Anita's Super Awesome Recitation Slides

15/18-213: Introduction to Computer Systems

Stacks and Buflab, 23 Sept 2013

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What's New (or Not)

- Bomb Lab is due Tuesday (tomorrow), 11:59 PM
  - Your late days are wasted here
  - Student: "But if you wait until the last minute, then it only takes a minute!"
    - Not (quite) true
- Buf Lab out Tuesday (tomorrow), 11:59 PM
  - Hacking the stack
- Stacks will be on the exams
  - They're tough at first, but I believe in you ☺

Speaking of the Exam…

- **Midterm: Wed, 16 Oct – Sat, 19 Oct 2013**
- Covers everything up to, and including, caches.
  - Chapters 1-3 and 6 of textbook.
  - Up to and including Cache Lab.
  - Lectures up to and including Caches (1 Oct 2013).
- Recitation exam review the week of exam.
- "Read each chapter 3 times, work the practice problems, and do previous exams."
  - Do enough midterms until you feel comfortable with the material (at least 5 recent ones).
    - Depending on the semester, caches can be found in Exam 2.

To Those Who Want A Cool Shell

- http://www.contrib.andrew.cmu.edu/~anitazha/15213_tips.html
  - Scroll down to the part about “Shell of Choice”
  - Follow the directions
  - Your terminal will look something like this:

```
catshark           5:30 AM
hammerheadshark    6:00 AM
houndshark         6:30 AM
lemonshark         7:00 AM
makoshark          7:30 AM


 _____________________
< Do your best Anita! >
 ---------------------
        \   ^__^
         \  (oo)\_______
            (__)\       )\/\
                ||----w |
                ||     ||
anitazha@houndshark   ~]$
```

Journey Through Time

- Basic Assembly Review
  - Jump Tables vs. Sparse Switch
  - Terminology
- Stacks
  - IA32 Stack Discipline
  - Function Call Overview
  - Stack Walkthrough
  - Extras on x86(_64) stacks
- Buf Lab Quick Start
  - Essential Items of Business
  - Miscellany
- Demo…?

Assembly Coverage: Jump Tables

- Jump tables
  - Think of it as an array of addresses in memory
    - Use jump instructions to execute from these addresses
  - Using assembly it is possible to index into the array
  - Each entry of will hold addresses of instructions

Jump Table Example

- The tip-off is something like this:
  - `jmpq *0x400600(,%rax,8)`
    - Empty base means implied 0
    - `%rax` is the "index"
    - 8 is the "scale" (64-bit machine addresses are 8 bytes)
    - * indicates a dereference (like in C notation)
      - Like `leal`: does not do a dereference with parenthesis
  - Put it all together: "Jump to the address stored in the address 0x400600 + %rax*8"
- Using GDB (example output): x/8g 0x400600

```
0x400600: 0x00000000004004d1 0x00000000004004c8
0x400610: 0x00000000004004c8 0x00000000004004be
0x400620: 0x00000000004004c1 0x00000000004004d7
0x400630: 0x00000000004004c8 0x00000000004004be
```

Assembly Coverage: Sparse Switch

- Sparse switch vs. jump tables
  - Jump tables work if every entry has a jump location
  - Sparse switches cover cases where there are less densely packed cases
    - Does not make sense to allocate space for 100 entries if only 1 and 100 are used as cases
    - In the following example: uses labels to go to the next instruction

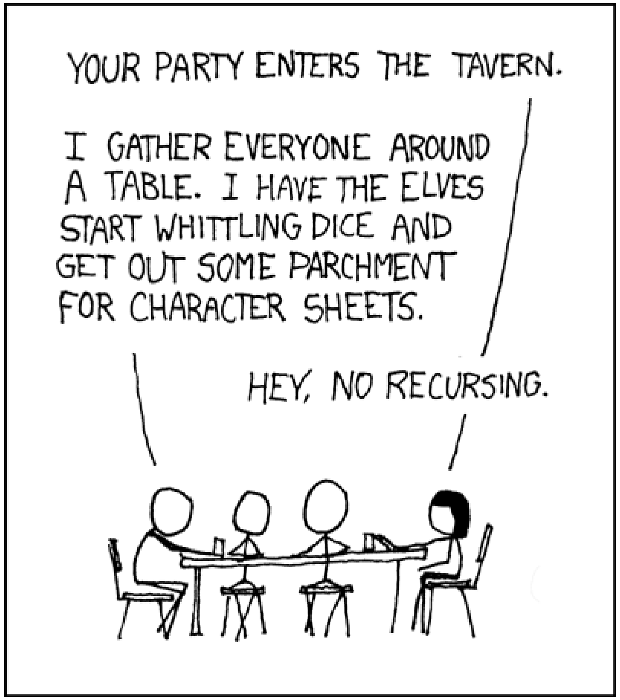
Sparse Switch Example

```c
int div111(int x) {
  switch(x) {
    case   0: return 0;
    case 111: return 1;
    case 222: return 2;
    case 333: return 3;
    case 444: return 4;
    case 555: return 5;
    case 666: return 6;
    case 777: return 7;
    case 888: return 8;
    case 999: return 9;
    default: return -1;
  }
}
```

```
movl 8(%ebp),%eax # get x
cmpl $444,%eax  # x:444
je L8
jg L16
cmpl $111,%eax  # x:111
je L5
jg L17
testl %eax,%eax # x:0
je L4
jmp L14
```

```
    . . .
L5:
    movl $1,%eax
    jmp L19
L6:
    movl $2,%eax
    jmp L19
L7:
    movl $3,%eax
    jmp L19
L8:
    movl $4,%eax
    jmp L19
    . . .
```

Some Kind of Stack Motivation



"In order to support general recursion, a language needs a way to allocate different activation records for different invocations of the same function. That way, local variables allocated in one recursive call can coexist with local variables allocated in a different call." (credits to stack overflow)

Definitions and Conventions

- Register
  - Some place in hardware that stores bits
    - Like boxes on the side of memory
- Caller save
  - Saved by the caller of a function
  - Before a function call, the caller must save any caller save register values it wants preserved
- Callee save
  - Saved by the callee of a function
  - The callee is required to save/ restore values in these registers if it is using these registers in the function

Aside: Why both?

