COMP201

Computer Systems & Programming

Lecture #20 – Security Vulnerabilities

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Spring 2022

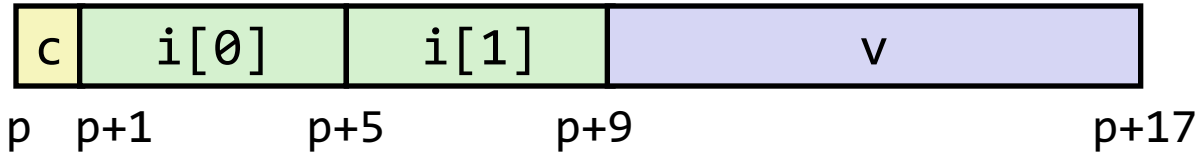
Recap

- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- Structures
  - Allocation
  - Access
  - Alignment

Recap: Structures & Alignment

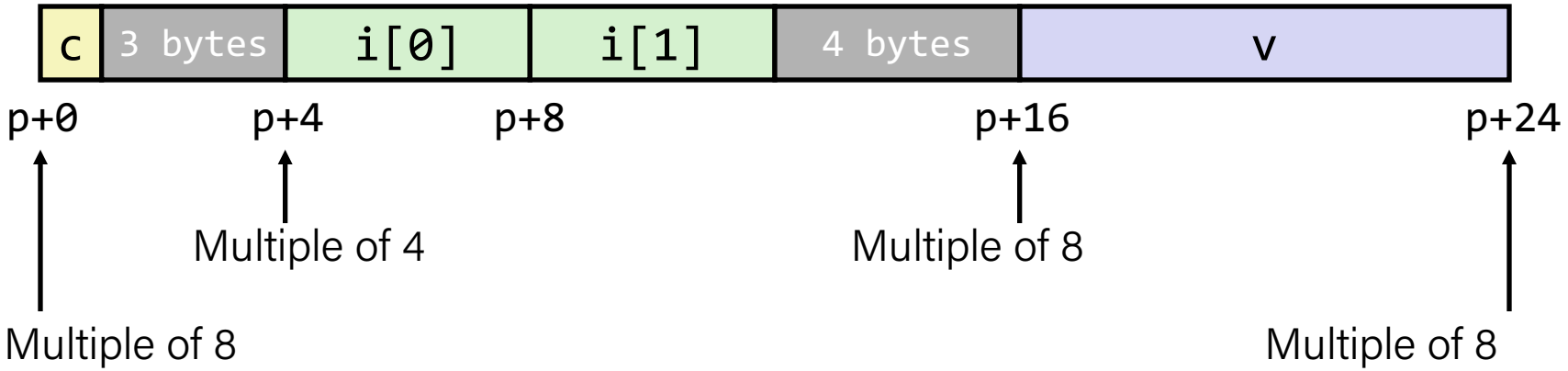
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

Unaligned Data



Aligned Data

- Primitive data type requires K bytes
- Address must be multiple of K



Recap: Specific Cases of Alignment (x86-64)

- 1 byte: `char`, ...
  - no restrictions on address
- 2 bytes: `short`, ...
  - lowest 1 bit of address must be 0_2
- 4 bytes: `int`, `float`, ...
  - lowest 2 bits of address must be 00_2
- 8 bytes: `double`, `long, char *`, ...
  - lowest 3 bits of address must be 000_2
- 16 bytes: `long double` (GCC on Linux)
  - lowest 4 bits of address must be 0000_2

Recap: Satisfying Alignment with Structures

Within structure:

