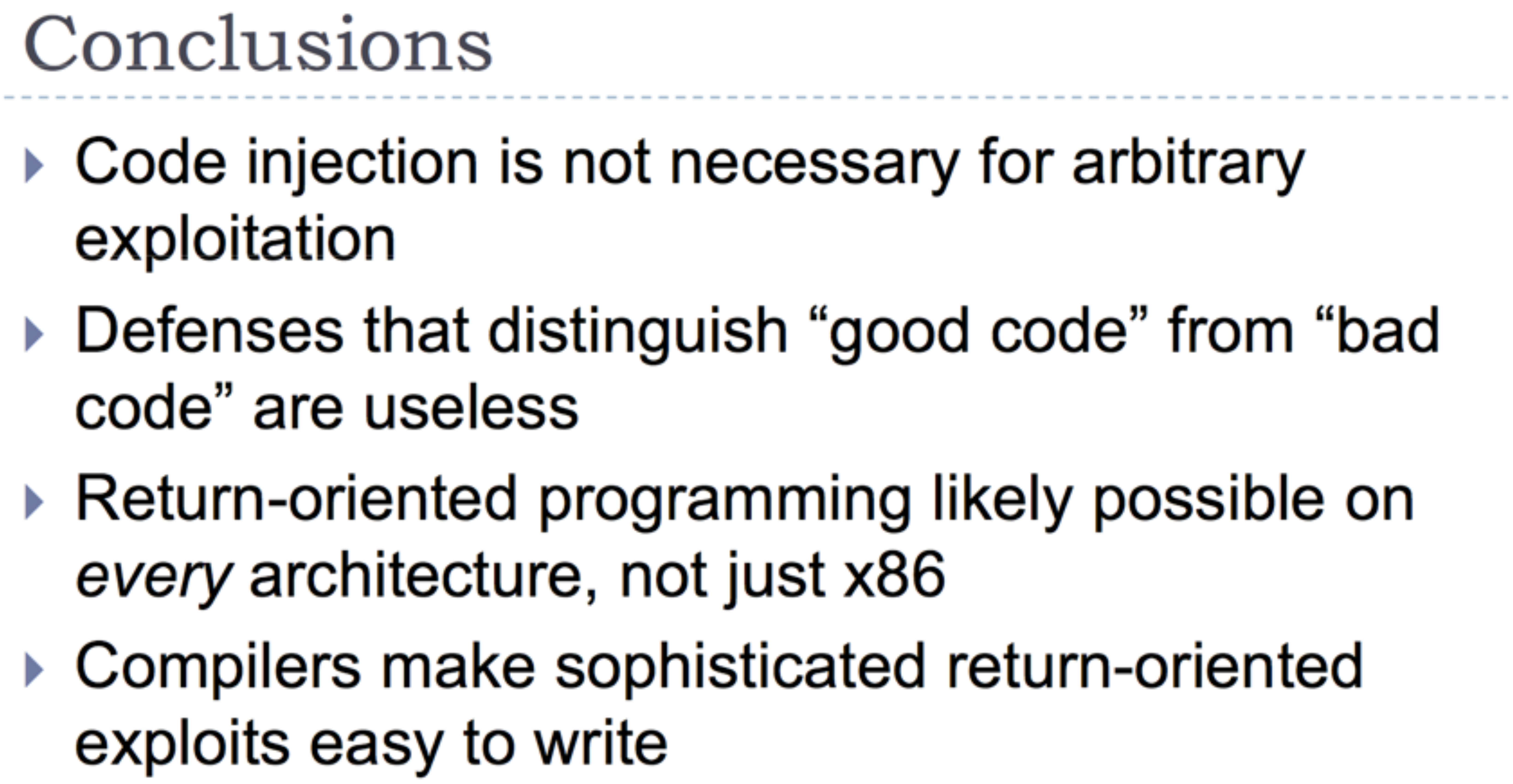
Finding instruction sequences

- Any instruction sequence ending in “ret” is useful — could be part of a gadget

- **Algorithmic problem**: recover all sequences of valid instructions from libc that end in a “ret” insn
- Idea: at each ret (c3 byte) look back:
  - are preceding *i* bytes a valid length-*i*insn?
  - recursefrom found instructions
- Collect instruction sequences in a trie



