15-213 Recitation 5: Attack Lab

8 Feb 2016

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Agenda

- Reminders
- Stacks
- Attack Lab Overview
- Appendix: Arrays
- Appendix: Structs
- Appendix: More Assembly

Images: openclipart.org

Reminders

- Bomb lab is due **tomorrow!**
  - “But if you wait until the last minute, it only takes a minute!” - ***NOT!***
  - Don't waste your grace days on this assignment
- Attack lab will be released **tomorrow!**

Image credit: tzunghaor / openclipart.org

Stacks

- Last-In, First-Out
  - just like a stack of plates
  - pushes and pops to preserve registers must be in **opposite** order
- x86 stack grows **down**
  - lowest address is “top”

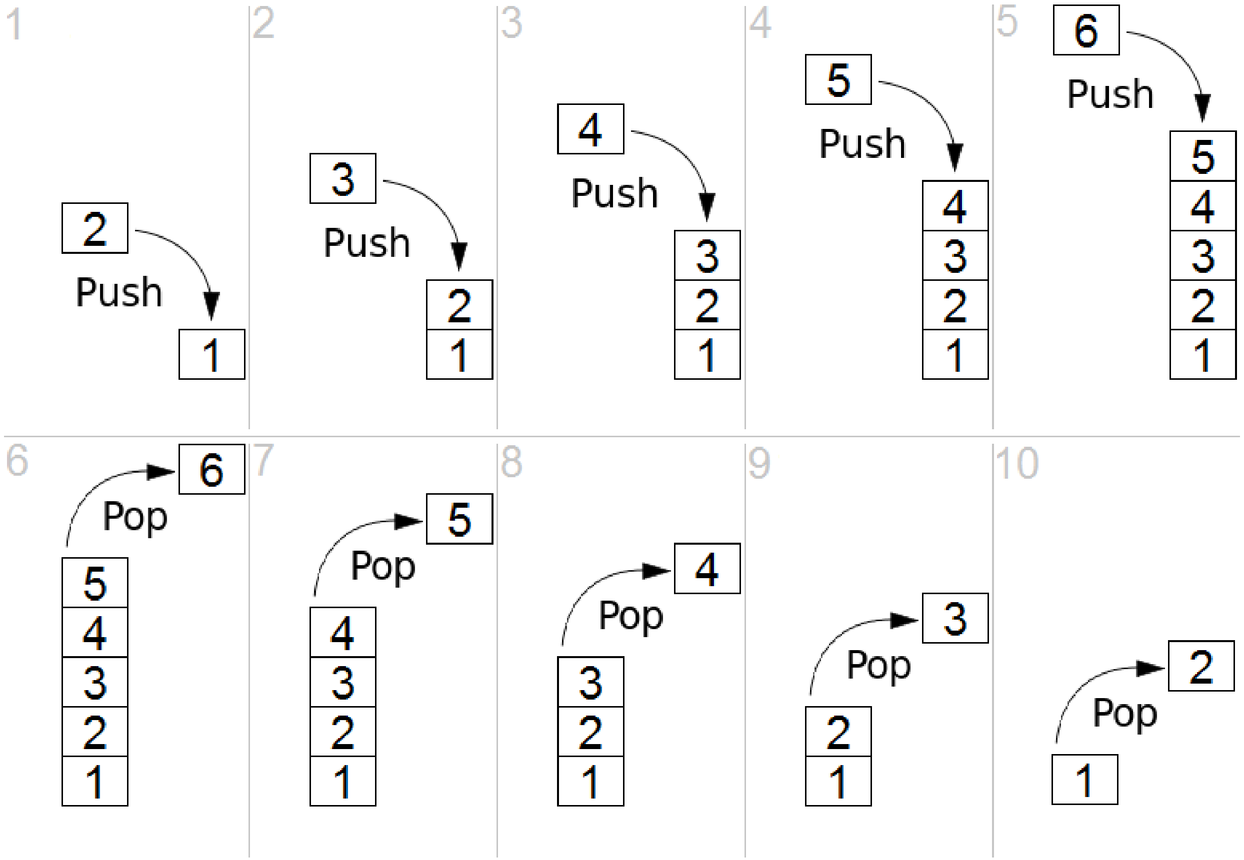


Image credit: Wikimedia Commons

Stacks

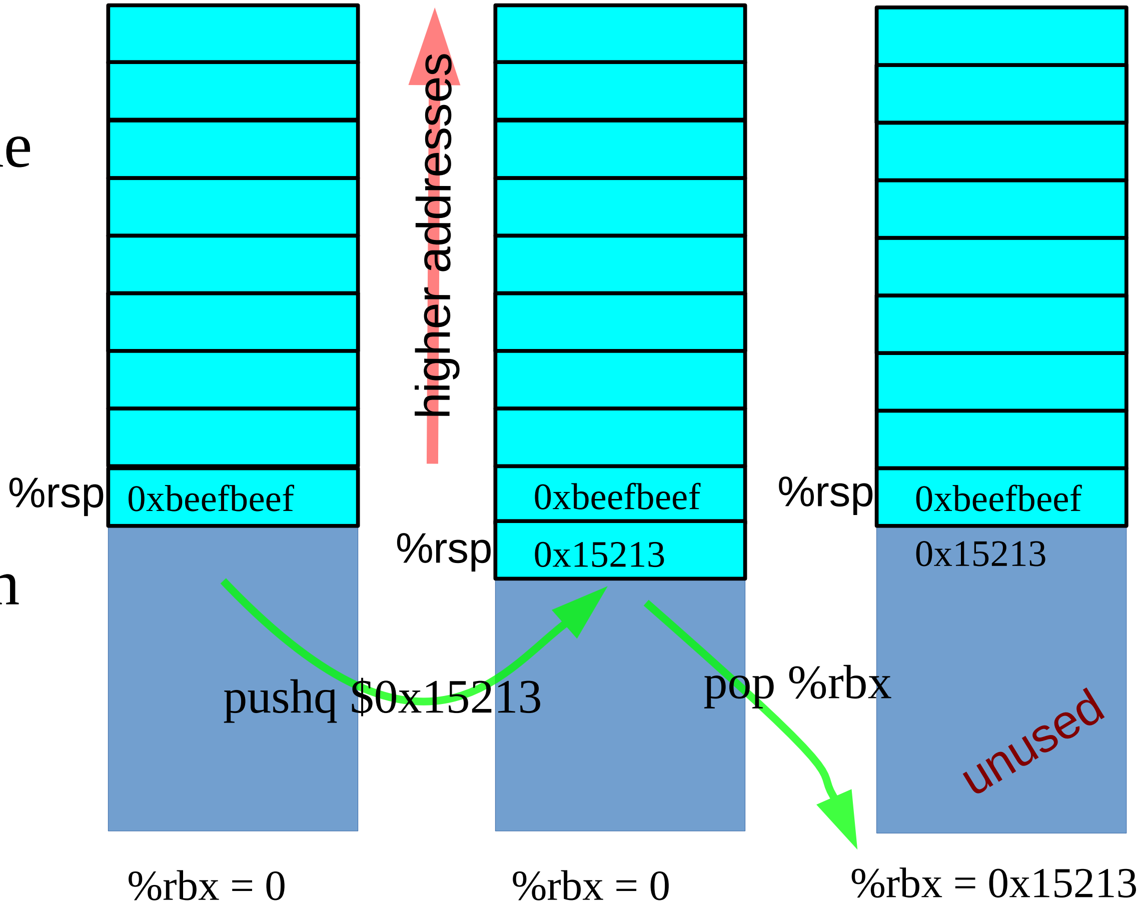
- %rsp contains the address of the topmost element of the stack
- `pushq {value}` is same as

  sub $8,%rsp

  mov {value}, (%rsp)
- only constants and registers can be pushed
- `popq {reg}` is equivalent to

  mov (%rsp), {reg}

  add $8, %rsp



Stacks

- Stacks are useful for recursion
  - each call of the function gets a separate copy of arguments and local variables