- Why do we have both caller and callee save?
  - Performance
  - Not all registers need to be saved

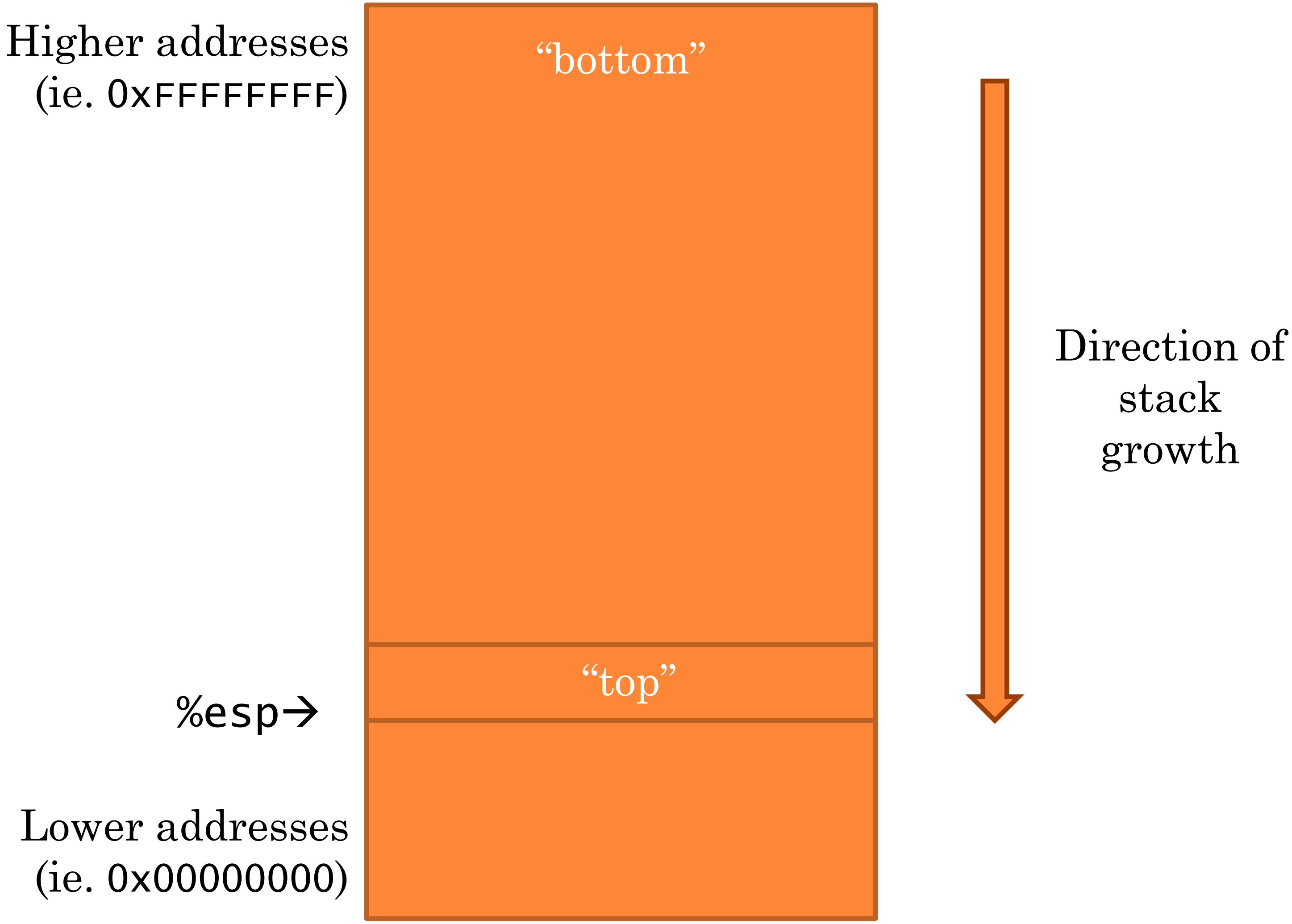
IA32 Registers

- 6 general purpose registers
  - Caller save
    - `%eax, %ecx, %edx`
    - Saved by the caller of a function
  - Callee save
    - `%ebx, %edi, %esi`
    - Saved by the callee of a function

Special IA32 Registers

- Base Pointer
  - `%ebp`
  - Points to the “bottom” of the stack frame
    - The location of old `%ebp` that gets pushed on entry
- Stack Pointer
  - `%esp`
  - Points to the “top” of the stack
    - *Usually* whatever was last pushed on the stack
- Instruction Pointer (Program Counter)
  - `%eip`
  - Points to the next instruction to be executed