ROP Conclusions

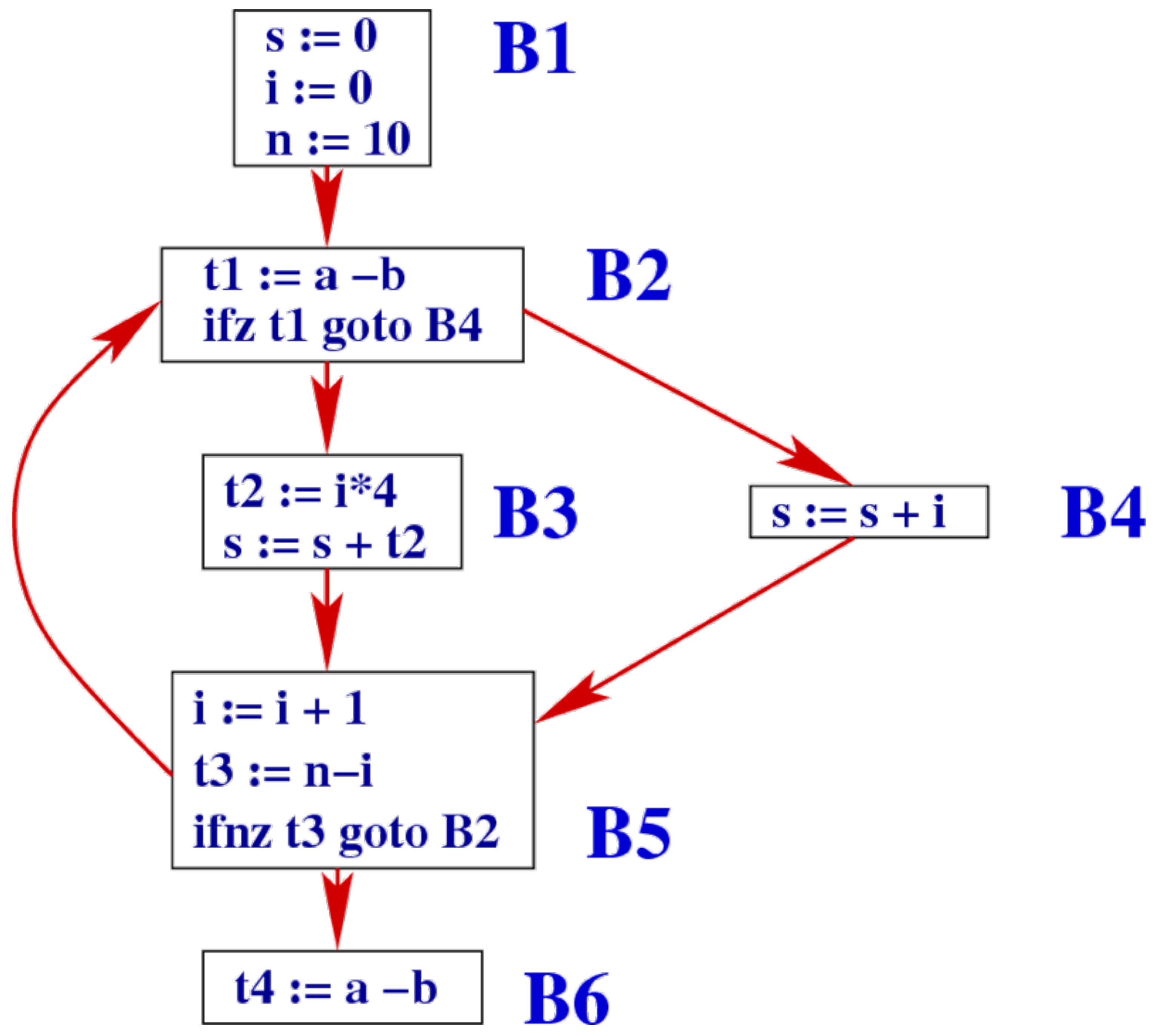


Conclusions

- Code injection is not necessary for arbitrary exploitation
- Defenses that distinguish “good code” from “bad code” are useless
- Return-oriented programming likely possible on *every* architecture, not just x86
- Compilers make sophisticated return-oriented exploits easy to write

Control-Flow Integrity

- Goal: Ensure that process control follows source code
  - Adversary can only choose authorized control-flow sequences
- *Build* a model from source code that describes legal control flows
  - E.g., control-flow graph
- *Enforce* the model on program execution
  - Instrument indirect control transfers
    - Jumps, calls, returns, ...
- Challenges
  - Building accurate model
  - Efficient enforcement



