CSE 127 Computer Security

Stefan Savage,
Spring 2020, Lecture 6

Control Flow Vulnerabilities: ROP and CFI

Recall from last class

- Recall: Data Execution Prevention (DEP/W^X)
  - Prevent attacker input (which is data) from being interpreted as code by marking data pages as non-executable
    - One exception: applications like browsers that explicitly mark some of their data as executable to Just-In-Time compilation (JIT)
  - Win!

- Is there another way for an attacker to execute arbitrary code even without the ability to inject it into the victim process?

Code Reuse Attacks

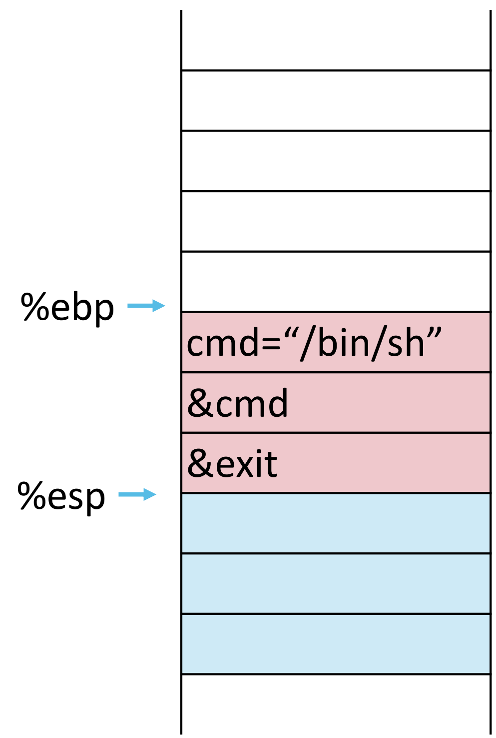
- Use the code that's already there
- What code is already there?
  - Program + shared libraries (including libc)

Return-To-Libc

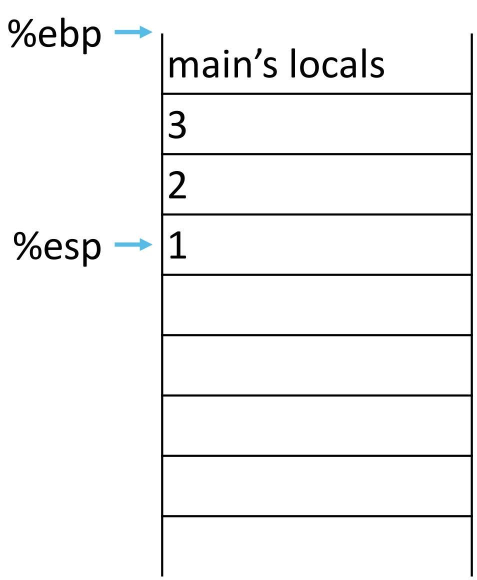
- What can we find in libc?
  - "*The system() library function uses fork(2) to create a child process that executes the shell command specified in command using execl(3) as follows:*
    `execl("/bin/sh", "sh", "-c", command, (char *) 0);`"
  - Need to find the address of:
    - `system()`
    - String "/bin/sh"
  - Overwrite the return address to point to start of `system()`
  - Place address of "/bin/sh" on the stack so that `system()` uses it as the argument
    - To be clean, you also want to push exit() on the stack so it will shut down gracefully

Return-To-Libc

- What we want to get to
  - Transfer control to address of system() in libc
  - Setup stack frame to look like a normal call to system()
    - **int system(const char *_command_);**
    - &exit() system call is in the slot where the return address would be
    - &cmd is the argument
    - It points to the string "/bin/sh" stored further down the stack

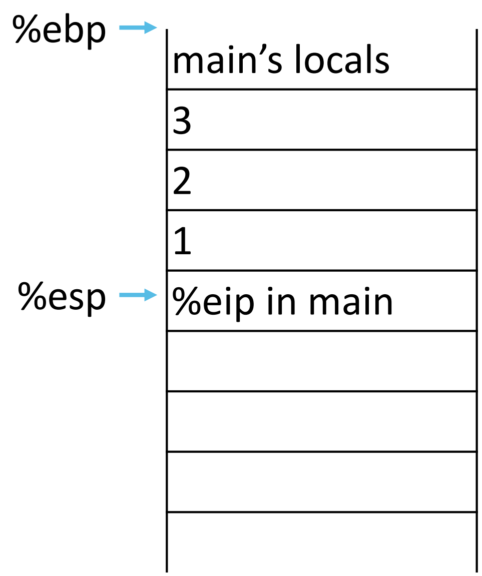


Review: calling and returning



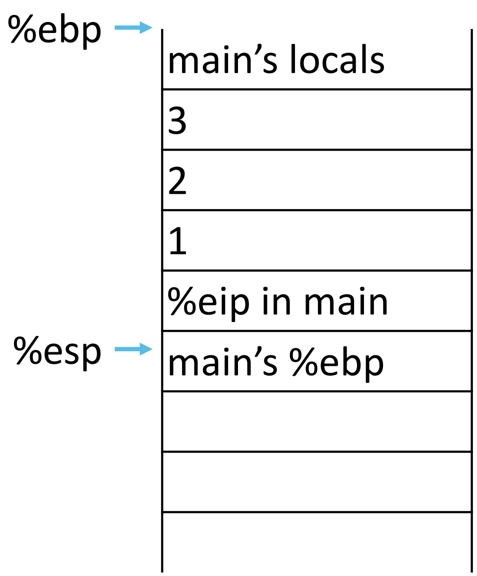
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



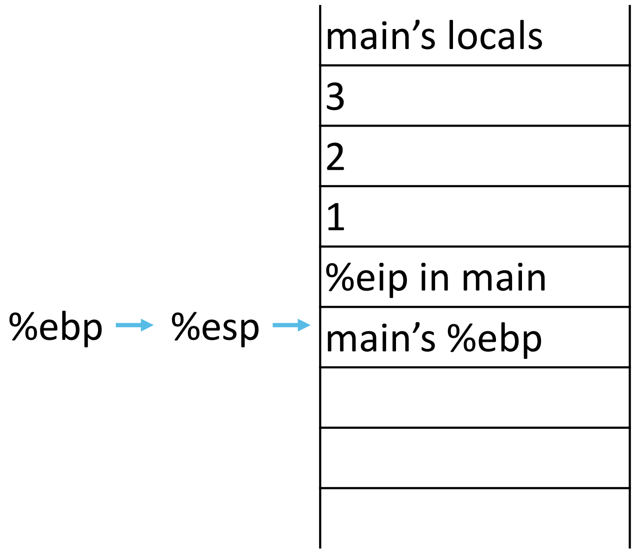
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



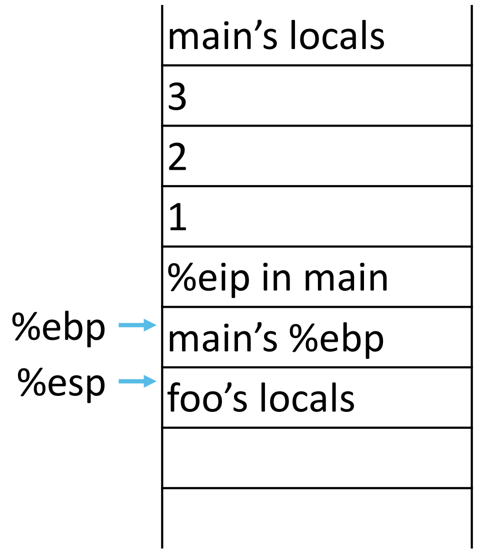
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



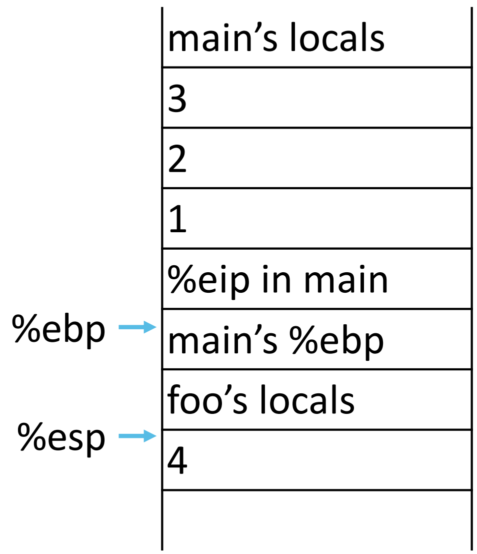
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