  - the separate copy is needed for a limited time only – until the call returns
  - callee always ends before caller
- This is called “stack discipline”

- Stack space is allocated in Frames
  - state for a single instantiation of a function

Register Saving Conventions

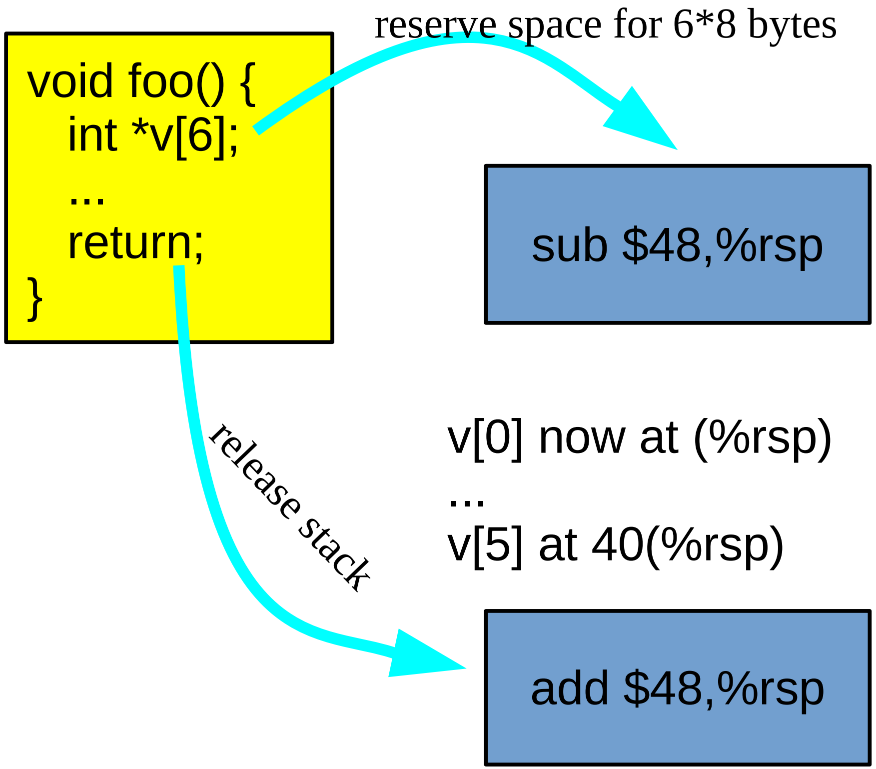
- Caller-Saved
  - called function may do as it wishes with the register
  - must save/restore register in caller's stack frame if it still needs the value after a function call
  - registers used as function arguments are always caller-saved
  - result register `%rax` is also caller-saved
- Callee-Saved
  - if the function wants to change the register, it must save the original value in its stack frame and restore it before returning
  - the calling function may store temporary values across function calls in callee-saved registers

x86-64 Register Usage Conventions

`%rax`	return value	`%r8`	argument #5
`%rbx`	callee saves	`%r9`	argument #6
`%rcx`	argument #4	`%r10`	caller saves
`%rdx`	argument #3	`%r11`	caller saves
`%rsi`	argument #2	`%r12`	callee saves
`%rdi`	argument #1	`%r13`	callee saves
`%rsp`	stack pointer	`%r14`	callee saves
`%rbp`	callee saves	`%r15`	callee saves