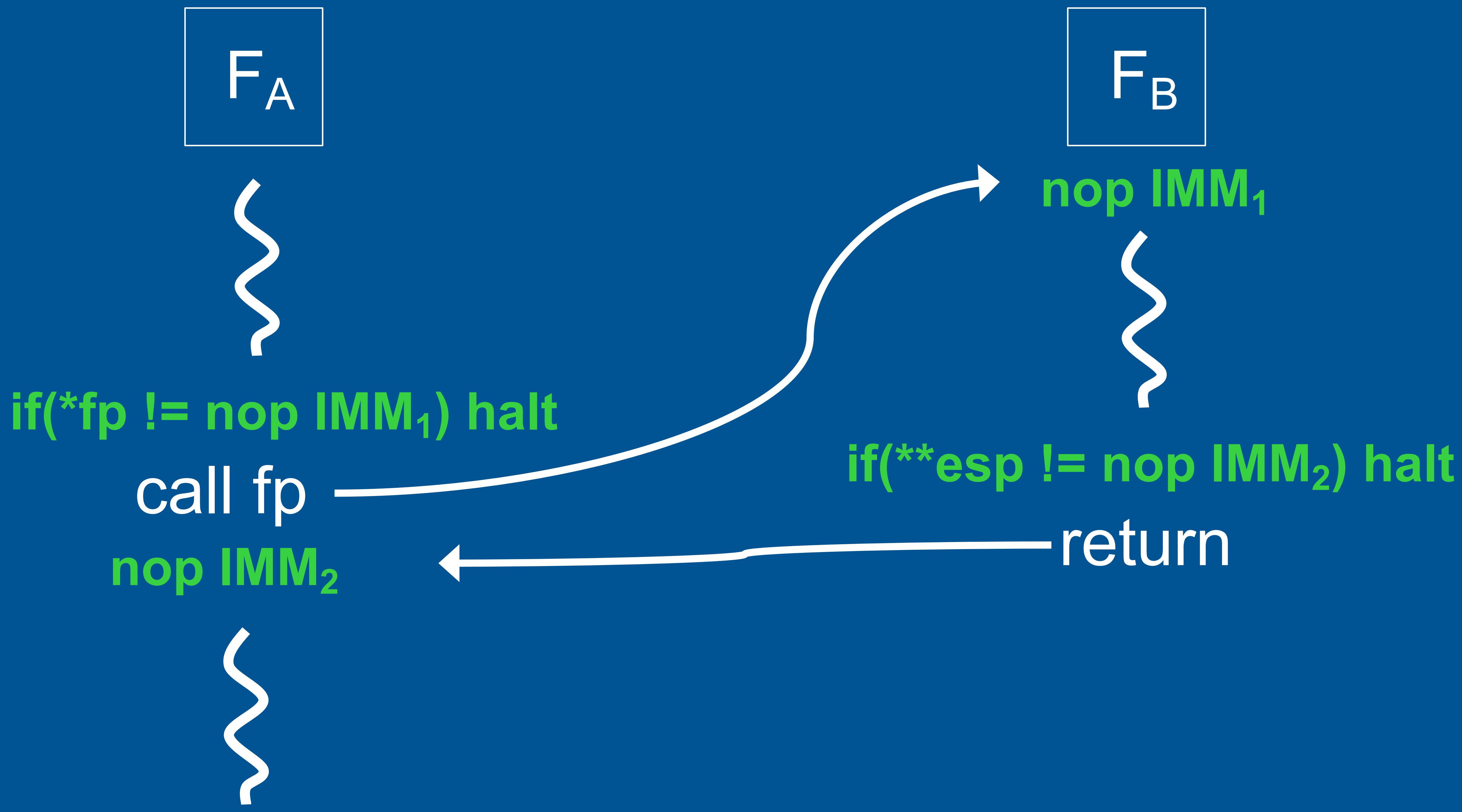
Basic Block: a basic block is a straight-line code sequence with no branches in except to the entry and no branches out except at the exit.