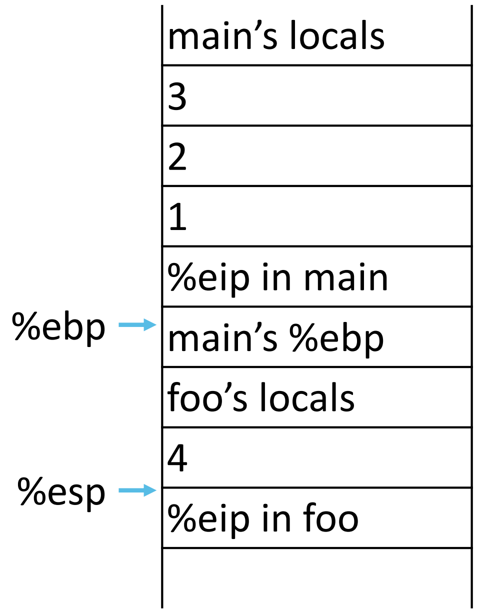
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



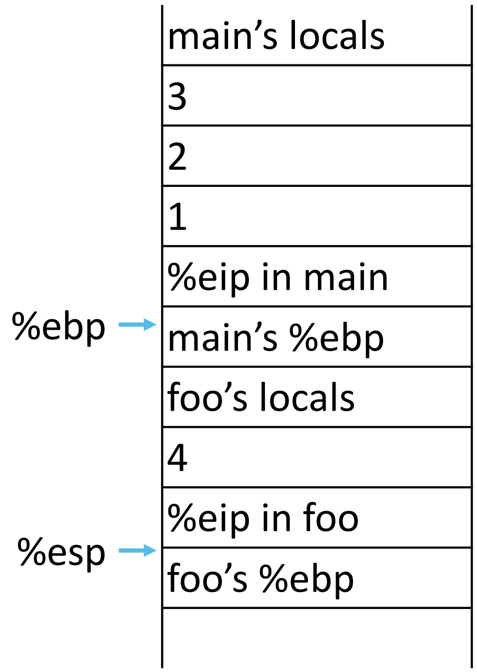
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



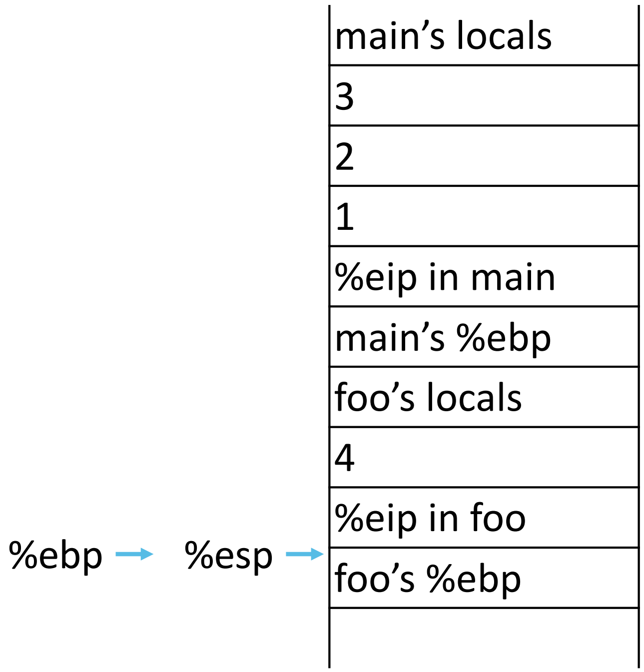
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



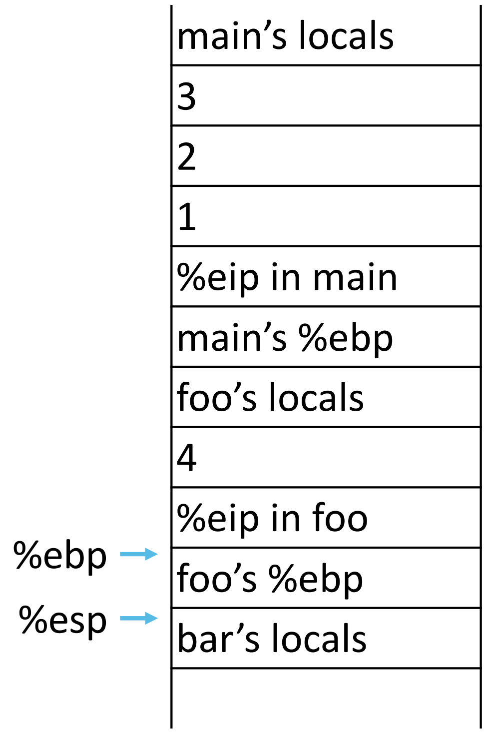
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



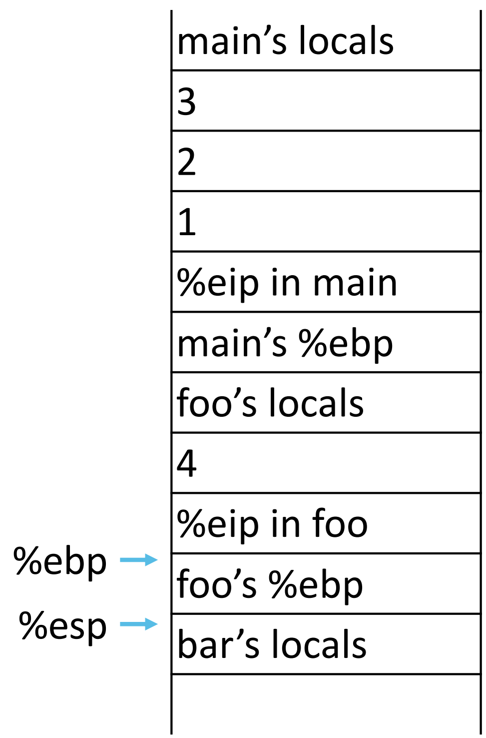
main()
-> foo(1,2,3)
——> bar(4)

Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

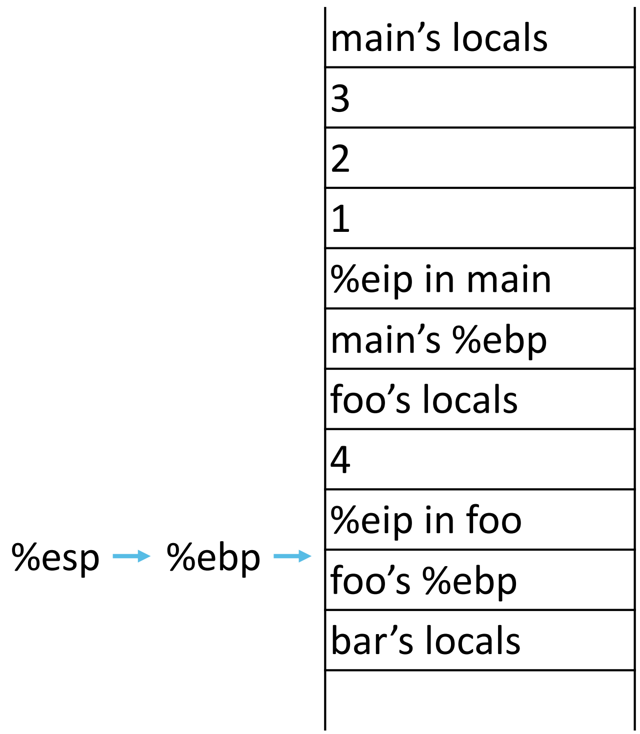
Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

leave = mov %ebp, %esp
pop %ebp

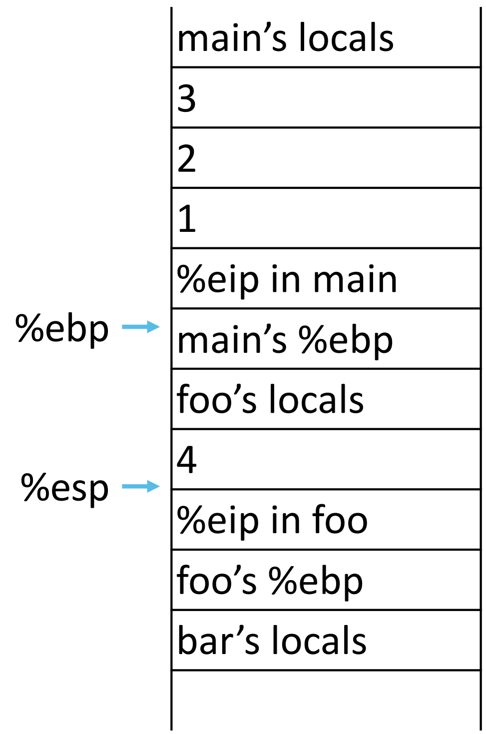
Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