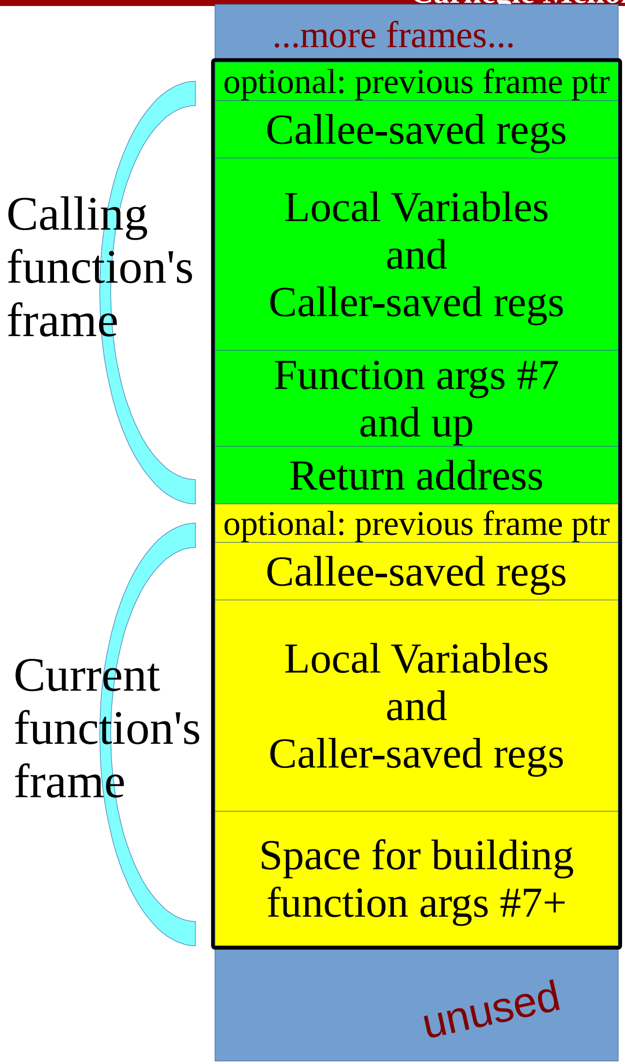
Local Variables

- Local variables which can't be stored in registers are stored on the stack
  - this includes arrays, structs, and anything which has its address taken
- Storage is allocated by simply decrementing %rsp the appropriate amount
- Cleanup consists of incrementing %rsp to free the stack space



Stack Frames

- A frame can have many parts, but only those needed by the function are actually present
  - we consider the function args and return address to be part of the *caller's* frame because they are pushed *before* control transfers to the callee
- Function args 7+ are stored in order from lowest address to highest
  - equivalent to pushing in reverse order
  - access by offsetting from own stack frame
- When present, frame pointers let you traverse the chain of stack frames



Smashing the Stack

- What if a function has a bug that causes it to write beyond its own frame, possibly on some specific program input?
  - We call such overwrites "smashing the stack"
  - If the return address is overwritten, we could end up *anywhere* when the function returns
  - Classic article: "Smashing the Stack for Fun and Profit" by Aleph One (1996).

Attack Lab

- The goal of this lab is to figure out some input to be fed to a program to make it do things it was never designed for
  - You'll do this by smashing the stack
- In the process, you will learn how to prevent and defend against such attacks
- **READ THE WRITEUP!** It shows you the techniques and helper programs you'll need to successfully exploit your target program.

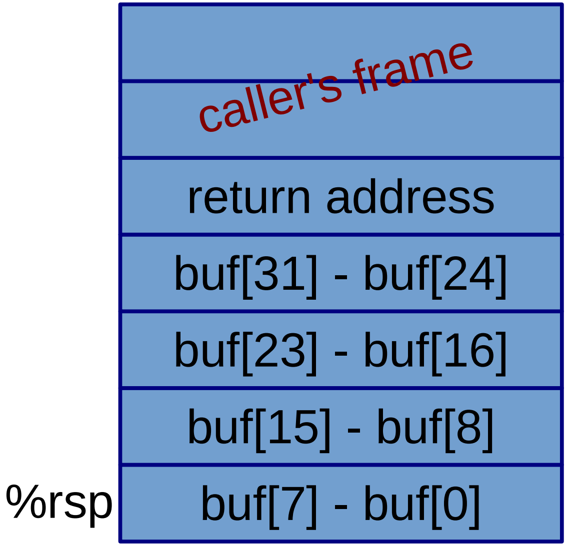
Attack Lab: Code Injection

- You'll be given two compiled programs with a buffer-overflow vulnerability
- Part 1 has you smashing the stack to place code of your own on the stack to create the necessary conditions to call the target function
  - this means you'll have to craft the appropriate bytes in your attack string and then jump to them somehow once they're on the stack

Code Injection Example

- `strcpy` copies from `input` up to and including a NUL byte ('\0')
- if there are more than 31 bytes before the NUL, `strcpy` will write beyond the end of `buf`
- the next thing on the stack is the return address for vuln()....

```
void vuln(char *input) {
    char buf[32];
    ...
    strcpy(buf, input);
    return;
}
```

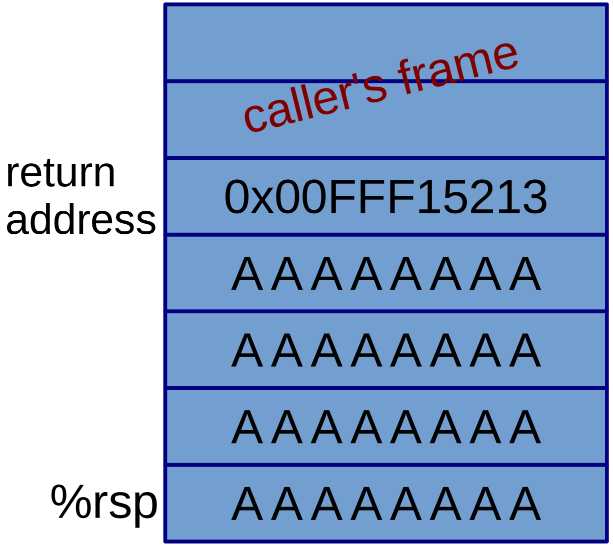


Code Injection Example

```
void vuln(char *input) {
    char buf[32];
    ...
    strcpy(buf, input);
    return;
}
```