IA32 Terminology



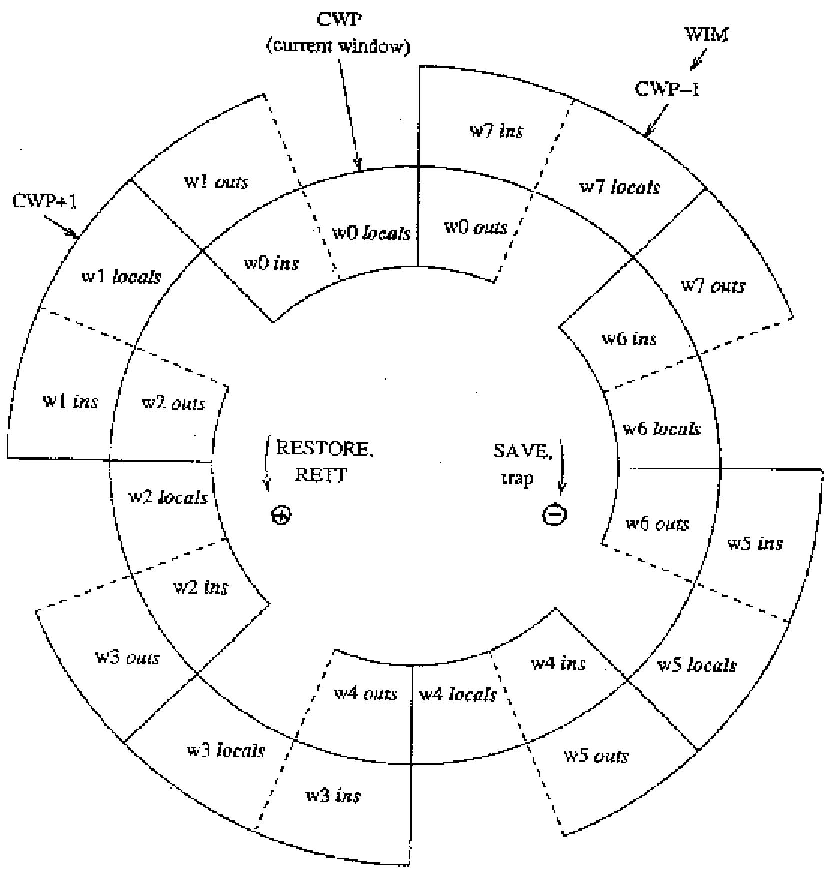
Aside: Technology Note (Again!)

- This class is (strictly) x86(_64)
  - Other architectures may have different conventions
    - May not use stacks at all (weird, I know)
  - Stacks grow down/ up depending on implementation
    - Very confusing to those new to stacks

Aside: Direction of Growth

- Stack direction REALLY doesn't matter
  - Direction of growth is dependent on the processor
  - May be selectable for up/down
  - …Or some other direction…?

BAM! Circular Stack!



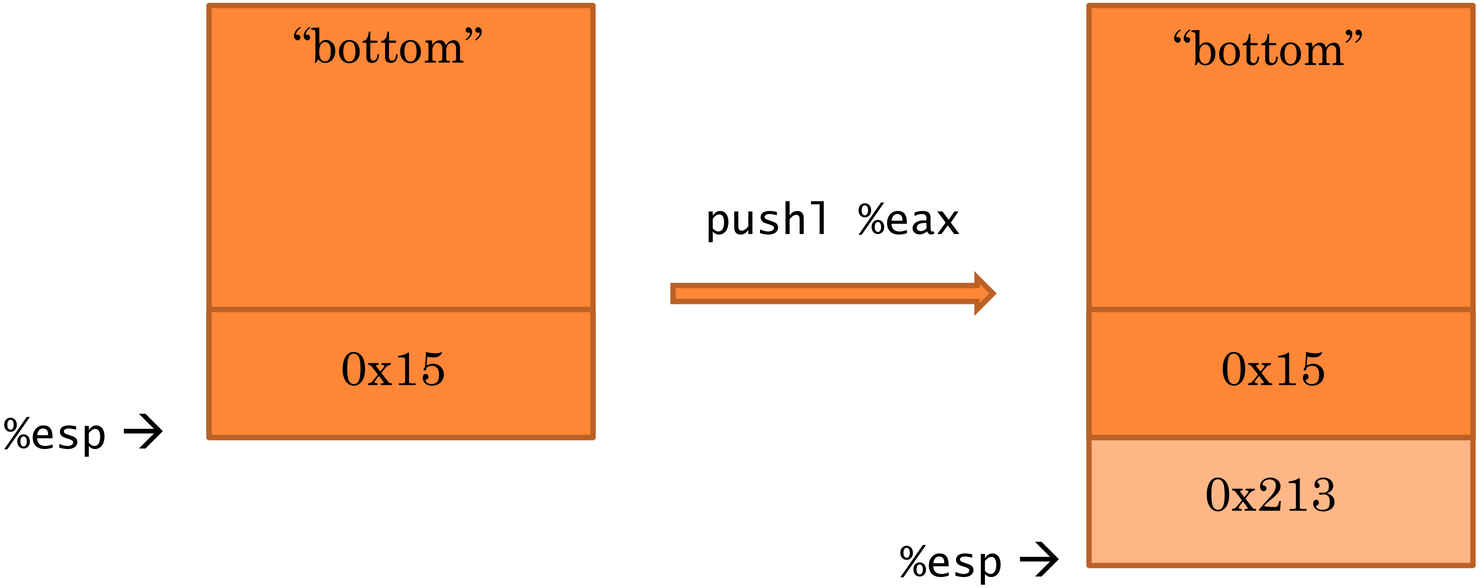
SPARC (scalable processor architecture) Architecture