- Must satisfy each element's alignment requirement

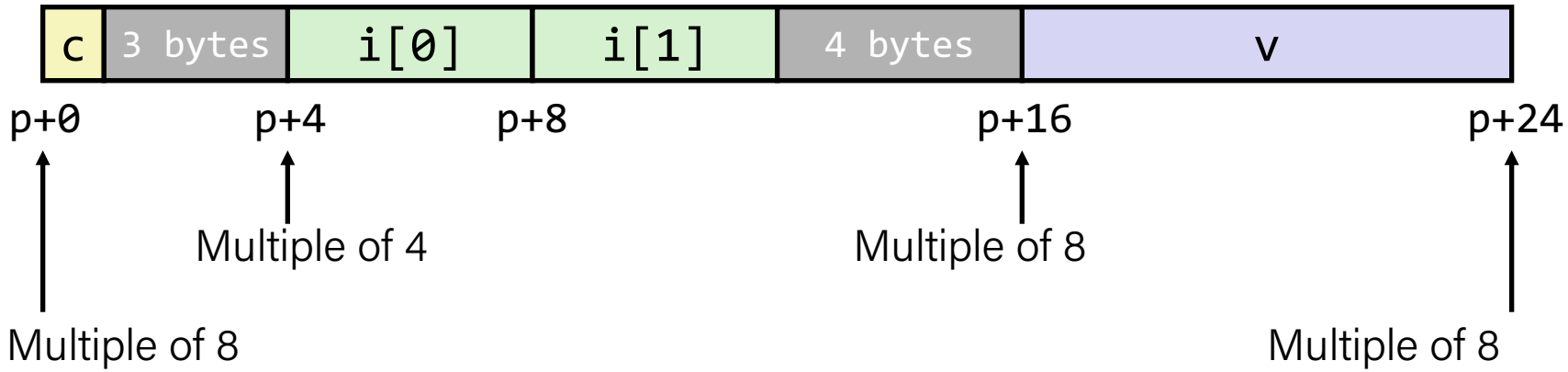
Overall structure placement

- Each structure has alignment requirement K
  - K = Largest alignment of any element
- Initial address & structure length must be multiples of K

```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

Example:

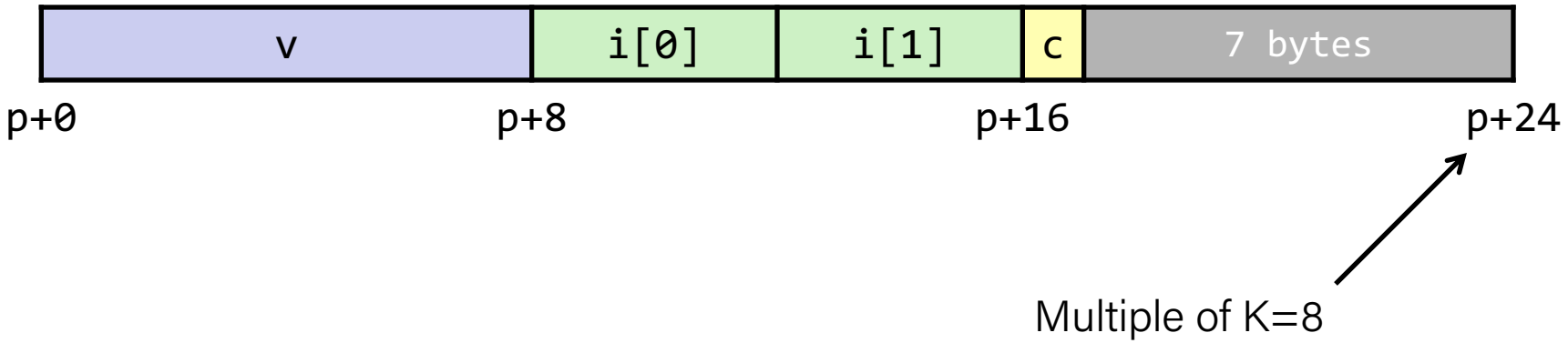
- K = 8, due to **`double`** element



Recap: Overall Alignment Requirement

- For largest alignment requirement K
- Overall structure must be multiple of K

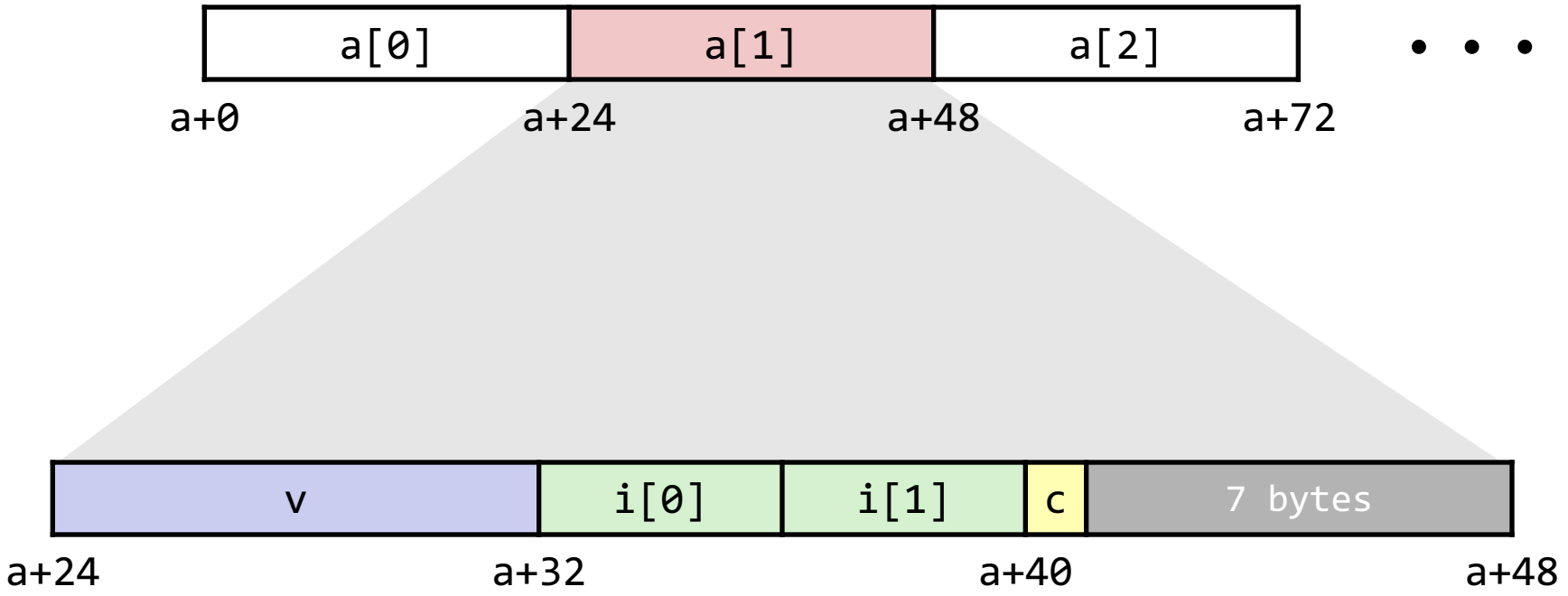
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Recap: Arrays of Structures