- Simplest case: we just need to jump to a different address
  - fill the buffer with anything, then overwrite the return address
  - if we need to jump to 0xFFF15213 instead of the original 0xFEEDBEEF, a possible value for input is

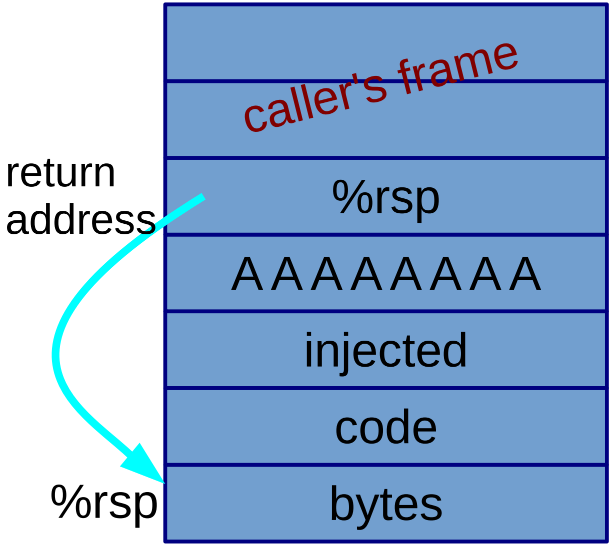
    0x41 (32 times) 0x13 0x52 0xF1 0xFF 0x00
  - remember byte order!
- After the `strcpy`, the stack will look as shown



Code Injection Example

- If we need to insert actual code on the stack, we must first figure out the value of %rsp!
  - run a copy of the program and break at the call to strcpy
- Put your exploit code in the buffer, and overwrite the return address with the address of the buffer
  - use **gcc** and **objdump** to generate the byte sequences for your injected code
  - code can't contain NUL bytes (newlines if exploiting `gets`)

```
void vuln(char *input) {
    char buf[32];
    ...
    strcpy(buf, input);
    return;
}
```



Attack Lab: The Stack Has Protections!

- Modern CPUs allow data areas to be marked as non-executable
  - so you can't place exploit code on the stack and jump to it
- OSes use Address Space Layout Randomization to keep addresses unpredictable
  - an attack that works on one run might not on the next!
- Compiled code commonly uses “stack canaries”
  - unpredictable values stored between on-stack buffers and return address
  - if the value changes, the program is aborted rather than returning from the function (because the return address might have been corrupted)

Attack Lab: Return-Oriented Programming

- In Part 2 of Attack Lab, the program has stack protections in place
- If we can't build our code on the stack, we have to find snippets of existing code (“gadgets”) that we can stitch together with an appropriate sequence of return addresses on the stack
  - hence the name ROP
  - we just need to find the right byte sequences – those exact instruction sequences don't actually have to be a deliberate part of the program!

ROP: Finding Gadgets

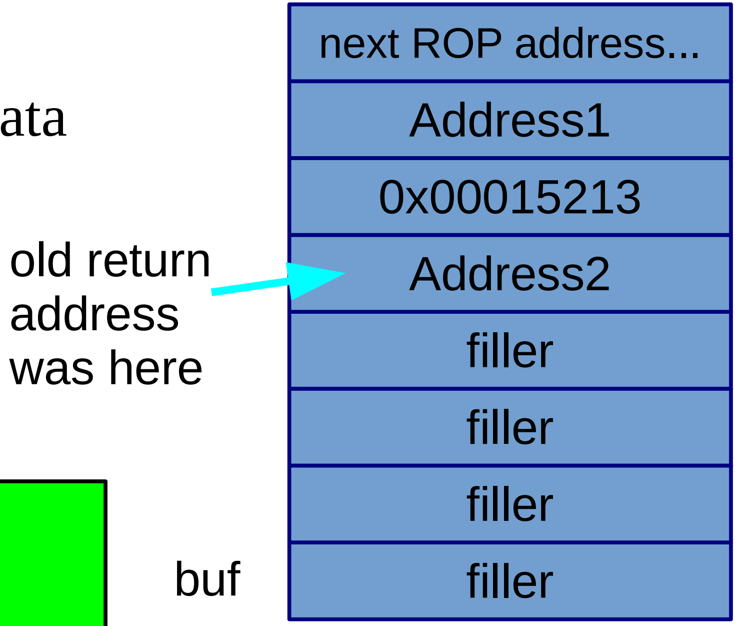
- Look for byte sequences corresponding to an interesting instruction followed by `ret`
  - e.g. 0x59 0xC3 would be `pop %rbx; ret`
- Need to be creative in the instructions we execute
  - we probably can't find `mov $0x15213, %rax`
  - but we could stitch together the equivalent from
    - `pop %rbx`
    - `mov %rbx, %rax`
    - and a value of 0x15213 on the stack

Example inspired by content created by Professor David Brumley

ROP: The Exploit

```
void vuln(char *input) {
    char buf[32];
    ...
    strcpy(buf, input);
    return;
}
```

- Find the gadgets
- Overflow the buffer to overwrite the return address and higher stack addresses with ROP instructions
  - each is a gadget address followed by any data the gadget pops off the stack