Software Control Flow Integrity

Techniques, Proofs, & Security Applications

Jay Ligatti summer 2004 intern work with:
Úlfar Erlingsson and Martín Abadi

Our Mechanism



F_A

if(*fp != nop IMM_1) halt

call fp

nop IMM_2

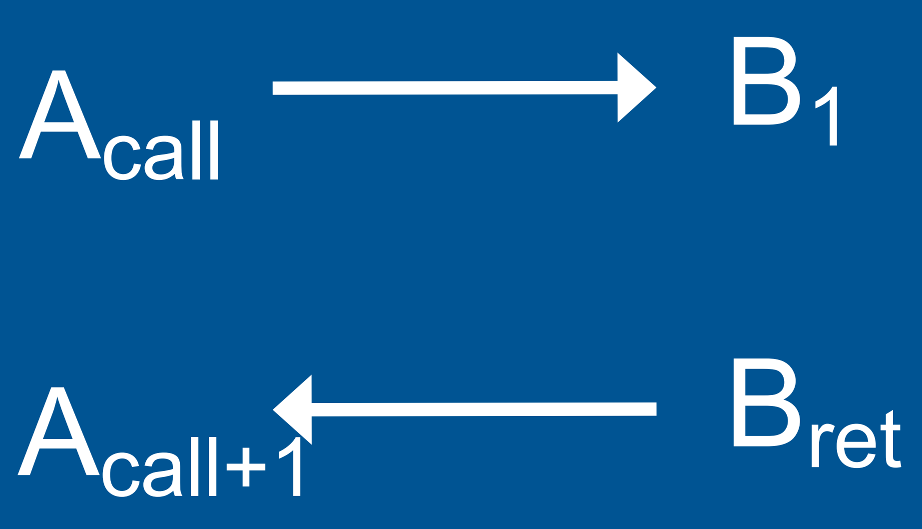
F_B

nop IMM_1

if(esp != nop IMM_2) halt**

return

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



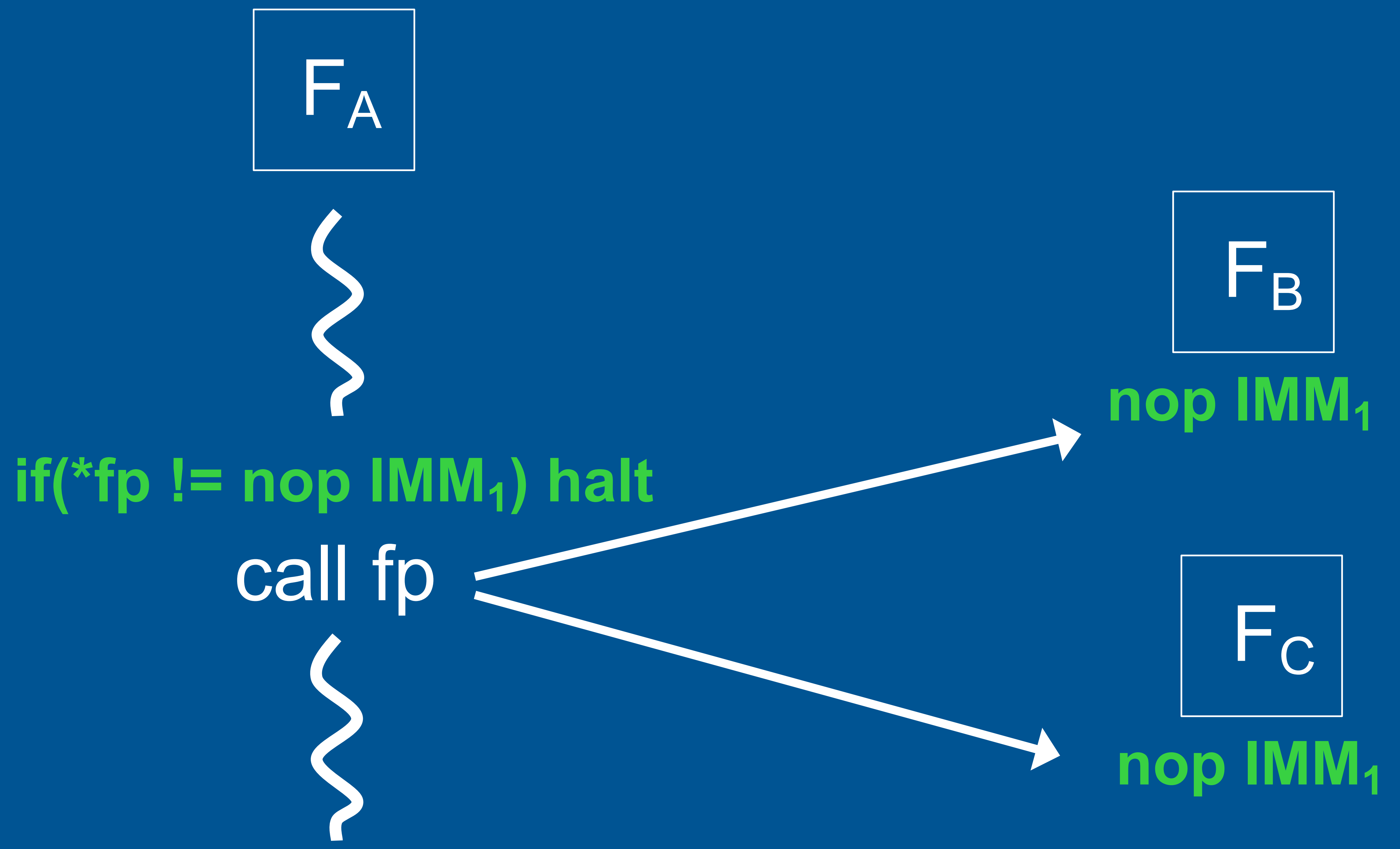
CFG excerpt

$A_{call} \longrightarrow B_1$