```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```

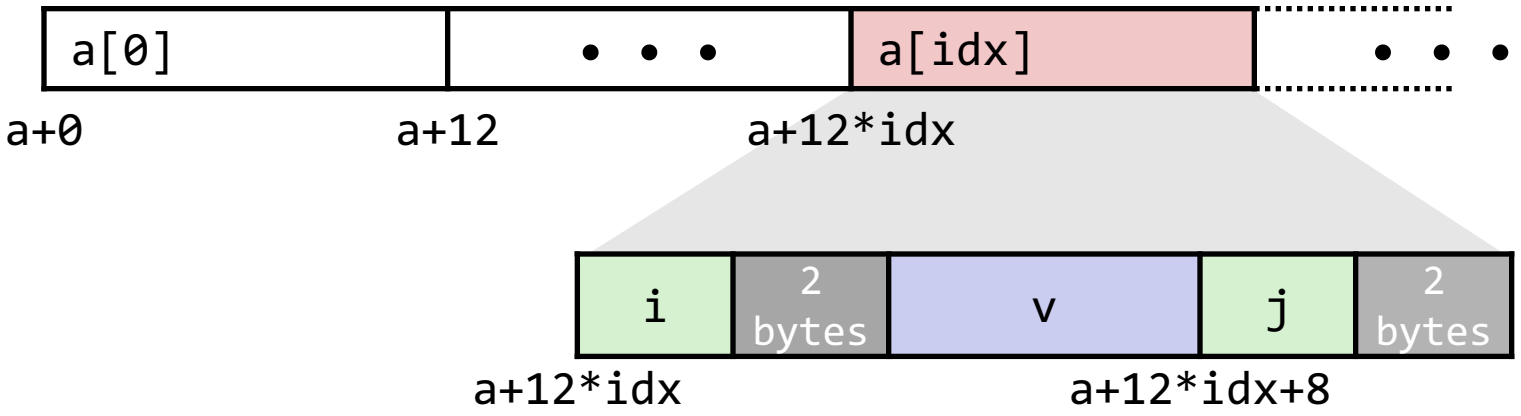
- Overall structure length multiple of K
- Satisfy alignment requirement for every element



Recap: Accessing Array Elements

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```

- Compute array offset `12*idx`
  - `sizeof(S3)`, including alignment spacers
- Element `j` is at offset 8 within structure
- Assembler gives offset `a+8` (resolved during linking)




```
short get_j(int idx) {
  return a[idx].j;
}
```

```
# %rdi = idx
leaq (%rdi,%rdi,2),%rax # 3*idx
movzwl a+8(,%rax,4),%eax
```