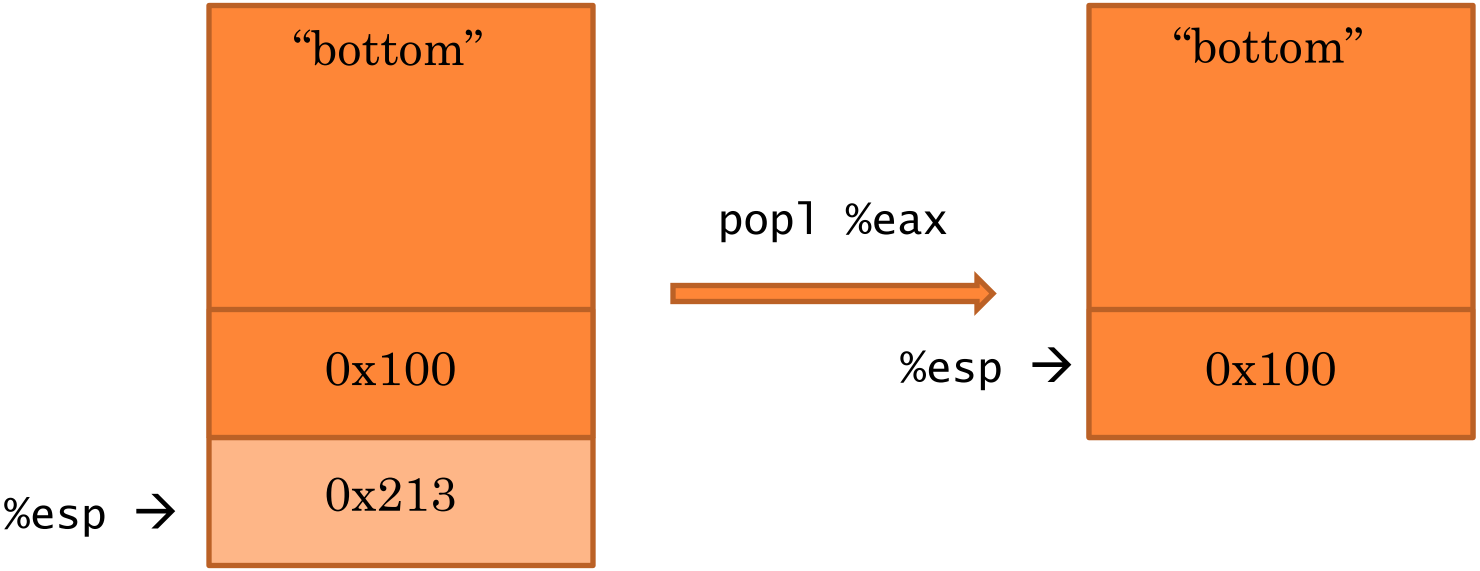
Aside: Direction of Growth

- Examples from StackOverflow
  - x86 - down
  - SPARC - in a circle
  - System z - in a linked list (down, at least for zLinux)
  - ARM - selectable
  - PDP11 - down

What Happens in IA32: Push

- Pushing on the stack

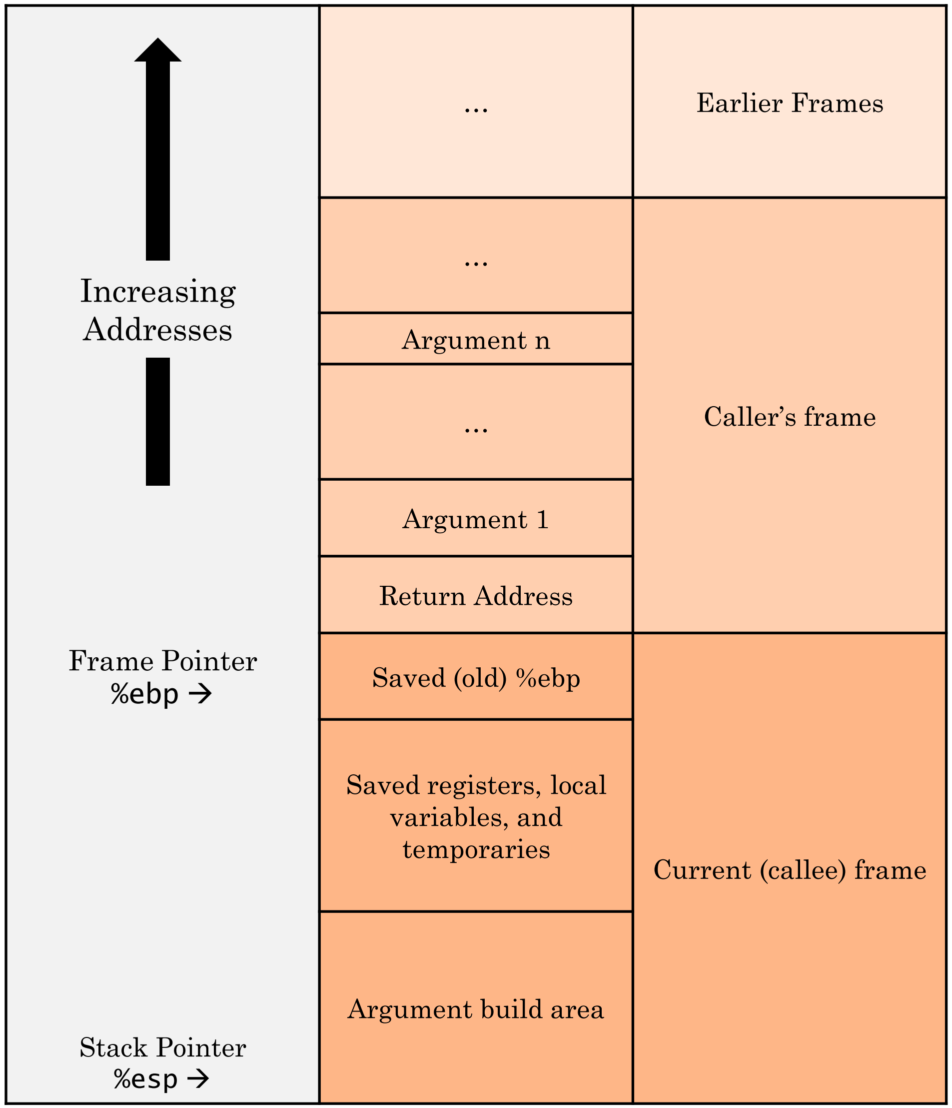


- In general, `pushl` translates to (in AT&T syntax):
  - ```
    subl $0x4, %esp
    movl src, (%esp)
    ```
    ```

What Happens in IA32: Pop

- Popping off the stack



- In general, `popl` translates to (in AT&T syntax):
  - ```
    movl (%esp), dest
    addl $0x4, %esp
    ```
    ```

Stack Frames Whatchamacallits?