$A_{call+1} \longleftarrow B_{ret}$

Our Mechanism

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



F_A

if(*fp != nop IMM_1) halt

call fp

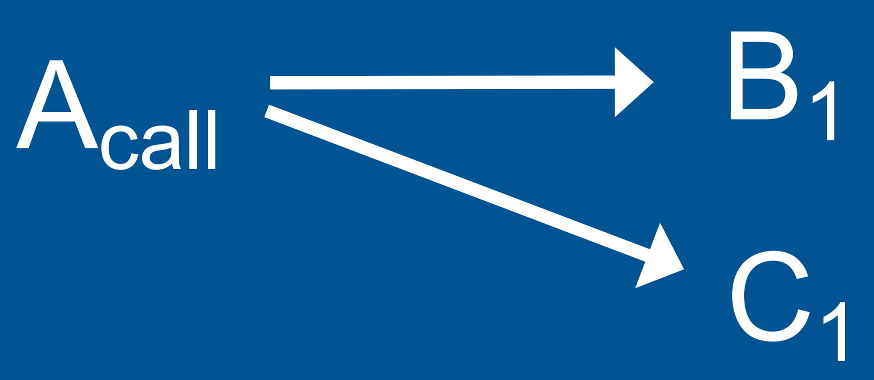
F_B

nop IMM_1

F_C

nop IMM_1

CFG excerpt



A_{call}

B_1

C_1

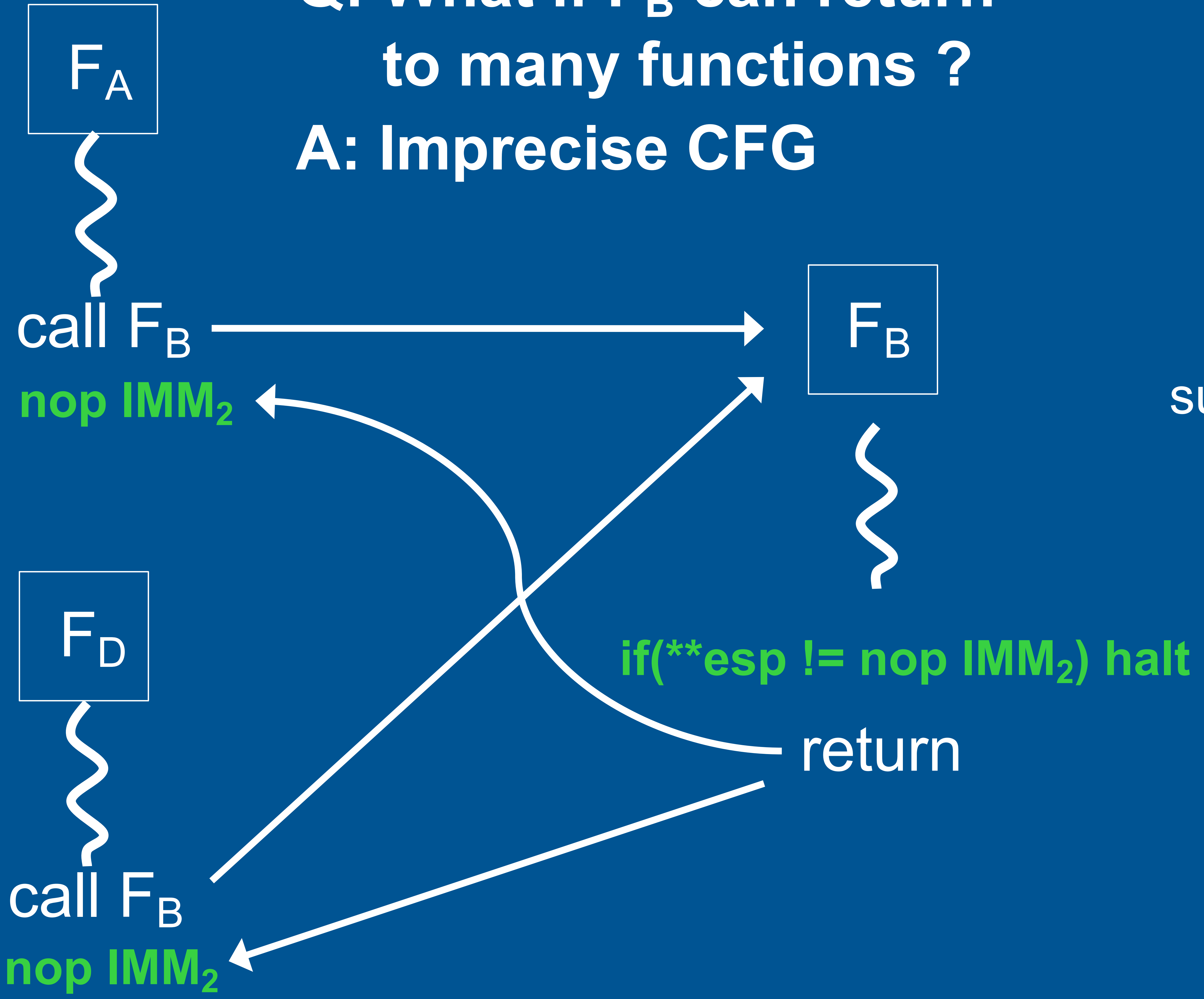
$succ(A_{call}) = \{B_1, C_1\}$

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

Our Mechanism

Q: What if F_B can return to many functions ?