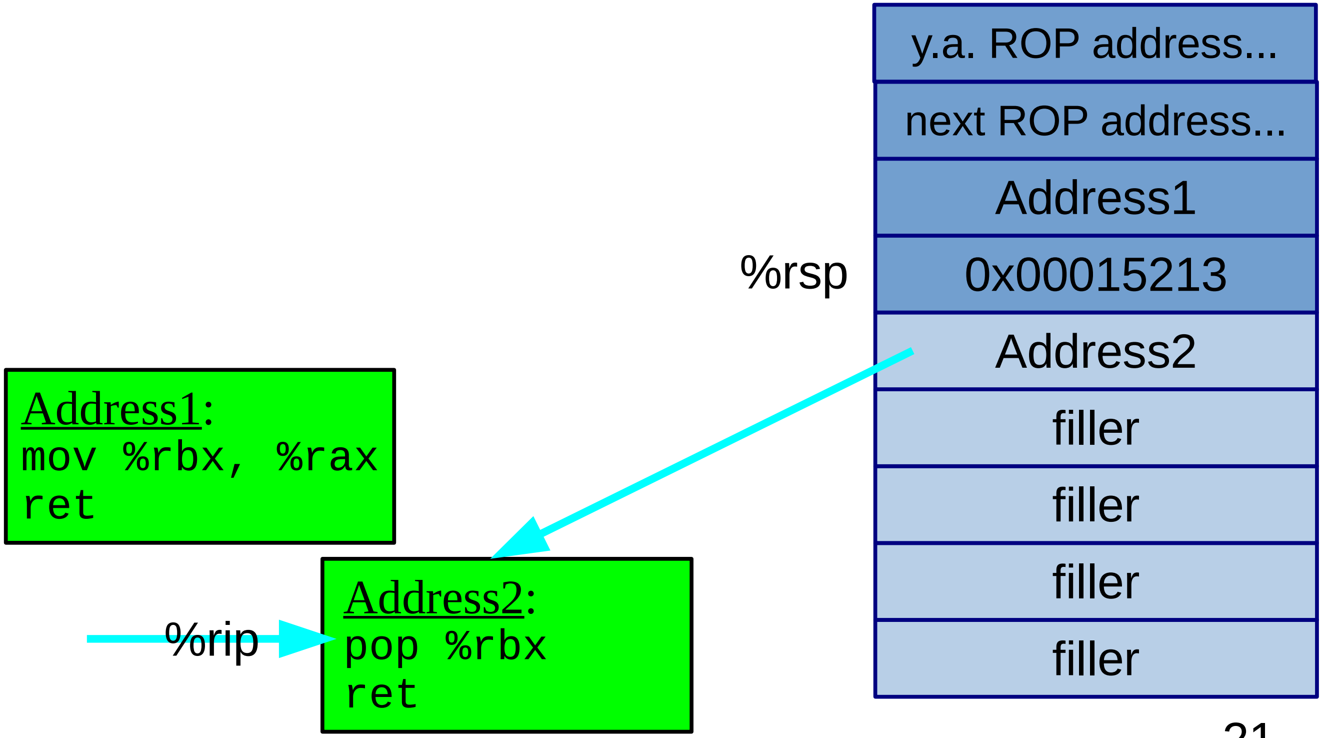
Address1:
```
mov %rbx, %rax
ret
```

Address2:
```
pop %rbx
ret
```


Example inspired by content created by Professor David Brumley

ROP: The Exploit Runs

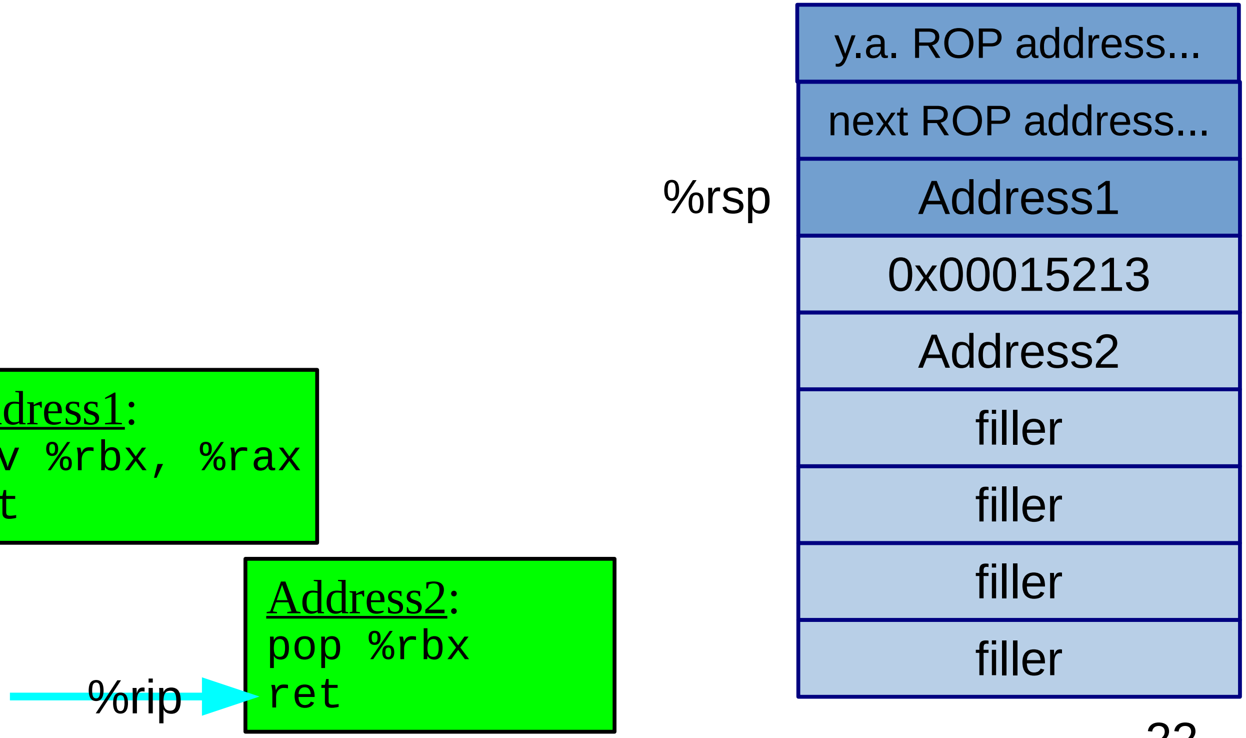
- When vuln() returns, we jump to Address2 instead of the original caller
  - %rax = ?
  - %rbx = ?