- Every function call gets a "stack frame"
- All the useful stuff can go on the stack!
  - Local variables (scalars, arrays, structs)
    - What the compiler couldn't fit into registers
  - Callee/caller save registers
  - Temporary variables
  - Arguments
- Stacks can make recursion work!
- Key idea: "Storage for each *instance* of procedure call" (stolen out of 15-410 slides)

So THAT'S What it Looks Like…



Roles of a (Function) Caller

- Caller
  - Save (push) relevant caller save registers
  - Push arguments
  - Call function
- Caller after function return
  - “Remove” (add to `%esp` or pop) arguments
  - Restore (pop) saved caller save registers

Roles of a (Function) Callee

- Callee
  - Push `%ebp` (save stack frame)
  - Copy (move) `%esp` into `%ebp`
  - Save (push) callee save registers it wants to use
- Callee before return
  - Restore (pop) callee save registers previously saved
  - Copy (move) `%ebp` into `%esp`
    - Moves stack pointer to the saved `%ebp`
  - Restore (pop) `%ebp`

Function Calls, Other Operations

- Implied operations
  - "`call`" implicitly pushes return address
    - Return address is always of the instruction after the call
  - "`ret`" implicitly pops return address into `%eip`
    - Becomes the next instruction to execute!

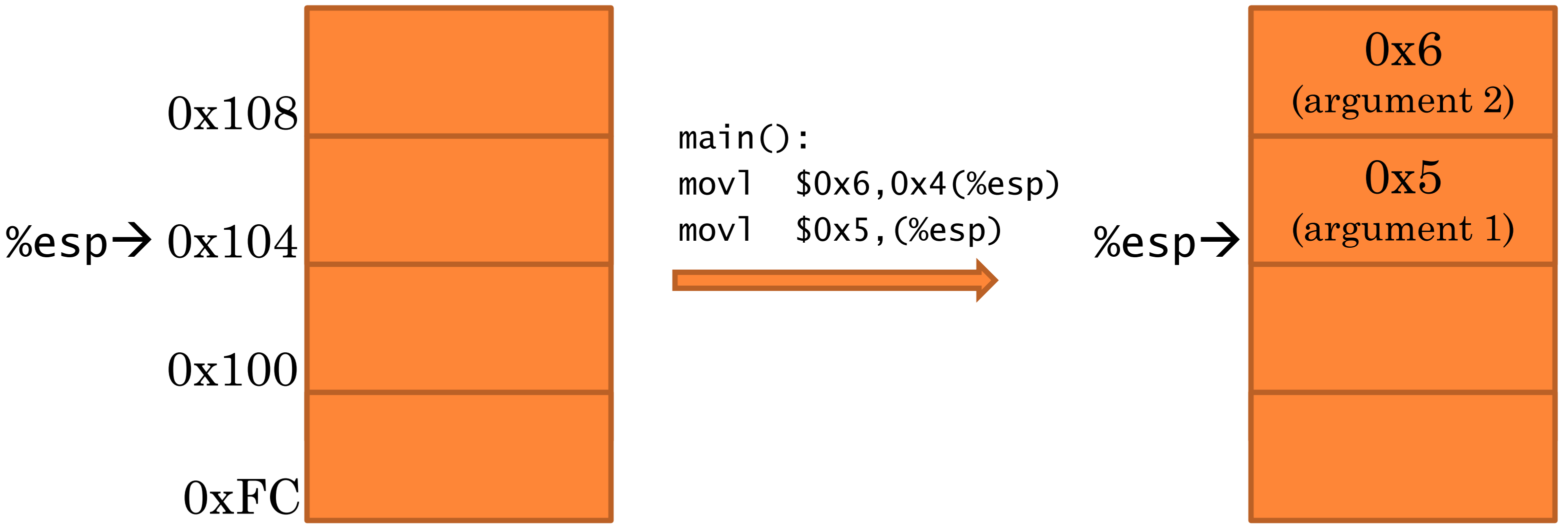
Stack Frames in Action

C Code	Disassembly

`int main() {`
`    return addition(5, 6);`
`}`
 	
`int addition(int x, int y) {`
`    return x+y;`
`}`
	`08048394 <main>:`
	` 8048394:  55                    push   %ebp`
	` 8048395:  89 e5                 mov    %esp,%ebp`
	` 8048397:  83 e4 f0              and    $0xfffffff0,%esp`
	` 804839a:  83 ec 10              sub    $0x10,%esp`
	` 804839d:  c7 44 24 04 06 00 00  movl   $0x6,0x4(%esp)`
	` 80483a4:  00`
	` 80483a5:  c7 04 24 05 00 00 00  movl   $0x5,(%esp)`
	` 80483ac:  e8 02 00 00 00        call   80483b3 <addition>`
	` 80483b1:  c9                    leave`
	` 80483b2:  c3                    ret`
	
	`080483b3 <addition>:`
	` 80483b3:  55                    push   %ebp`
	` 80483b4:  89 e5                 mov    %esp,%ebp`
	` 80483b6:  8b 45 0c              mov    0xc(%ebp),%eax`
	` 80483b9:  8b 55 08              mov    0x8(%ebp),%edx`
	` 80483bc:  8d 04 02              lea    (%edx,%eax,1),%eax`
	` 80483bf:  c9                    leave`
	` 80483c0:  c3                    ret`

Breakdown: Argument Build

- Build the arguments (note: 2 instructions are executed in this example)