A: Imprecise CFG



F_A

call F_B

nop IMM_2

F_D

call F_B

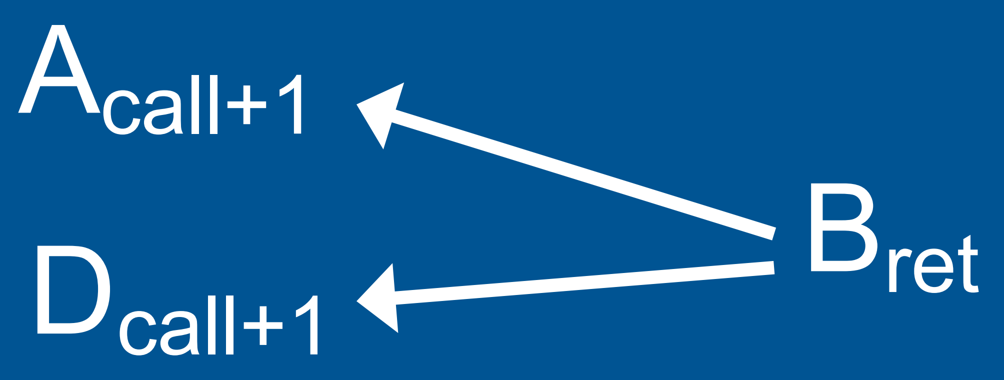
nop IMM_2

F_B

if(esp != nop IMM_2) halt**

return

CFG excerpt



A_{call+1}

B_{ret}

D_{call+1}

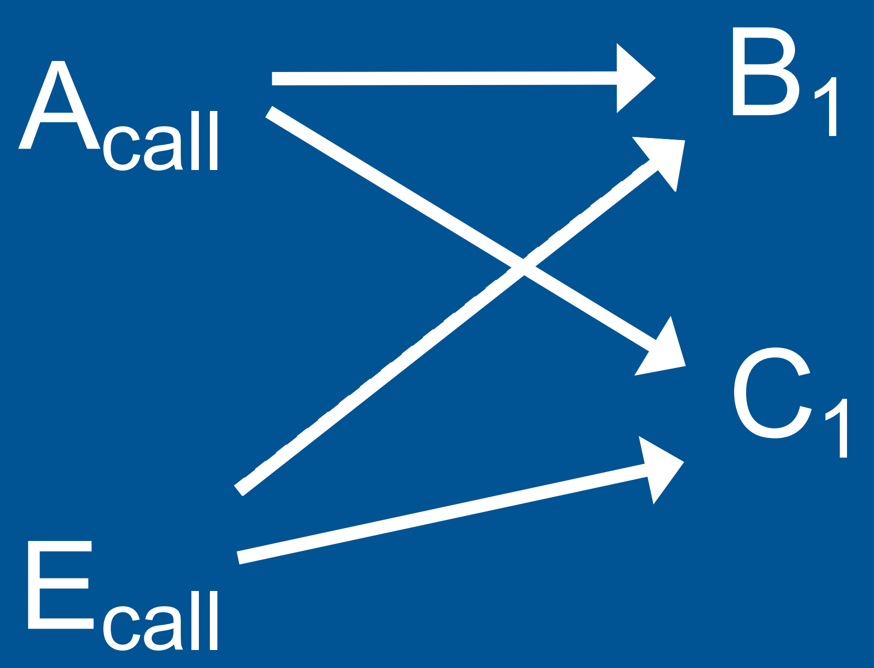
$succ(B_{ret}) = \{A_{call+1}, D_{call+1}\}$

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

Our Mechanism

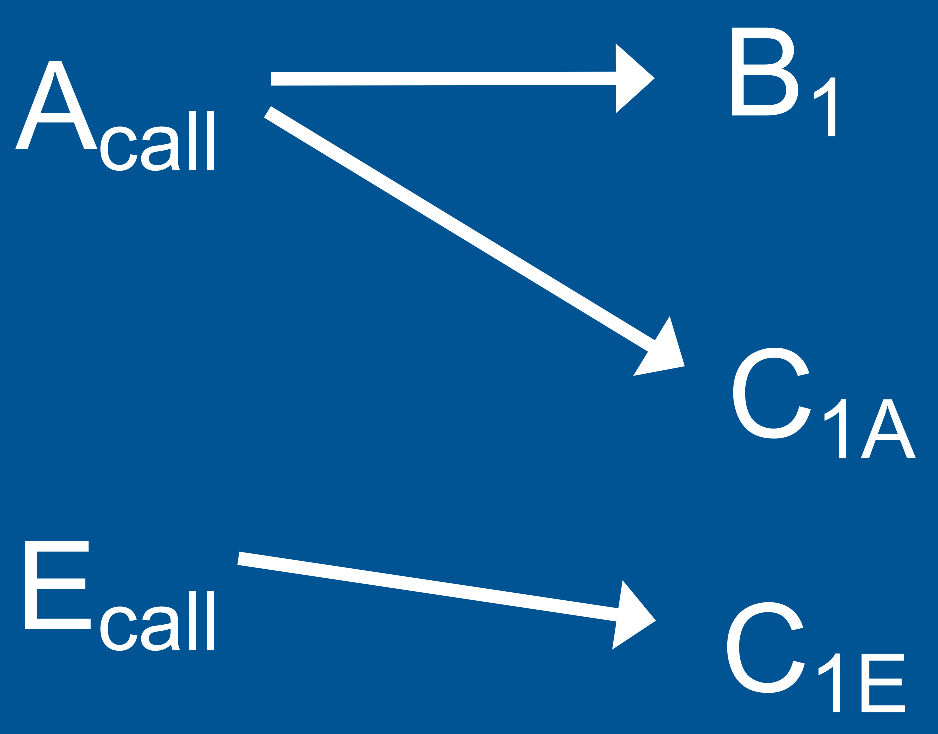
Solution I: Allow the imprecision

CFG excerpt



Solution II: Duplicate code to remove zig-zags

CFG excerpt



CFG Imprecision

- Best reduced by a technique developed in the "HyperSafe" system
  - "HyperSafe: A Lightweight Approach to Provide Lifetime Hypervisor Control-Flow Integrity" IEEE Symposium on Security and Privacy, 2010
- On indirect call (forward edge)
  - Check the proposed target against the set of legal targets from the CFG
- On return (backward edge)
  - Check the proposed return location against the set of legal return locations from the CFG
- Tricky to make that efficient (see the paper)