Example inspired by content created by Professor David Brumley

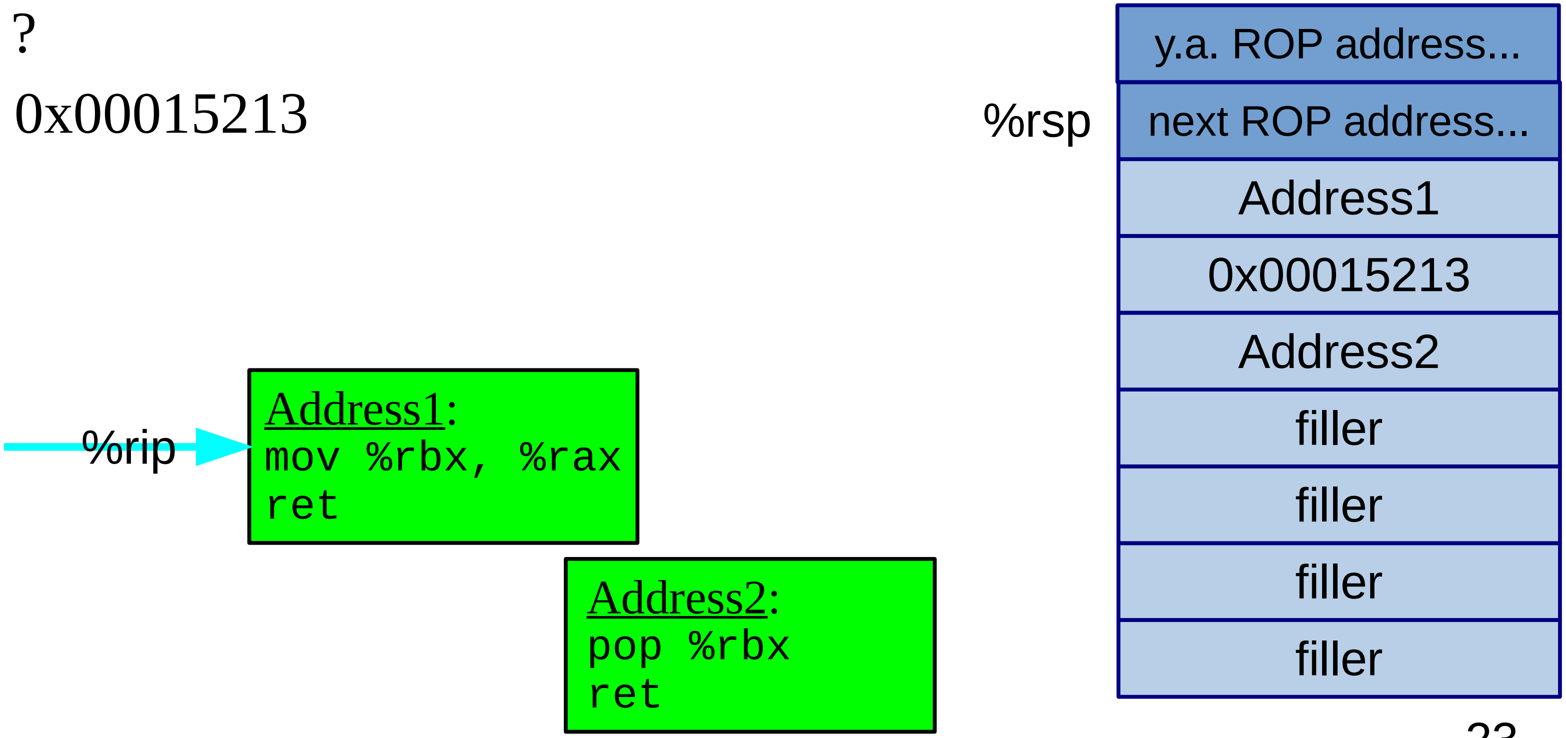
ROP: The Exploit Runs

- The gadget at Address2 pops the top item off the stack
  - %rax = ?
  - %rbx = 0x00015213