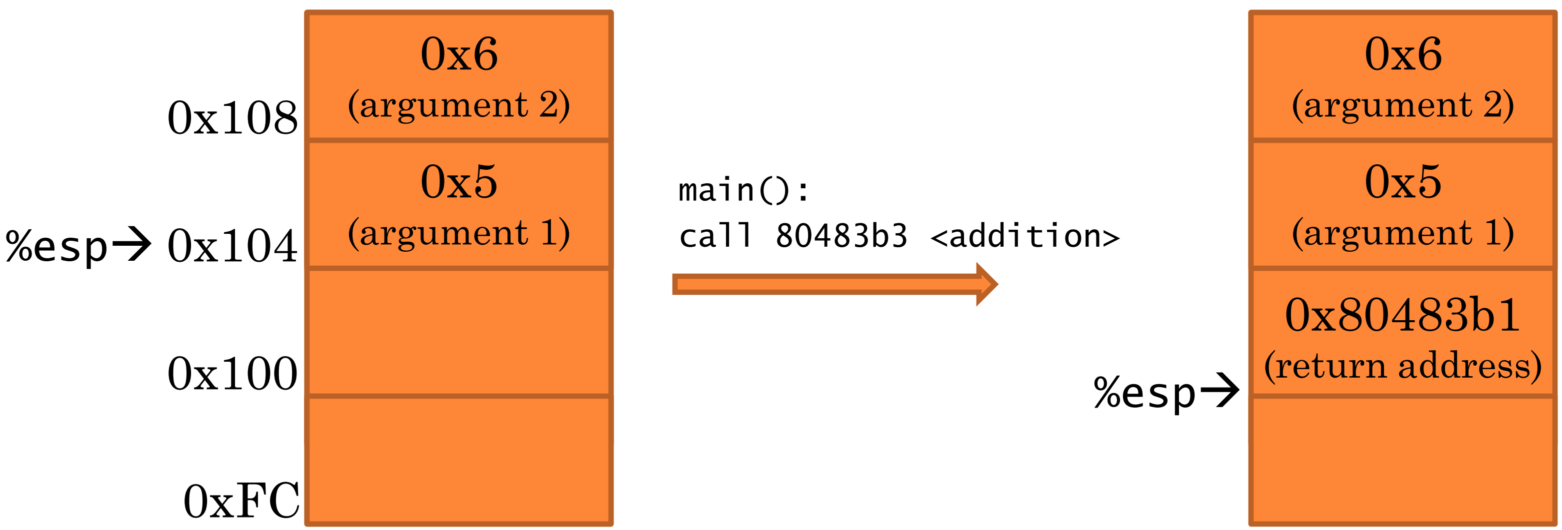


Before	After

`%esp = 0x104`
`%ebp = 0x200`
`%eip = 0x804839d`
	`%esp = 0x104`
	`%ebp = 0x200`
	`%eip = 0x80483ac`

Breakdown: Function Call

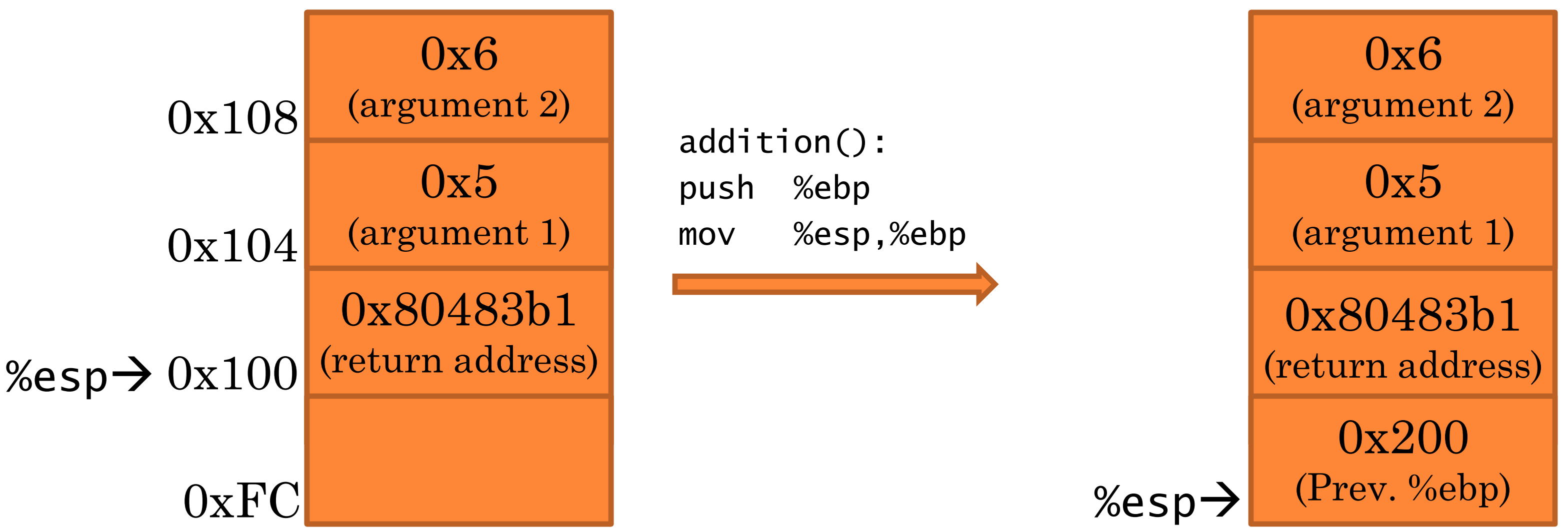
- Call the function



Before	After
%esp = 0x104	%esp = 0x100
%ebp = 0x200	%ebp = 0x200
%eip = 0x80483ac	%eip = 0x80483b3

BREAKDOWN: CALLEE SETUP

- Stack frame set up (note: 2 instructions are executed in this example)



Before	After
%esp = 0x100 %ebp = 0x200 %eip = 0x80483b3	%esp = 0xFC %ebp = 0xFC %eip = 0x80483b6

Break From the Example.. Kind of

- Accessing an argument

Address	Value
0x108	0x6 (argument 2)
0x104	0x5 (argument 1)
0x100	0x80483b1 (return address)
0xFC	0x200 (Prev. %ebp)

Argument	Location
Argument 2	`0xC(%ebp)`
Argument 1	`0x8(%ebp)`

- In the current frame, arguments are accessed via references to `%ebp`
  - Notice how argument 1 is at `0x8(%ebp)`, not `0x4(%ebp)`