leave = mov %ebp, %esp
pop %ebp

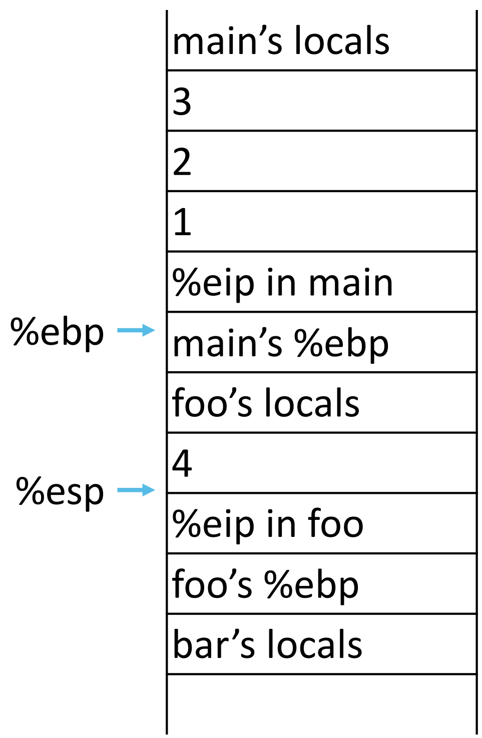
Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

leave = mov %ebp, %esp
pop %ebp

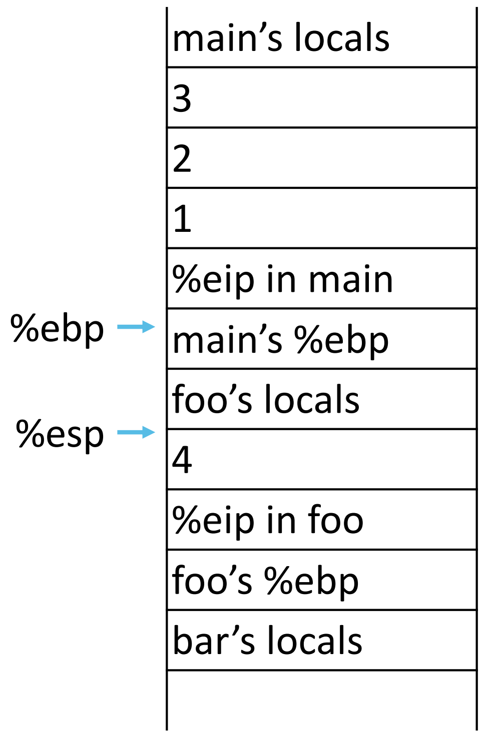
Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

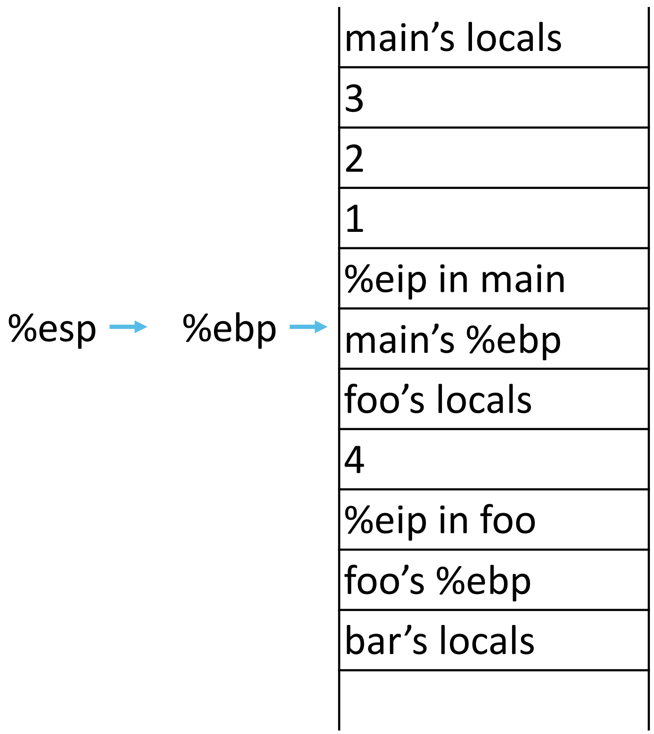
ret = pop %eip

Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

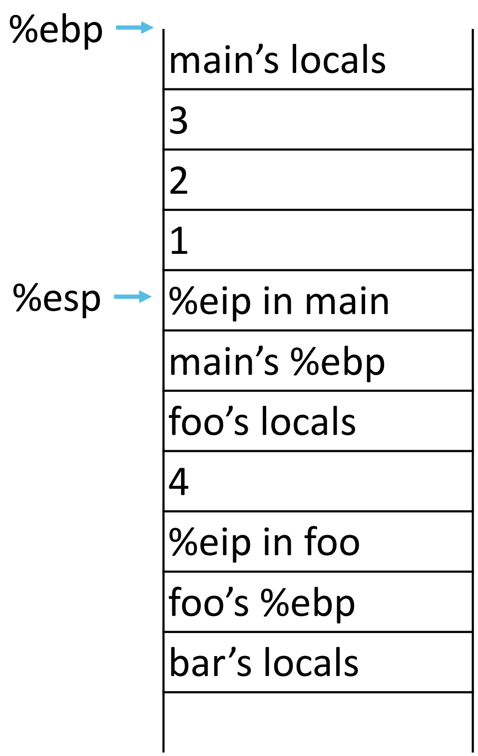
Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

leave = mov %ebp, %esp
pop %ebp

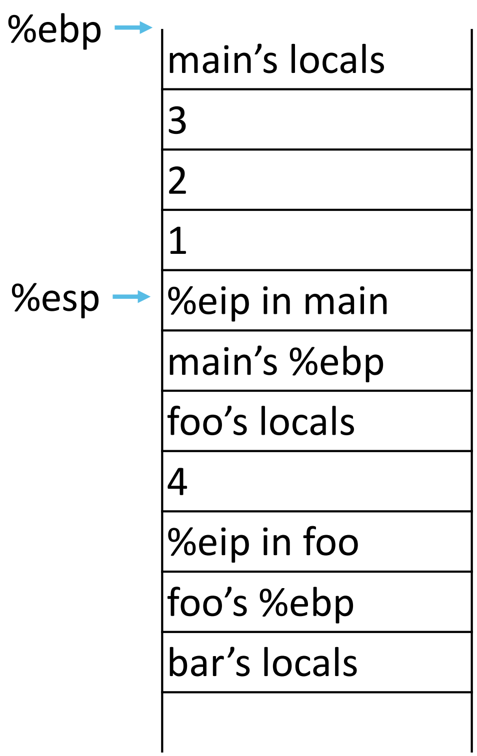
Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

leave = mov %ebp, %esp
pop %ebp

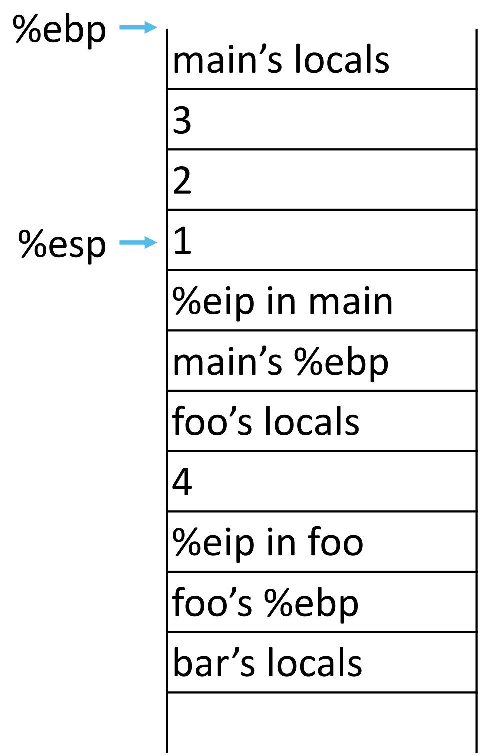
Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

ret = pop %eip

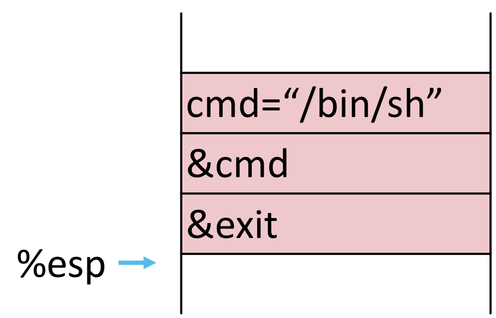
Review: calling and returning



main()
-> foo(1,2,3)
——> bar(4)