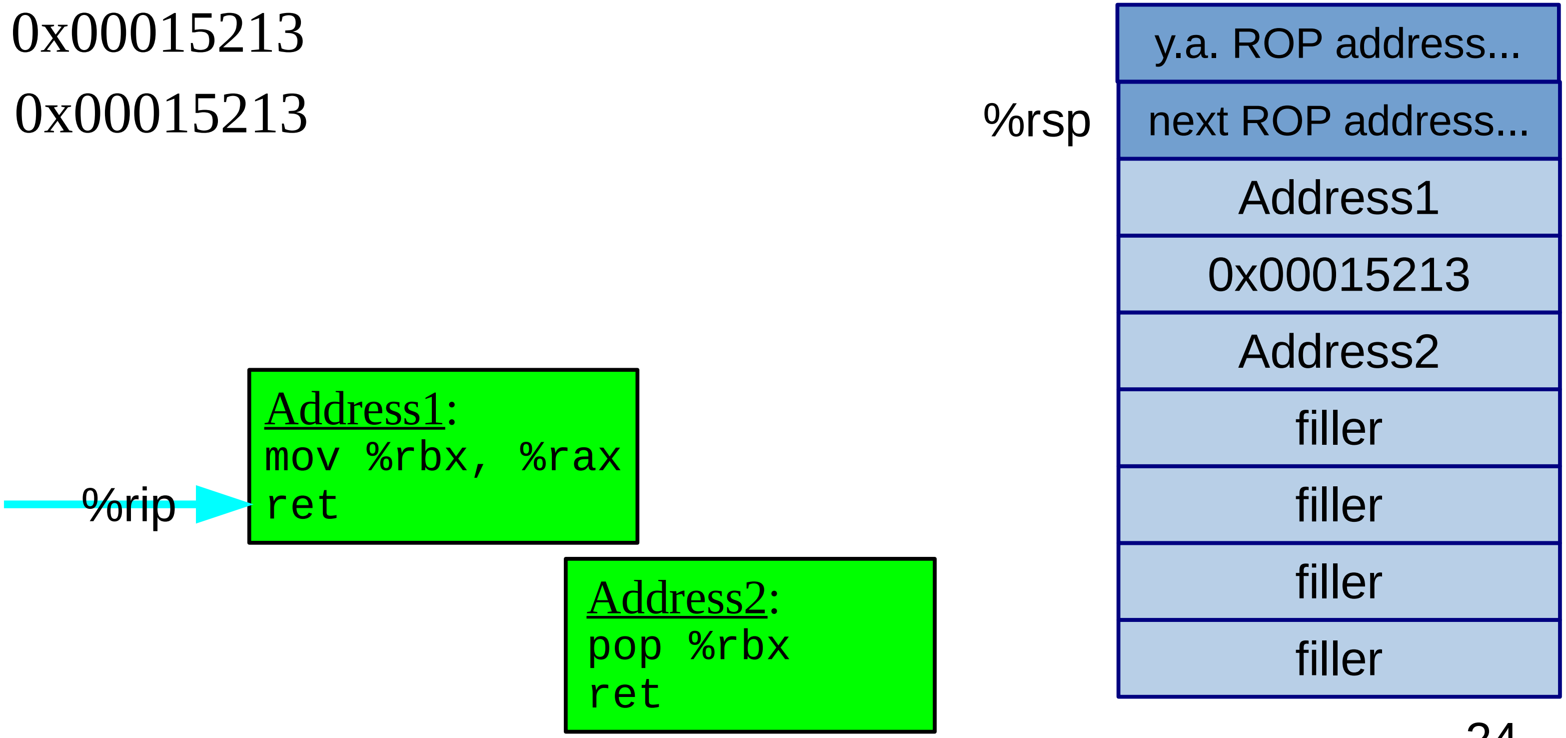
ROP: The Exploit Runs

- Next, the gadget at Address2 returns, which puts us at Address1
  - %rax = ?
  - %rbx = 0x00015213



ROP: The Exploit Runs

- The gadget at Address1 now copies %rbx into %rax
  - %rax = 0x00015213
  - %rbx = 0x00015213



ROP: The Exploit Runs

- Finally, the gadget at Address1 returns, taking us to the next gadget
  - %rax = 0x00015213
  - %rbx = 0x00015213
- We've now executed the equivalent of
  - `mov $0x15213, %rax`
- (with a side effect)

Address1:
```
mov %rbx, %rax
ret
```

Address2:
```
pop %rbx
ret
```

Attack Lab Tools

- **gcc -c file.s**
  - convert the assembly code in <u>file.s</u> to object code in <u>file.o</u>
- **objdump -d file.o**
  - disassemble the code in file.o; shows the actual bytes for the instructions
- **./hex2raw**
  - convert hex codes into raw ASCII strings to pass to targets
- **gdb**
  - determine stack addresses
- **paper and pencil**
  - for drawing stack diagrams

More Useful GDB Commands

`x/[n]i` <address>	disassemble *n* instructions at <address>
`b` <loc> `if` <cond>	conditional breakpoint, stop only if <cond> true
`cond` <bp> <cond>	add condition to existing breakpoint <bp>
`commands` <bp>	execute commands when breakpoint <bp> hit
`tbreak` <loc>	set temporary breakpoint – auto-deletes when hit!
`finish`	run until current frame (function) returns, and print return value
`layout asm`	split the screen into separate disassembly and command windows
`layout reg`	show register window as well (after `layout asm`)

If You Get Stuck

- **Please read the writeup.** ***Please read the writeup.*** ***<u>Please read the writeup.</u>*** ***Please read the writeup!***
- CS:APP Chapter 3
- View lecture notes and course FAQ at http://www.cs.cmu.edu/~213
- Office hours Sunday through Thursday 5:00-9:00pm in WeH 5207
- Post a **private** question on Piazza
- `man gdb`, gdb's `help` command

Remember...

Appendix: Arrays

- In C, the name of an array is interpreted as a pointer to the first element
  - `A` is the same as `&A[0]`
- Array subscripting is just a synonym for pointer arithmetic:
  - `A[1]` equals `*(A + 1)`
- This translates almost directly into assembly. x = A[5] becomes

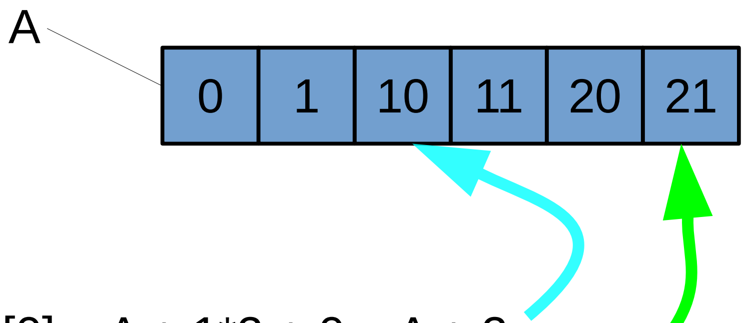
```
mov $5, %rax
mov {address of A}, %rbx
mov (%rbx, %rax, 4), %rdx
```

- We simply scale the index by the size of an element and add that to the starting address

Two-dimensional Arrays

- Arrays elements can themselves be arrays
- As with one-dimensional arrays, the elements are stored in order in memory
- C only supports compile-time sized multi-dimensional arrays – you need to compute the corresponding index as if the array were one-dimensional for run-time sizing

```
int A[3][2] = {
   { 0, 1 },
   { 10, 11 },
   { 20, 21 } };
```