Let's Review the Code Again

C Code

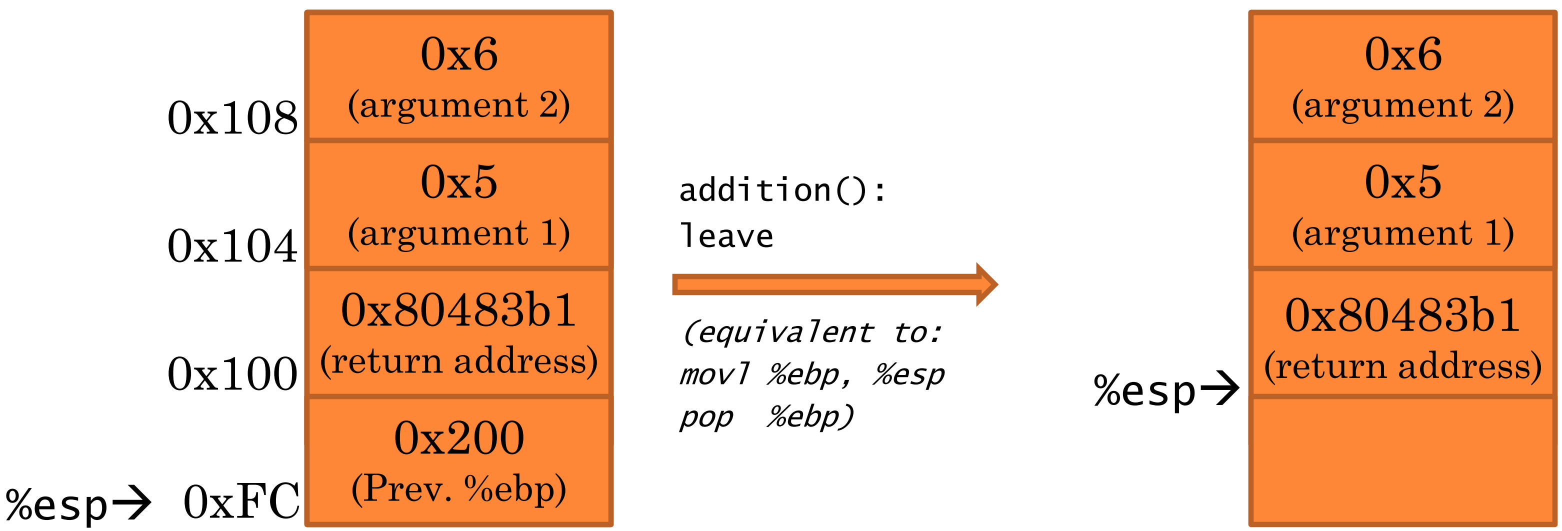
```c
int main() {
    return addition(5, 6);
}

int addition(int x, int y)
{
    return x+y;
}
```

Disassembly

```
08048394 <main>:
 8048394:       55                      push   %ebp
 8048395:       89 e5                   mov    %esp,%ebp
 8048397:       83 e4 f0                and    $0xfffffff0,%esp
 804839a:       83 ec 10                sub    $0x10,%esp
 804839d:       c7 44 24 04 06 00 00    movl   $0x6,0x4(%esp)
 80483a4:       00
 80483a5:       c7 04 24 05 00 00 00    movl   $0x5,(%esp)
 80483ac:       e8 02 00 00 00          call   80483b3 <addition>
 80483b1:       c9                      leave
 80483b2:       c3                      ret

080483b3 <addition>:
 80483b3:       55                      push   %ebp
 80483b4:       89 e5                   mov    %esp,%ebp
 80483b6:       8b 45 0c                mov    0xc(%ebp),%eax
 80483b9:       8b 55 08                mov    0x8(%ebp),%edx
 80483bc:       8d 04 02                lea    (%edx,%eax,1),%eax
 80483bf:       c9                      leave
 80483c0:       c3                      ret
```

Breakdown: Preparing to Return

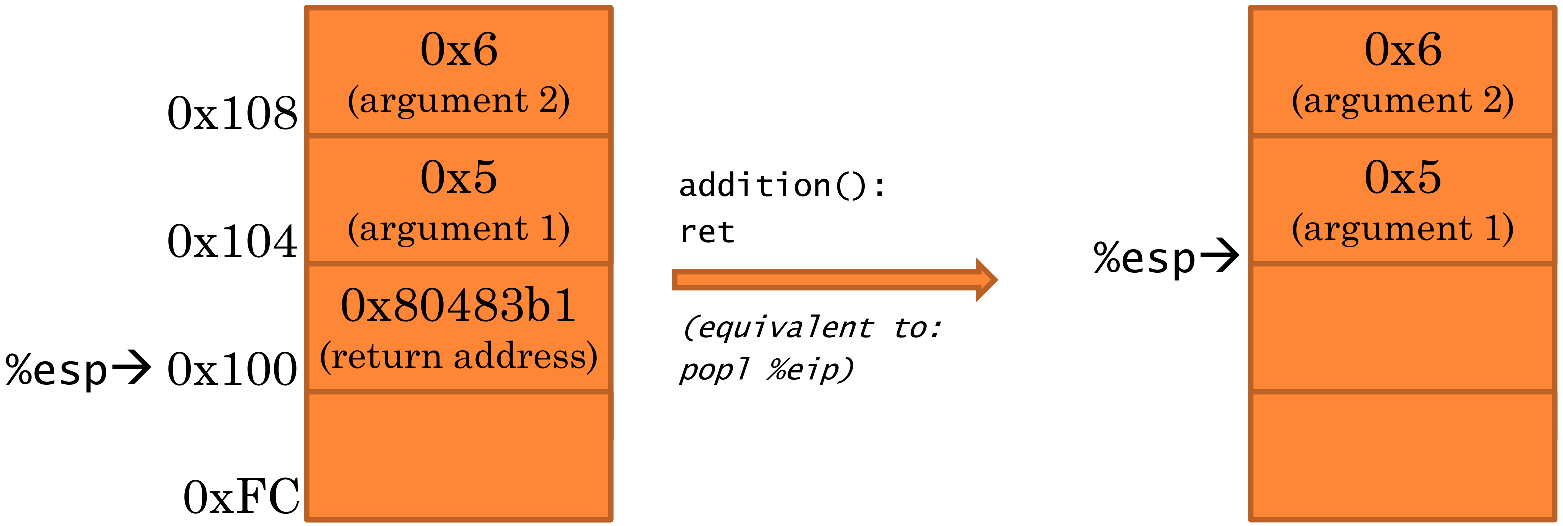
- Preparing to return from a function



Before	After
%esp = 0xFC %ebp = 0xFC %eip = 0x80483bf	%esp = 0x100 %ebp = 0x200 %eip = 0x80483c0