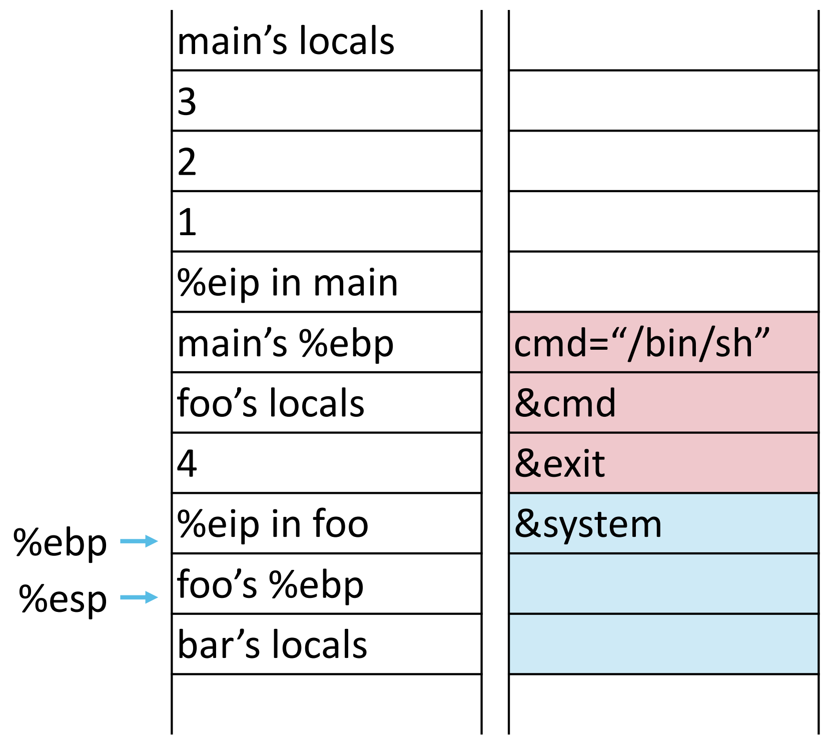
Suppose bar() had a stack overflow

- Our goal: call system("/bin/sh")
- Remember: Need to set up stack frame that looks like a legit call to system:

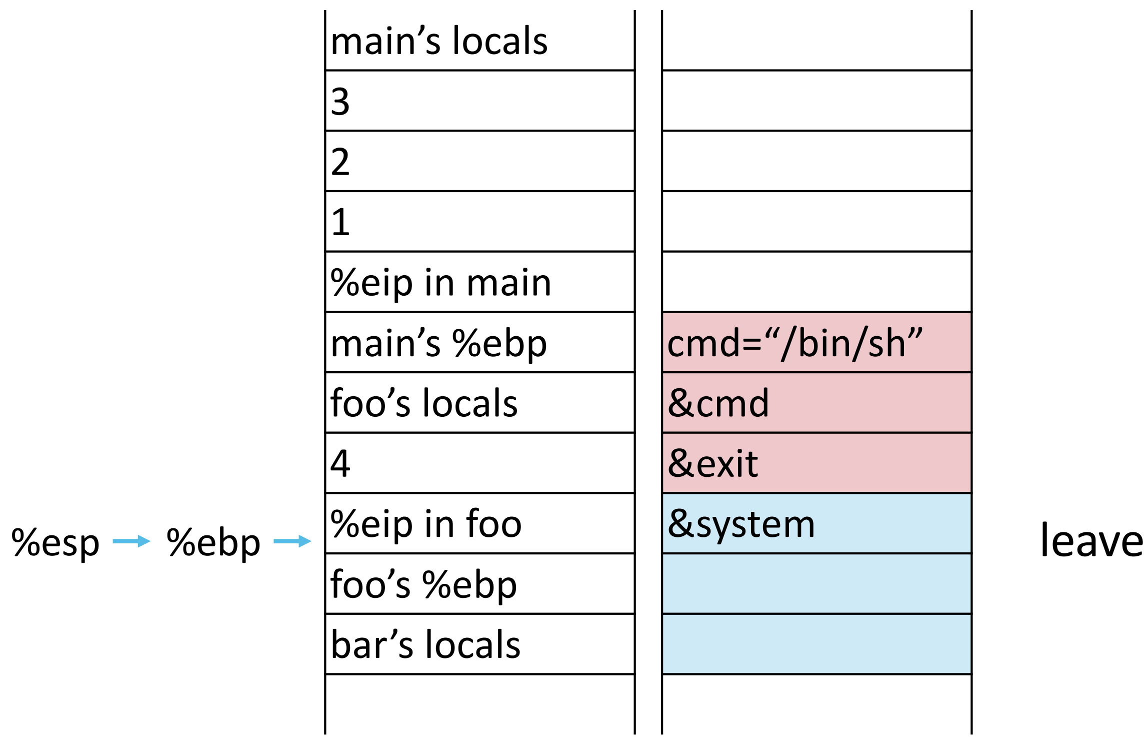


- But we're not going to use the `call` instruction to jump to system; we're going to use `ret`