&A[1][0] = A + 1*2 + 0 = A + 2

&A[2][1] = A + 2*2 + 1 = A + 5

for MxN array, &A[i][j] = A + i*N + j

Appendix: Structs

- Structures are a way to bundle together related data/variables
- Elements of a structure may be of any type, including pointers, arrays and *other* structures (no recursive regress allowed!)
- Structs can be the elements of an array
- Access parts of the structure by name, rather than by index as for arrays

```
struct info {
    int whole_num;
    double float_num;
    char string[9];
} S[5];
/* init 2nd array element */
S[1].whole_num = 15213;
S[1].float_num = 15.213;
strcpy(S[1].string,"15-213");
```

Structs

- Structures are a way to bundle together related data/variables
- Elements of a struct declared variable any type, including p...s, arrays and *other* structures (no recursive regress allowed!)
- Structs can be the elements of an array
- Access parts of the structure by name, rather than by index as for arrays

type name

member

```
struct info {
    int whole_num;
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} S[5];
/* init 2nd array element */
S[1].whole_num = 15213;
S[1].float_num = 15.213;
strcpy(S[1].string,"15-213");
```

Structs

- The type name of a struct can be used in future variable declarations – given the declaration on the previous slide, we can now say

```
struct info T;
```

- This declares variable `T` to be of the same type as the elements of array `S`.

- The type name is optional when declaring a variable – that creates an *anonymous* structure type.
- You can also declare a structure type without declaring any variables:

```
struct st { int m1; float m2; };
```

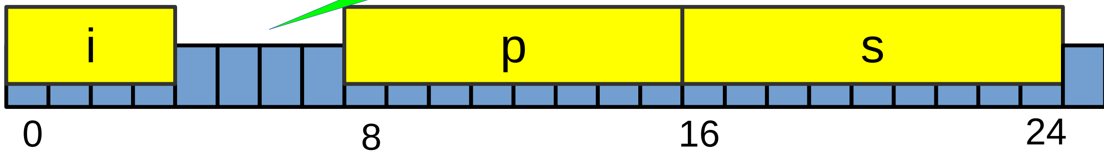
Structs: Memory Layout

- Struct members are placed a multiple of their own size from the start of the struct
  - some architectures require such alignment to even access the member
  - x86 doesn't care, but will be slower whenever misalignment causes two memory accesses
- Minimize size by putting largest members first
  - array elements count as individual members

```
struct s1 {
   int i;
   double *p;
   char s[9];
} ;
```

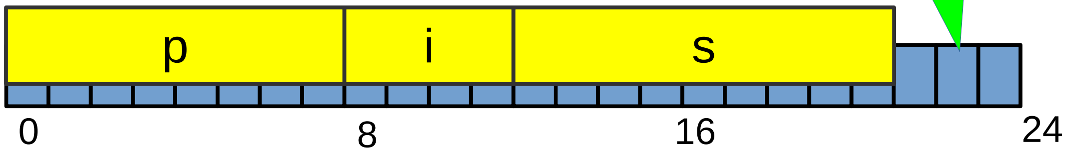
4 bytes of alignment padding

sizeof s1 = 32




```
struct s2 {
   double *p;
   int i;
   char s[9];
} ;
```

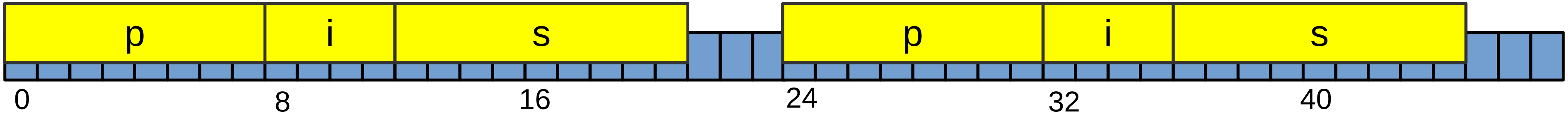
Size must be multiple of strictest alignment

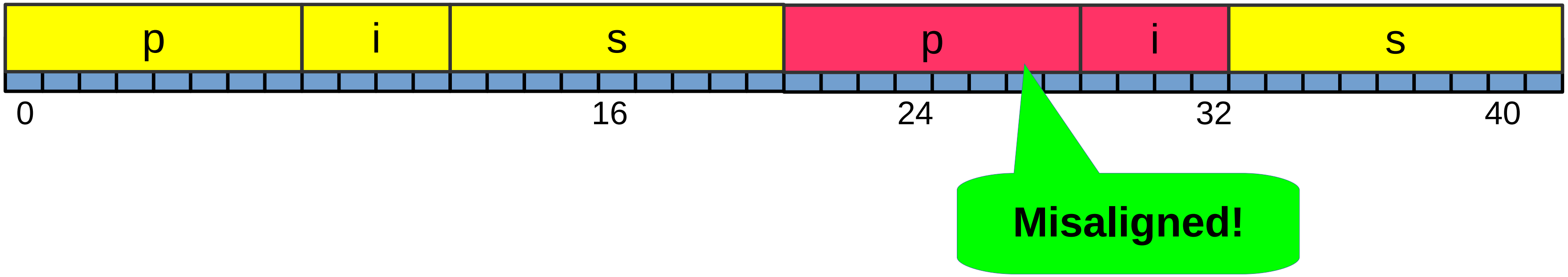


sizeof s2 = 24

Arrays of Structs

- Requiring struct sizes to be a multiple of their strictest alignment supports arrays
- Otherwise, not all members would be aligned in every array element





Appendix: More Assembly

- Some instructions you may encounter
  - `cltq` ("Convert Long To Quad") -- sign-extend %eax into %rax
  - `cmov`*`X`* ("Conditional Move") -- executes move only if condition *X* is true
  - `movzbl` ("MOVe w/ Zero-extension, Byte to Long")
  - `nop` ("No Operation") -- do nothing
  - `nopl` ("No Operation, Long") -- multi-byte instruction that does nothing
    - used to align function start addresses to a multiple of 16 bytes
  - `repz retq` – see Recitation 4
  - `mov %fs:0x28, %rax`
    - beyond the scope of the course; %fs is a *segment register*, which here is used to implement thread-local storage