Shadow Stack

- What should be the target of a return instruction?
  - Return to caller
  - But, need a way to protect return value
- Shadow stack
  - Stack that can only be accessed by trusted code (e.g., software fault isolation)
  - Off limits to overflows

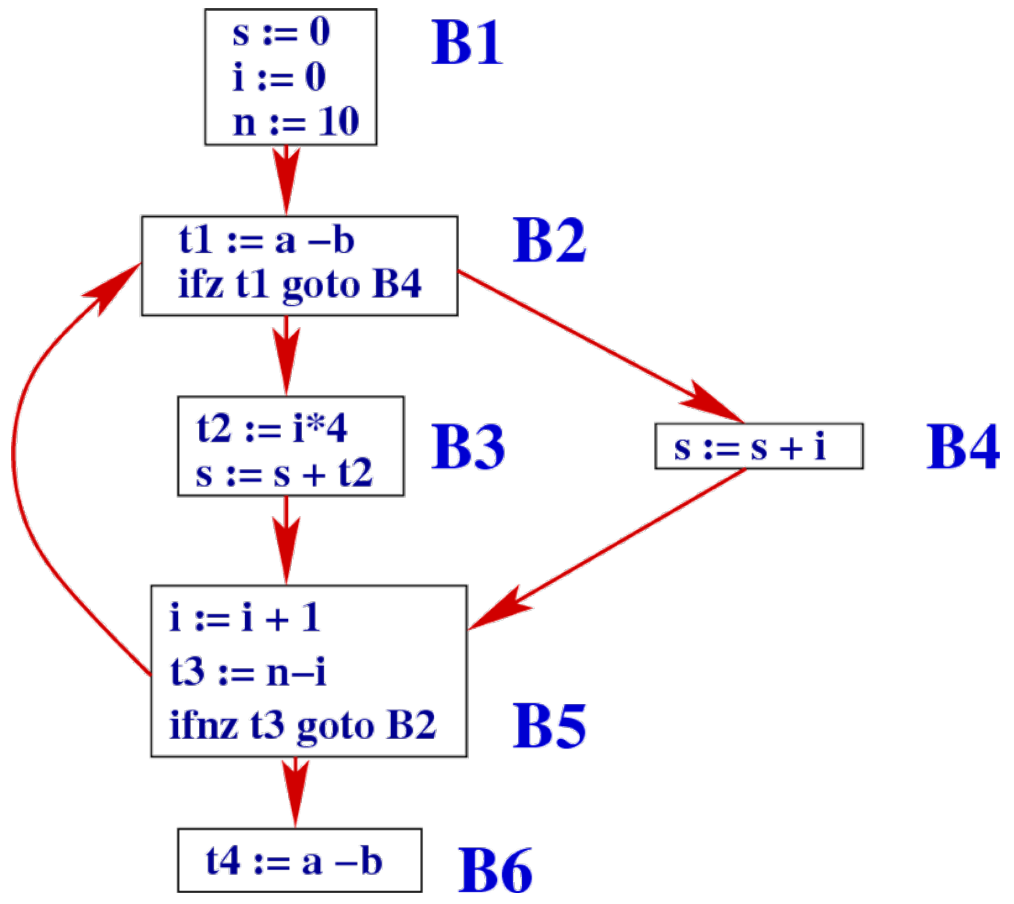
CFG Computation

- What should be the target of a call instruction?
  - Direct call - hard coded, so no problem
  - Indirect call (function pointer) - would be any legal value for the function pointer
    - That is, anywhere it can point
    - The "points-to" problem in general, which is undecidable
- So, there are various techniques to over-approximate the target set for each indirect call

More Challenges

- Predicting return targets can be hard
    - Exceptions, signals, and setjmp/longjmp
- Runtime generation of indirect jumps
    - E.g., dynamically linked libraries
- Indirect jumps using arithmetic operators
    - E.g., assembly

- Is enforcing fine-grained CFI sufficient to prevent exploits?



Recent Result

- Suppose a program is protected by fine-grained CFG on calls and a shadow stack on returns
- Further suppose that the program contains an "arbitrary write primitive" (e.g., based on a memory error)
- For these programs, exploits can be generated over 80% of the time, even against CFI defenses
  - "Block Oriented Programming: Automating Data-Only Attacks", ACM CCS 2018
- Exploits follow CFG, but manipulate memory to complete exploit
  - Called "data-oriented programming"

Alternatives to CFI?