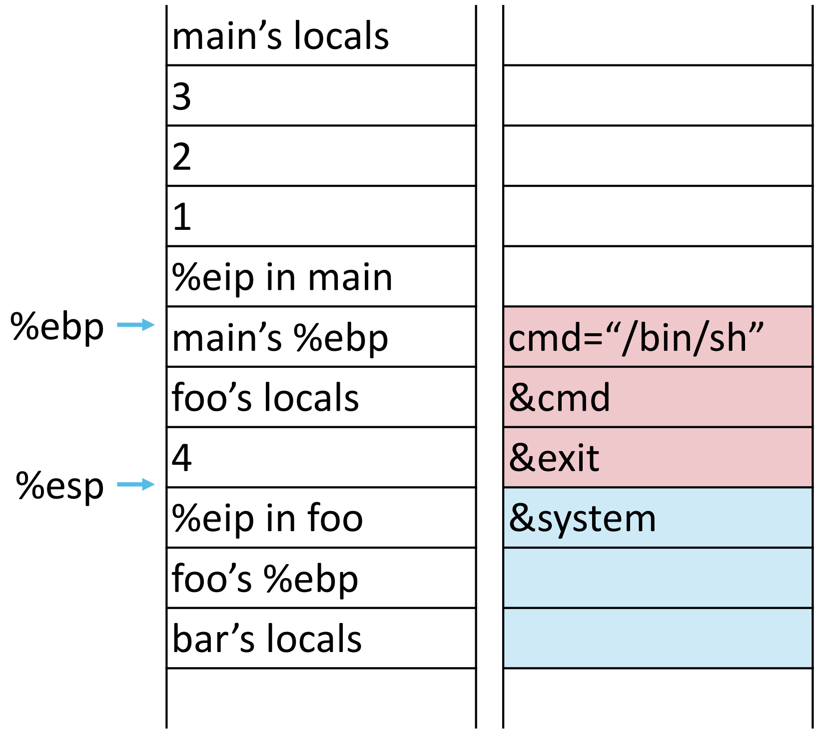
Hijacking control flow



Hijacking control flow

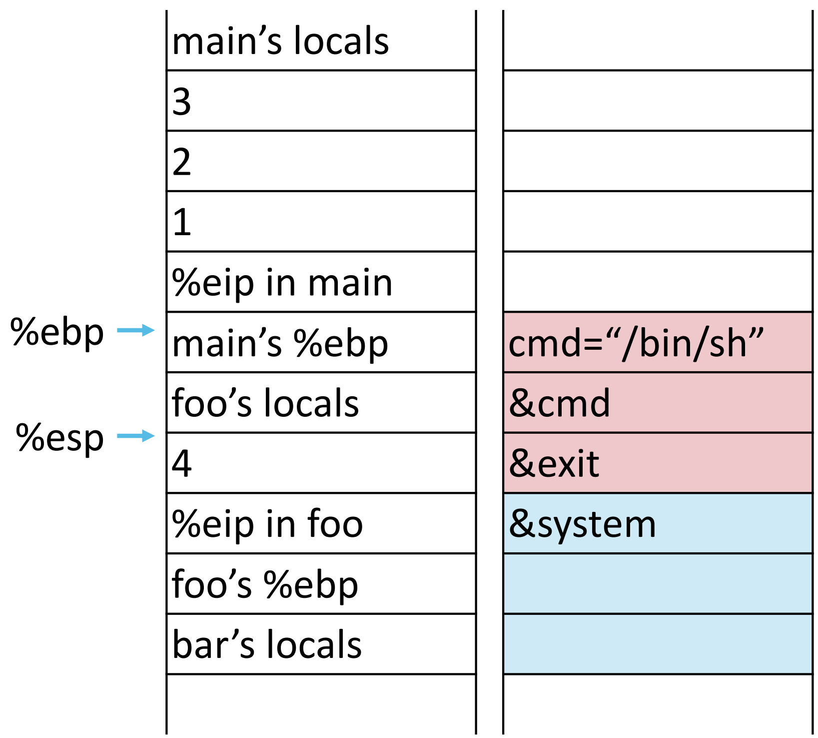


Hijacking control flow

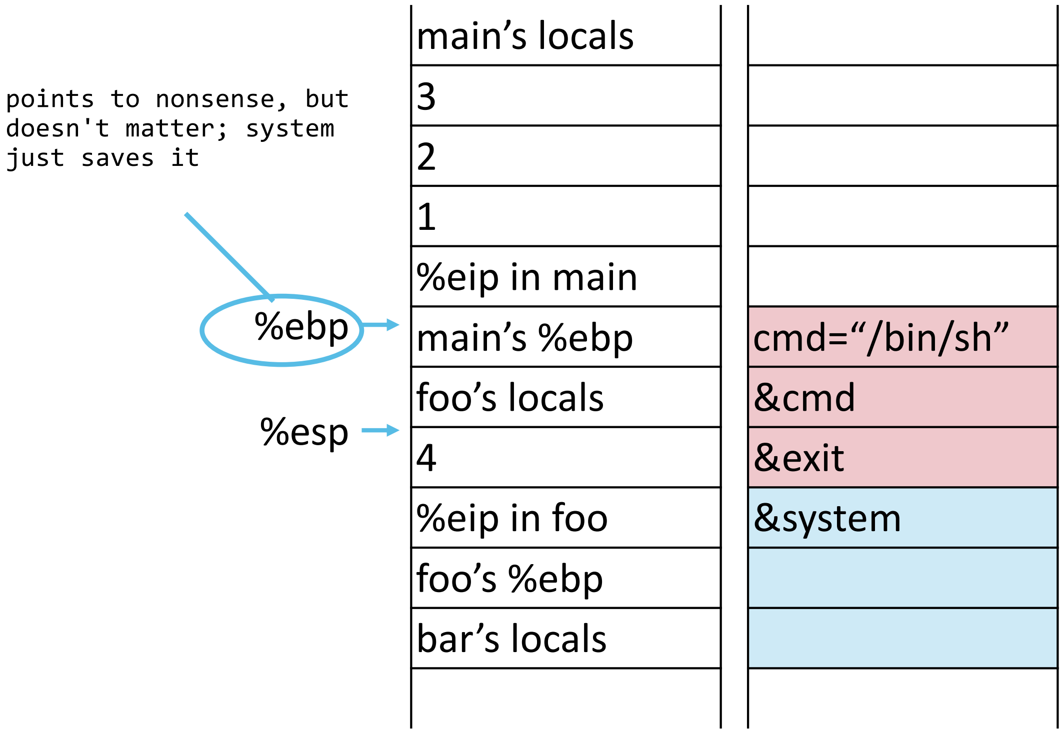


ret (go to system())

Hijacking control flow

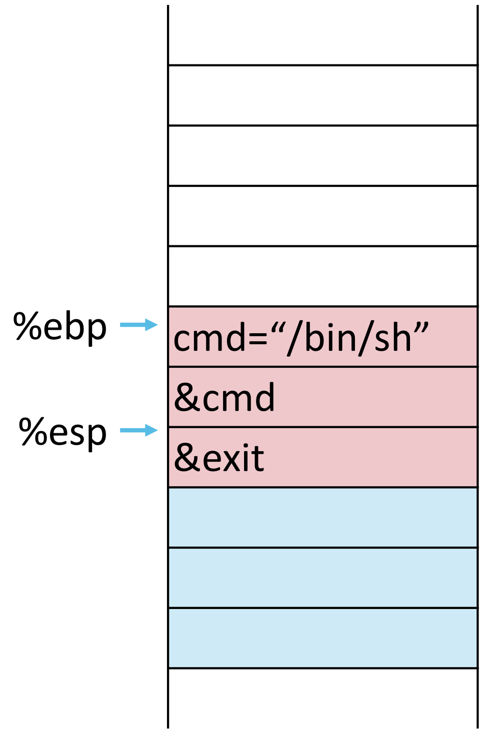


Hijacking control flow



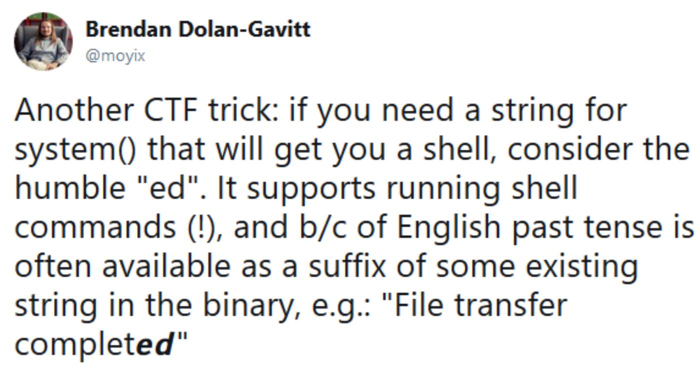
Hijacking control flow

- Stack frame that looks like a normal call to system:



Return To Libc

- Many different variants
- What else can attackers do by calling available functions with parameters of their choosing?
  - Move shellcode to unprotected memory
  - Change permissions on stack pages (mprotect())
  - Etc.


Brendan Dolan-Gavitt
@moyix

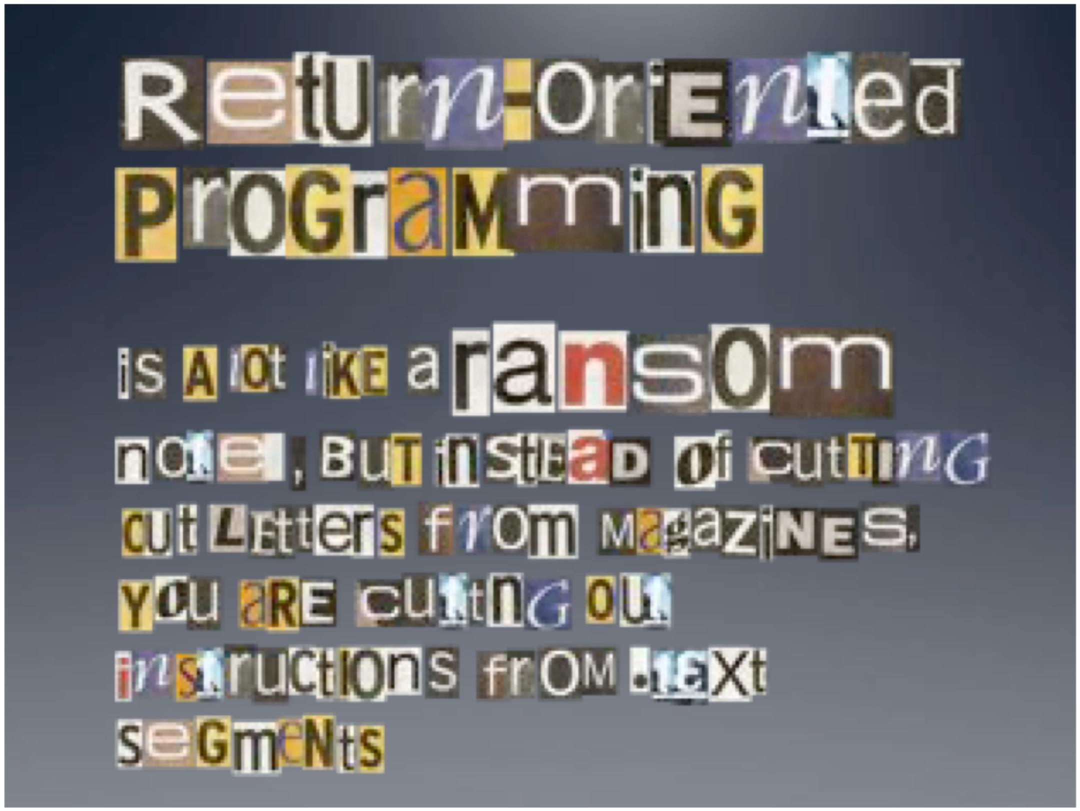
Another CTF trick: if you need a string for system() that will get you a shell, consider the humble "ed". It supports running shell commands (!), and b/c of English past tense is often available as a suffix of some existing string in the binary, e.g.: "File transfer complet***ed***"

Return Oriented Programming (ROP)

- What if we cannot find just the right function? Or need more complex computation?