Breakdown: Return

- Return from a function



Before	After
%esp = 0xFC %ebp = 0x200 %eip = 0x80483c0	%esp = 0x104 %ebp = 0x200 %eip = 0x80483b1

Stacks and Stuff on x86_64

- Arguments (≤ 6) are passed via registers
  - `%rdi, %rsi, %rdx, %rcx, %r8, %r9`
  - Extra arguments passed via stack!
    - IA32 stack knowledge still matters!
- Don't need `%ebp` as the base pointer
  - Compilers are smarter now
- Overall less stack use
  - Potentially better performance

And Floating Point?

- Floating point arguments are complicated
  - Out of the scope of this course
  - Some chips have a separate floating point stack
- Example of complication
  - x86_64 stack on function entry needs to be 16 byte aligned for floating point
  - And other potential issues you shouldn't worry about

BUFLAB

- A series of exercises asking you to overflow the stack and change execution
  - You do this with inputs that are super long and write over key stack values
  - **Incorrect inputs will not hurt your score**
- Seminal paper on stack corruption
  - *Smashing the Stack for Fun and Profit*

Basic Approach

- Examine the provided C code/ disassembly
  - Disassembling
    - `> objdump -d bufbomb > outfile`
  - Don't forget that GDB is still used for this lab!
- Find out how long to make your inputs
- Write exploits to divert program execution
- Profit

Buflab Tools

- `./makecookie` *`andrewID`*
  - Makes a unique “cookie” based on your Andrew ID
- `./hex2raw`
  - Use the hex generated from assembly to pass raw strings into bufbomb
  - Use with –n in the last stage
- `./bufbomb -t` *`andrewID`*
  - The actual program to attack
  - Always pass in with your Andrew ID so your score is logged
  - Use with –n in the last stage

How to Input Answers

- Put your byte code exploit into a text file
  - Then feed it through `hex2raw`
- Later stages: write (corruption) assembly
  - Compiling
    - `> gcc -m32 -c` *`example.s`*
  - Get the byte codes
    - `> objdump -d` *`example.o`* `>` *`outfile`*
  - Then feed it through `hex2raw`

Ways to Feed Byte Codes

- Option 1: Pipes
  - `> cat` *`exploitfile`* `| ./hex2raw | ./bufbomb -t` *`andrewID`*
- Option 2: Redirects
  - `> ./hex2raw <` *`exploitfile`* `>` *`exploit-rawfile`*
  - `> ./bufbomb -t` *`andrewID`* `<` *`exploit-rawfile`*
- Option 3: Redirects in GDB
  - `> gdb bufbomb`
  - `(gdb) run -t` *`andrewID`* `<` *`exploit-rawfile`*

Potential Points of Failure

- Don't use byte value 0A in your exploit
  - ASCII for newline
  - `Gets()` will terminate early if it sees this
- Multiple exploits submitted for the same level always takes the latest submission
  - So if you pass correctly once, but accidently pass the wrong exploit later, just pass the correct one again
- If you manage to execute your exploit….
  - GDB will say weird things
    - "Can't access memory…" etc.
    - Just ignore it and keep going
- Don't forget the –n flag on the last level

BUFLAB

- The writeup contains all the lab knowledge
  - How to use the tools
  - How to write corruption code
  - Even tells you how to solve the level (at a high level)!
- Please don't ask questions answered by the writeup
  - Or I will make this sad face: TT_TT
- The writeup is on Autolab
  - Couple links down from the handout

A Lesson on Endianness

- We're working with little endian
  - Least significant byte is at the lower address

Higher addresses …	Caller stack frame
Return Address	
Saved `%ebp`	← `%ebp`
Saved `%ebx`	
Canary	← Potential way to detect stack corruption
MSB `[7] [6] [5] [4]`	buf string (each char is a byte)
`[3] [2] [1] [0]` *LSB*	
… *Lower addresses*	

Example of Endian in Buf Lab

- Example byte code input:
  - 01 02 03 04
    05 06 07 08
    09 AA BB CC
    55 44 04 08
- Little Endian
  - Addresses will look as they normally do when they end up on the stack.
  - Here, value 0x08044455 reads as 0x08044455 on the stack.

Higher addresses …	
08 04 44 55	← Potentially overwritten return address
CC BB AA 09	
08 07 06 05	
04 03 02 01	← Input string address
… *Lower addresses*	

MISCELLANY BUT NECESSARY

- Canaries
  - Attempts to detect overrun buffers
  - Sits at the end of the buffer (array)
    - If the array overflows, *hopefully* we detect this with a change in the canary value….
- NOP sleds
  - The nop instruction means "no-op/ no operation"
    - In computer architecture it's like "pipeline bubbles"
  - Used to "pad" instructions (or exploits!)
    - Place your exploits at the end of the nop sled
    - Allows you to be "sloppier" in providing the return address of your exploit

Demo Time (if class isn't over yet)

- Byte code format
- Byte code feeding
- Example assembly
- Compiling assembly
  - *Not* assembling
- Assembly to byte code

Stolen Credits & Questions Slide

- xkcd: Tabletop Roleplaying
- StackOverflow: Supporting Recursion
- StackOverflow: Direction of Stack Growth
- Understanding the SPARC Architecture
- CS:APP p. 220 – Stack Frame Structure
- *Smashing the Stack for Fun and Profit*
- CS:APP p.262 – NOP sleds
- CS:APP p.263 – Stack Frame with a canary
- Double Mocha Latte Picture