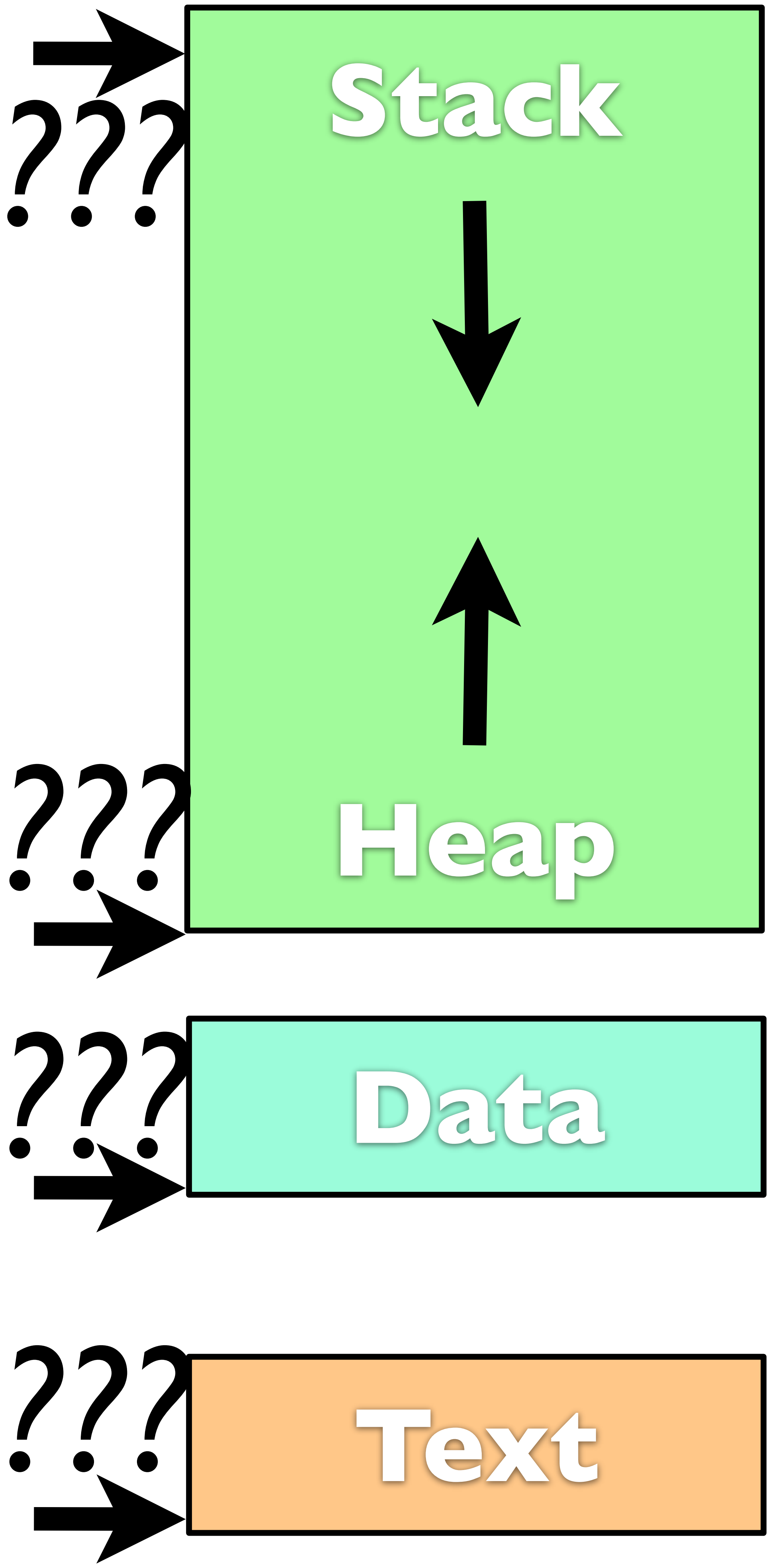
- What are the fundamental enablers of ROP attacks?
  - (1) CFI: violate control flow
  - (2) Adversary can choose gadgets
- Can we prevent adversaries from choosing useful gadgets?
  - In general, adversaries can create/obtain the same binary as is run by the victim
  - But, that need not be the case

Apply Crypto to Code?

- Can we randomize the program’s execution in such a way that an adversary cannot select gadgets?
- Given a secret key and a program address space, encrypt the address space such that
  - the probability that an adversary can locate a particular instruction (start of gadget) is sufficiently low
  - and the program still runs correctly and efficiently
- Called address space randomization

ASLR

- For control-flow attacks, attacker needs absolute addresses
- Address-space Layout Randomization (ASLR) randomizes base addresses of memory segments on each invocation of the program
  - Attacker cannot predict absolute addresses
- Heap, stack, data, text, mmap, …



ASLR Implementations

- Linux
  - Introduced in Linux 2.6.12 (June 2005)
  - Shacham et al. [2004]: 16 bits of randomization defeated by a (remote) brute force attack in minutes
  - Reality: ASLR for text segment (PIE) is rarely used
    - Only few programs in Linux use PIE
    - Enough gadgets for ROP can be found in unrandomized code [Schwartz 2011]

ASLR Limitations

- Attacks may leak randomization information
  - Disclosure attacks
  - Use buffer over-read to read unauthorized program memory (extract code or randomizing state)
- ASLR can be bypassed by information leaks about memory layout
  - E.g., format string vulnerabilities
- So, what can we do?
  - How do we avoid leaking the "key"?

Conclusion

- Control-flow attack defenses operate at two stages
  - Prevent attacker from getting control
    - StackGuard, heap sanity checks, ASLR, shadow stacks, ...
  - Prevent attacker from using control for malice
    - NX, W (xor) X, ASLR, Control Flow Integrity (CFI), ...
- For maximum security, a system may need to use a combination of these defenses
- *Q. Is subverting control-flow the only goal of an attacker?*