The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)

Hovav Shacham*
hovav@cs.ucsd.edu



ret Steve Checkoway
ret Dino Dai Zovi

Return Oriented Programming (ROP)

- What happens if we jump almost to the end of some function?
  - We execute the last few instructions, and then?
  - Then we return. But where?
  - To the return address on the stack. But we overwrote the stack with our own data so we control this address
    - Let's choose to return to another tail of an existing function
    - Rinse and repeat

Return Oriented Programming (ROP)

- ROP idea: make complex shellcode out of **existing application code**
- Stitching together arbitrary programs out of code gadgets already present in the target binary
  - ***ROP Gadgets***: code sequences ending in ret instruction.
  - Commonly added by compiler (at end of function)
  - But **also** (on x86) any sequence in executable memory ending in `0xC3 (ret)`.
    - x86 has variable-length instructions
    - Misalignment (jumping into the middle of a longer instruction) can produce new, unintended, code sequences

Aside: how Intel variable length instructions help ROP

- X86 instructions are variable length, yet can begin on any byte address
- Example:

```
81 c4 88 00 00 00 add $0x00000088, %esp
5f                pop %edi
5d                pop %ebp
c3                ret

00 5f 5d ad db    addb %bl, 93 (%edi)
C3                ret
```

- Result: more "function tails" to choose from

```
$otool -t /bin/ls |grep c3
0000000100000f70        39 48 38 7f 07 b8 ff ff ff ff 7d 02 5d c3 48 83
0000000100000fc0        00 00 7d 02 5d c3 48 83 c6 68 49 83 c0 68 48 89
0000000100001010        c3 48 83 c7 68 48 83 c6 68 5d e9 6b 35 00 00 55
0000000100001050        b8 01 00 00 00 7d 02 5d c3 48 83 c6 68 49 83 c0
00000001000010a0        7d 02 5d c3 48 83 c7 68 48 83 c6 68 5d e9 d8 34
00000001000010e0        48 7f 07 b8 01 00 00 00 7d 02 5d c3 48 83 c6 68
0000000100001120        7d 02 5d c3 48 83 c7 68 48 83 c6 68 5d e9 58 34
0000000100001150        b8 01 00 00 00 7d 02 5d c3 48 83 c6 68 48 83 c1
00000001000011a0        7d 02 5d c3 48 83 c7 68 48 83 c6 68 5d e9 d8 33
00000001000011e0        58 7f 07 b8 01 00 00 00 7d 02 5d c3 48 83 c6 68
0000000100001870        c0 09 c8 8a 0d ab 3c 00 00 89 c3 81 cb 80 00 00
0000000100001b70        5d d4 89 de e8 57 29 00 00 48 89 c3 48 85 db 0f
0000000100001c30        03 39 00 00 01 e9 52 01 00 00 0f b7 c0 83 f8 0d
0000000100001dd0        c3 48 8d 35 91 2d 00 00 eb 07 48 8d 35 c0 2d 00
0000000100001e20        36 0f b7 56 58 83 fa 07 75 02 5d c3 44 0f b7 c9
0000000100001ec0        00 48 8d 3d e2 2c 00 00 e8 21 26 00 00 48 89 c3
0000000100001f70        34 48 83 c3 02 80 f9 3a 75 19 80 7b fe 3a 75 13
0000000100001fa0        c3 84 c9 75 d0 44 89 b5 78 fb ff ff 45 89 e6 80
00000001000023b0        fb ff ff 74 5c 8b 78 74 e8 ef 20 00 00 48 89 c3
00000001000023e0        00 00 48 89 c3 48 85 db 0f 84 9a 04 00 00 48 89
0000000100002520        66 18 4d 8b 7e 20 41 8b 5e 30 48 63 c3 48 8d 34
0000000100002560        20 49 63 4e 30 41 89 04 8f 41 8b 5e 30 ff c3 41
0000000100002870        38 05 00 00 5b 41 5c 41 5d 41 5e 41 5f 5d c3 48
0000000100002970        c3 48 8d 3d 9e 22 00 00 48 8d 35 a1 22 00 00 48
0000000100002a30        ed 48 83 c3 68 48 89 df e8 4f 0b 00 00 89 c3 45
0000000100002a90        0f b7 7c 24 04 e8 28 0b 00 00 01 c3 89 d8 48 83
0000000100002aa0        c4 08 5b 41 5c 41 5d 41 5e 41 5f 5d c3 55 48 89
0000000100002c30        4f 28 48 8b 46 08 eb 0f 85 c0 45 8b 4f 38 48 8b
0000000100003200        00 48 83 c3 18 48 81 fb a8 01 00 00 75 84 bb 10
0000000100003260        45 89 fd 4c 8d bd b0 f7 ff ff 48 83 c3 18 48 83
00000001000032e0        5b 41 5c 41 5d 41 5e 41 5f 5d c3 48 8d 35 c5 18
0000000100003350        48 83 c4 08 5b 5d c3 48 8d 3d c6 1b 00 00 31 c0
00000001000034a0        c4 70 5b 41 5e 5d c3 e8 a0 0f 00 00 55 48 89 e5
0000000100003550        00 89 d8 48 83 c4 08 5b 5d c3 66 90 7e ff ff ff
00000001000035f0        00 00 00 5d c3 81 c1 00 60 00 00 81 e1 00 f0 00
00000001000036a0        75 06 48 83 c3 10 eb 69 48 8d 7b 68 e8 f7 0e 00
0000000100003740        5e 41 5f 5d c3 55 48 89 e5 41 57 41 56 41 55 41
0000000100003930        5c f0 ff ff 89 c3 48 8d 05 1b 1d 00 00 8b 08 85
0000000100003970        7c 04 85 c9 75 40 41 89 d4 89 c3 48 8d 05 b6 1c
0000000100003990        45 f8 e8 c3 0b 00 00 42 8d 04 2b 23 45 c8 44 89
00000001000039f0        83 c4 38 5b 41 5c 41 5d 41 5e 41 5f 5d c3 31 ff
0000000100003ac0        00 00 48 89 c3 8a 04 1a 88 45 d6 48 83 ca 01 48
0000000100003b00        f8 80 f9 30 75 36 83 c3 d0 41 89 1f 66 bb 01 00
0000000100003b40        9f 80 f9 07 77 08 83 c3 9f 41 89 1f eb 4e 89 c1
0000000100003b50        80 c1 bf 80 f9 07 77 12 83 c3 bf 41 89 1f 48 8b
0000000100003bd0        41 5d 41 5e 41 5f 5d c3 55 48 89 e5 41 56 53 41
0000000100003c30        c6 08 00 00 89 c7 44 89 f6 5b 41 5e 5d e9 e2 08
0000000100003c60        31 c0 48 83 c4 10 5d c3 55 48 89 e5 e8 e9 08 00
0000000100003c70        00 31 c0 5d c3 55 48 89 e5 41 56 53 89 f8 48 8d
0000000100003d10        5e 5d e9 b5 08 00 00 5b 41 5e 5d c3 55 48 89 e5
0000000100003e40        ff ff 4c 89 e6 4c 89 f9 e8 f5 06 00 00 48 89 c3
0000000100003e90        98 00 00 00 5b 41 5c 41 5d 41 5e 41 5f 5d c3 e8
```

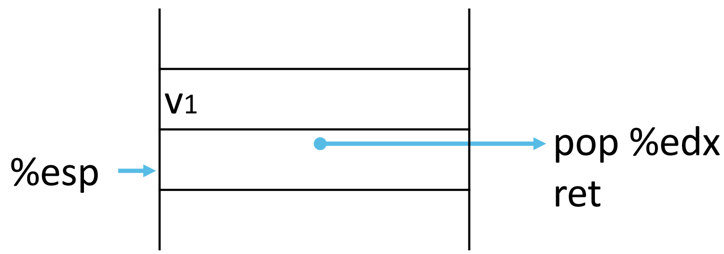
Return Oriented Programming (ROP)

- ROP idea: make shellcode out of **existing application code**.
- Stitching together arbitrary programs out of code gadgets already present in the target binary
  - ***ROP Gadgets***: code sequences ending in ret instruction.
  - Commonly added by compiler (at end of function)
  - But **also** (on x86) any sequence in executable memory ending in `0xC3 (ret)`.
    - x86 has variable-length instructions
    - Misalignment (jumping into the middle of a longer instruction) can produce new, unintended, code sequences
- Overwrite saved return address on stack to point to first gadget, the following word to point to second gadget, etc
- Stack pointer is the new instruction pointer in this crazy world

Return Oriented Programming

- "*Our thesis: In any sufficiently large body of x86 executable code there will exist sufficiently many useful code sequences that an attacker who controls the stack will be able, by means of the return-into-libc techniques we introduce, to cause the exploited program to undertake **arbitrary computation**.*"
  - *The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)* by Hovav Shacham
  - https://cseweb.ucsd.edu/~hovav/dist/geometry.pdf
- Turing-complete computation.
  - Load and Store gadgets
  - Arithmetic and Logic gadgets
  - Control Flow gadgets

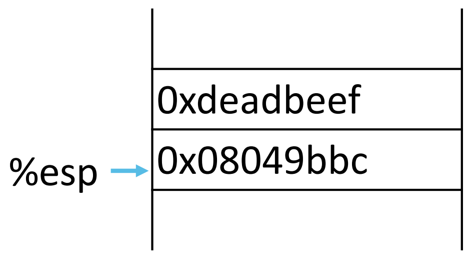
What does this gadget do?



relevant register(s):

%edx = 0x00000000

relevant stack:



relevant code:

%eip → 0x08049b62: nop
0x08049b63: ret
...
0x08049bbc: pop %edx
0x08049bbd: ret

relevant register(s):

%edx = 0x00000000

relevant stack:

0xdeadbeef

%esp → 0x08049bbc

relevant code:

0x08049b62: nop

%eip → 0x08049b63: ret

...

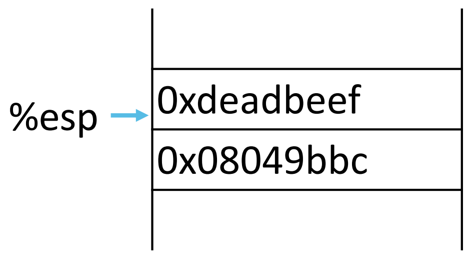
0x08049bbc: pop %edx

0x08049bbd: ret

relevant register(s):

%edx = 0x00000000

relevant stack:



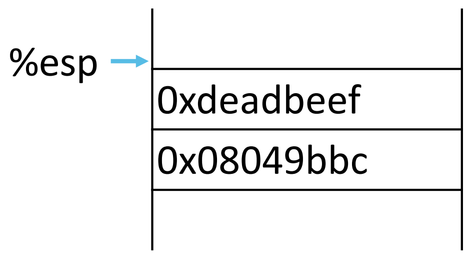
relevant code:

```
0x08049b62: nop
0x08049b63: ret
...
%eip → 0x08049bbc: pop %edx
       0x08049bbd: ret
```

relevant register(s):

%edx = 0xdeadbeef

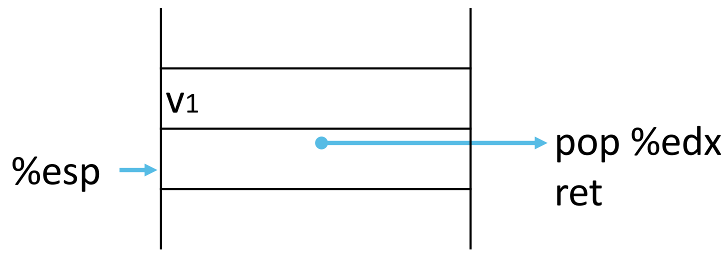
relevant stack:



relevant code:

0x08049b62: nop
0x08049b63: ret
...
0x08049bbc: pop %edx
%eip → 0x08049bbd: ret

What does this gadget do?

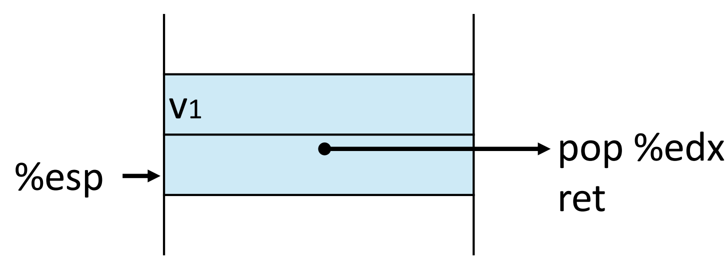


%edx = v_1

mov v_1, %edx

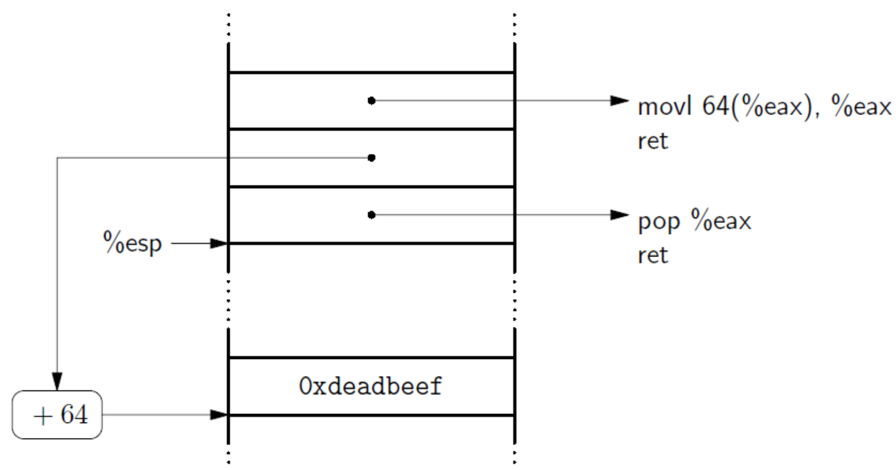
How dow you use this as an attacker?

- Overflow the stack with values and addresses to such gadgets to express your program
- E.g., if shellcode needs to write a value to %edx, use the previous gadget



Return Oriented Programming

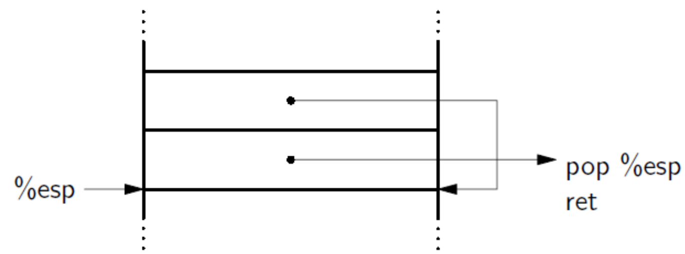
- Gadget for loading a value from memory
  - A bit more complex…
  - Attacker sets up stack so **address** of *value to be loaded* is on stack
    - Technically, 64 bytes less than addr
  - Return to gadget that pops that address into %eax
  - Return to gadget that loads the value based on address in %eax



https://cseweb.ucsd.edu/~hovav/dist/geometry.pdf

Return Oriented Programming

- Control Flow Gadgets
  - Stack pointer is effectively the new instruction pointer
  - To "jump" just pop a new value into %esp
  - Conditional jumps are more involved but still possible



https://cseweb.ucsd.edu/~hovav/dist/geometry.pdf

Return Oriented Programming

- Stack pointer acts as instruction pointer
- Manually stitching gadgets together gets tricky
  - Automation to the rescue!
  - Gadget finder tools, ROP chain compilers, etc.
  - All of this has been quasi-automated
- Also: not even really about "returns"… other variants target other kinds of deterministic control flow
- Well, heck…. what to do?

Control Flow Integrity

Control Flow Integrity

- Given a new attack technique, we must present a new countermeasure.
  - Such is the cycle of life

- ***Control Flow Integrity (CFI)***
  - Motivation: in almost all attacks we've seen attacker is overwriting jump targets (e.g., return address on stack, function pointers on heap, etc.)
    - What if we ensured that rets, calls, etc... could only go to *known good* targets
  - Basic idea: constraining the control-flow to only **legitimate paths determined in advance**
    - Match jump, call, and return sites to their target destinations
  - Many different implementations with different tradeoffs in protection strength and performance overhead.

Control Flow Integrity

- In almost all the attacks we looked at, the attacker is overwriting jump targets that are in memory (return addresses on the stack and function pointers on the stack/heap)
- **Idea:** don't try to stop the memory writes. Instead: restrict control flow to legitimate paths
  - I.e., ensure that jumps, calls, and returns can only go to allowed target destinations

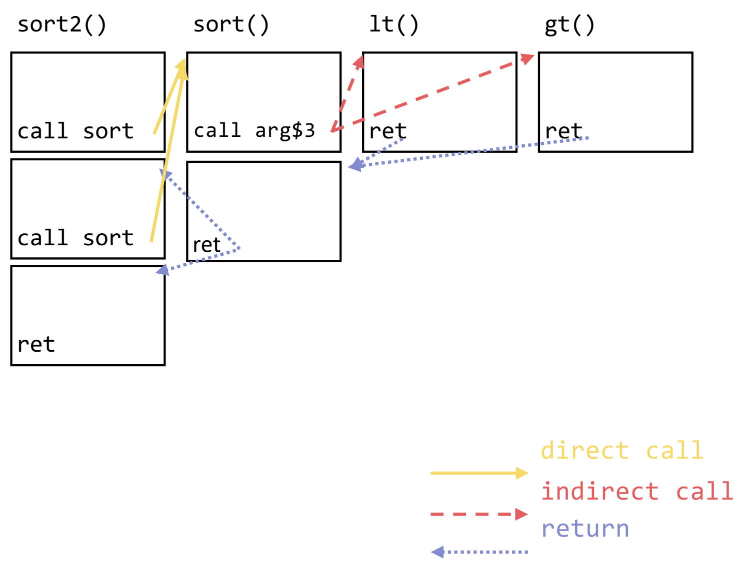
Control Flow Integrity

- Focus is on protecting indirect transfer of control flow instructions.
- ***Direct*** control flow transfer:
  - Advancing to next sequential instruction
  - Jumping to (or calling a function at) an address hard-coded in the instruction
  - These are static in code, so assume attacker can't control
    (if they can overwrite code segment its game over anyway)
- ***Indirect*** control flow transfer
  - Jumping to (or calling a function at) an address in register or memory
  - ***Forward path***: indirect calls and branches (e.g., a function you are calling)
  - ***Reverse path***: return addresses on the stack (returning from a called function)

What's a legitimate target?

Look at the program control-flow graph (CFG)!

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

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

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



Control Flow Integrity

- Basic Design:
  - Restrict all control transfers to the control flow graph
  - Assign **labels** to all indirect jumps and their targets
  - Before taking an indirect jump, validate that target label matches jump site
    - Like stack canaries, but for control flow targets
  - Hardware support is essential to make enforcement efficient

  - Absent that, make performance/precision tradeoffs

CFI: Example of Labels

Original code

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

Instrumented code

```
B8 77 56 34 12    mov   eax, 12345677h    ; load ID-1
40                inc   eax               ; add 1 for ID
39 41 04          cmp   [ecx+4], eax      ; compare w/dst
75 13             jne   error_label       ; if != fail
FF E1             jmp   ecx               ; jump to label
```

```
3E 0F 18 05    prefetchnta               ; label
78 56 34 12        [12345678h]           ;    ID
8B 44 24 04    mov  eax, [esp+4]         ; dst
...
```

Jump to the destination only if the tag is equal to “12345678”

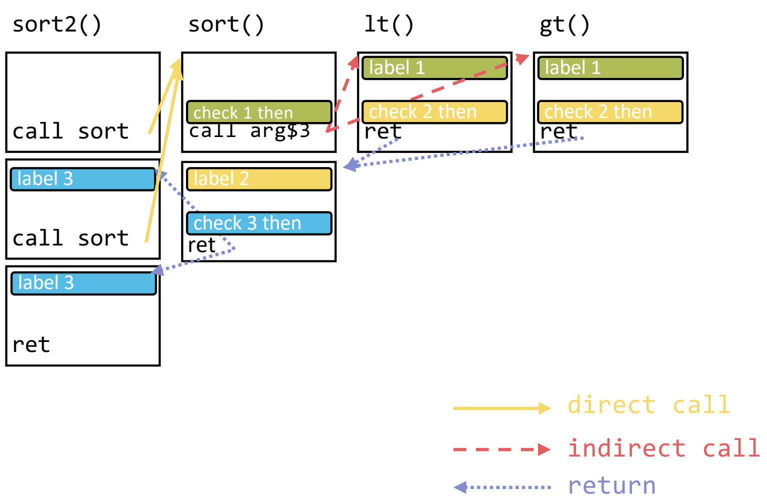
Abuse an x86 assembly instruction to insert “12345678” tag into the binary

Fine grained CFI (Abadi et al.)

- Statically compute CFG
- Dynamically ensure program never deviates
  - Assign label to each target of indirect transfer
  - Instrument indirect transfers to compare label of destination with the expected label to ensure it's valid

Fine grained CFI (Abadi et al.)

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

bool lt(int x, int y) {

  return x < y;

}

bool gt(int x, int y) {

  return x > y;

}
```

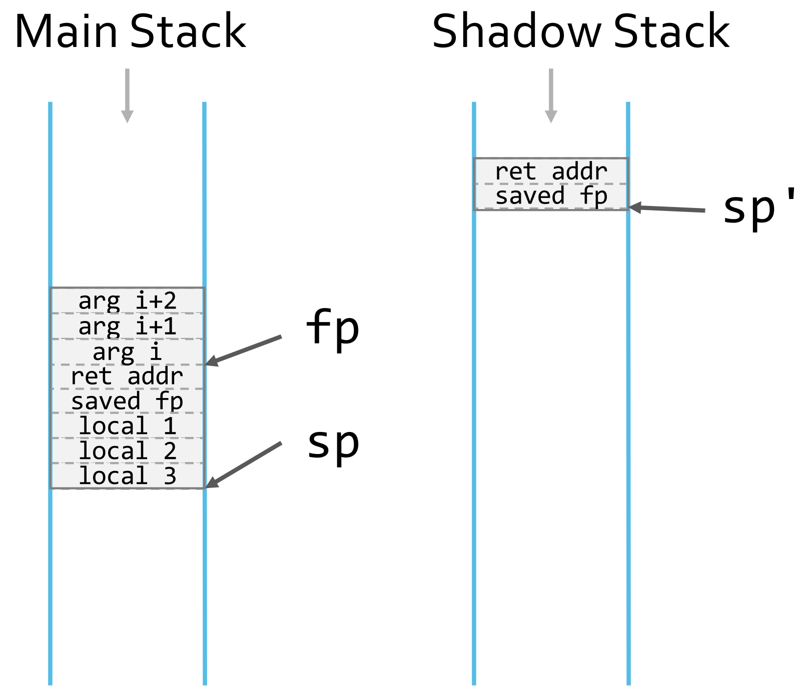


Fine grained CFI (Abadi et al.)

- Statically compute CFG
- Dynamically ensure program never deviates
  - Assign label to each target of indirect transfer
  - Instrument indirect transfers to compare label of destination with the expected label to ensure it's valid
- To really make this work well, need a "shadow stack"
  - Second, protected stack just for control data, to ensure that you are returning to function you called from

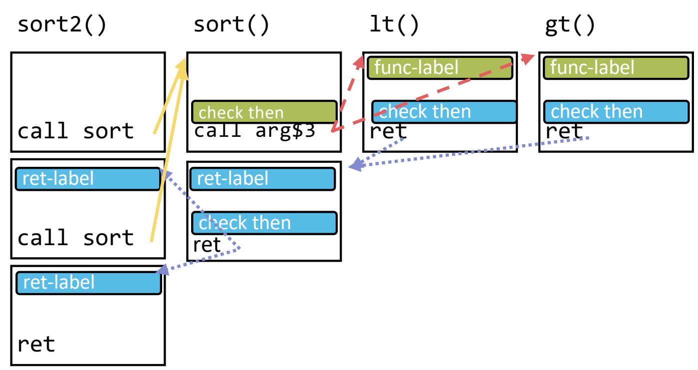
Shadow Stack

- Shadow Stack
  - On function entry, save a [shadow] copy of function call control flow data (return addresses and frame pointers) into another location
  - On function exit, compare the version on the stack to the shadow copy
- Requires compiler support
- Requires hardware support to be fast
  - Intel CET Shadow Stack in the future
- Not widely deployed/available



Coarse-grained CFI (e.g., bin-CFI)

- Tradeoff speed for precision
  - Identify if control transfer is *clearly wrong*, but not that it is right
  - **Only two labels, no shadow stack**
- Label for destination of indirect calls (forward)
  - Make sure that every indirect call lands on a function entry
- Label for destination of rets and indirect jumps (reverse)
  - Make sure every indirect jump lands at start of a basic block



CFI Tradeoffs and Bypass Opportunities

- Overhead
  - Additional computation is needed before every free branch instruction.
  - Additional code size is needed before every free branch instruction and at each location (the label).
- Scope
  - Data is not protected
  - CFI does not protect against interpreters
  - Needs reliable DEP (if you can change code all bets are off)
- Precision
  - If you don't validate **all** data-dependent control transfers, can still create gadgets
    - E.g., can still call system() with coarse grained CFI
    - Lots of potential gadgets on return path (you really need a Shadow Stack)
  - Performance/Precise tradeoff creates holes
    - *Out of Control: Overcoming Control-Flow Integrity*
    - *Stitching the Gadgets: On the Ineffectiveness of Coarse Grained CFI*
  - *Aside: C++ is a huge huge problem due to virtual functions*
- Some version of CFI is used on both Apple iOS and Google Android

Summary

- Code reuse attacks bypass DEP by using existing code
  - E.g., Return to libc
- Return-oriented Programming
  - Generalizes idea. You can synthesize arbitrary malicious computation out benign code, by stitching it together with control flow
  - The stack is a convenient place to do this stitching
- Control-flow integrity
  - Promise to provide general-purpose protection against control flow vulnerabilities
  - Gets part of the way there at significant cost, but still bypassable due to limited precision

Next Lecture…

System Security