Practice 3: Alignment

Determine the offset of each field, the total size of the structure, and its alignment requirement for x86-64.

```
struct mystruct {
    int *a;
    float b;
    char c;
    short d;
    float e;
    double f;
    int g;
    char *h;
};
```

Field	***a**	**b**	**c**	**d**	**e**	**f**	**g**	***h**	Total	Alignment
Size	8	4	1	2	4	8	4	8	??	8

Practice 3: Alignment

Determine the offset of each field, the total size of the structure, and its alignment requirement for x86-64.

```
struct mystruct {
    int *a;
    float b;
    char c;
    short d;
    float e;
    double f;
    int g;
    char *h;
};
```

Field	*a	b	c	d	e	f	g	*h	Total	Alignment
Size	8	4	1	2	4	8	4	8	48	8
Offset	0	8	12	14	16	24	32	40		

no extra padding is necessary to satisfy overall alignment requirement

Practice 3: Alignment

Determine the offset of each field, the total size of the structure, and its alignment requirement for x86-64.

```
struct mystruct {
    int *a;
    float b;
    char c;
    short d;
    float e;
    double f;
    int g;
    char *h;
};
```

Field	***a**	**b**	**c**	**d**	**e**	**f**	**g**	***h**	Total	Alignment
Size	8	4	1	2	4	8	4	8	48	8
Offset	0	8	12	14	16	24	32	40		

no extra padding is necessary to satisfy overall alignment requirement

Rearranged structure with minimum wasted space:

Field	***a**	**f**	**h**	**b**	**e**	**g**	**d**	**c**	Total	Alignment
Size	8	8	8	4	4	4	2	1	40	8
Offset	0	8	16	24	28	32	36	38		

1 bytes padded to satisfy alignment requirement

Plan for Today

- Floating Point
- Memory Layout
- Buffer Overflow

Disclaimer: Slides for this lecture were borrowed from

—Randal E. Bryant and David R. O'Hallaroni's CMU 15-213 class

—Ruth Anderson's UW CSE 351 class

Lecture Plan

- Floating Point
- Memory Layout
- Buffer Overflow

Background

- History
  - x87 FP
    - Legacy, very ugly
  - Streaming SIMD Extensions (SSE) FP
    - SIMD: single instruction, multiple data
    - Special case use of vector instructions
  - AVX FP
    - Newest version
    - Similar to SSE
    - Documented in book

Programming with SSE3

XMM Registers

- 16 total, each 16 bytes
- 16 single-byte integers

- 8 16-bit integers

- 4 32-bit integers

- 4 single-precision floats

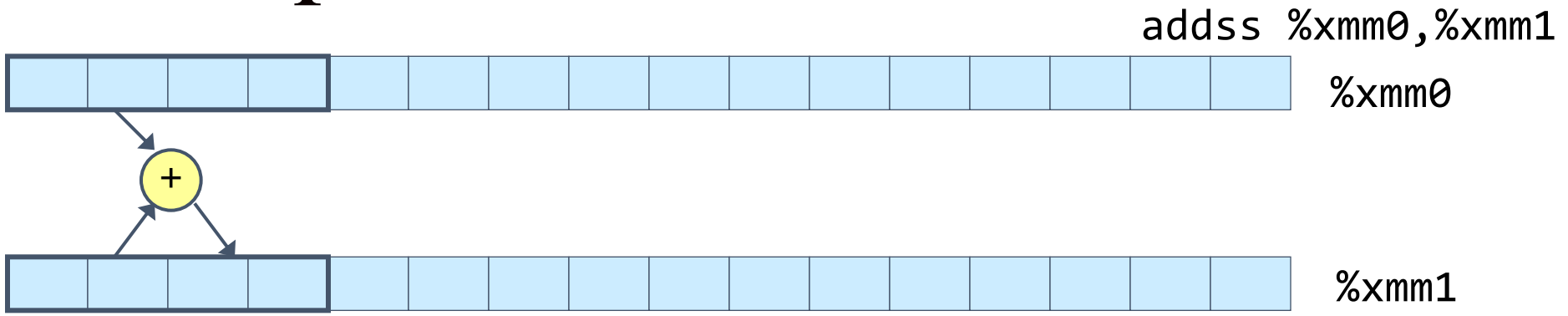
- 2 double-precision floats

- 1 single-precision float

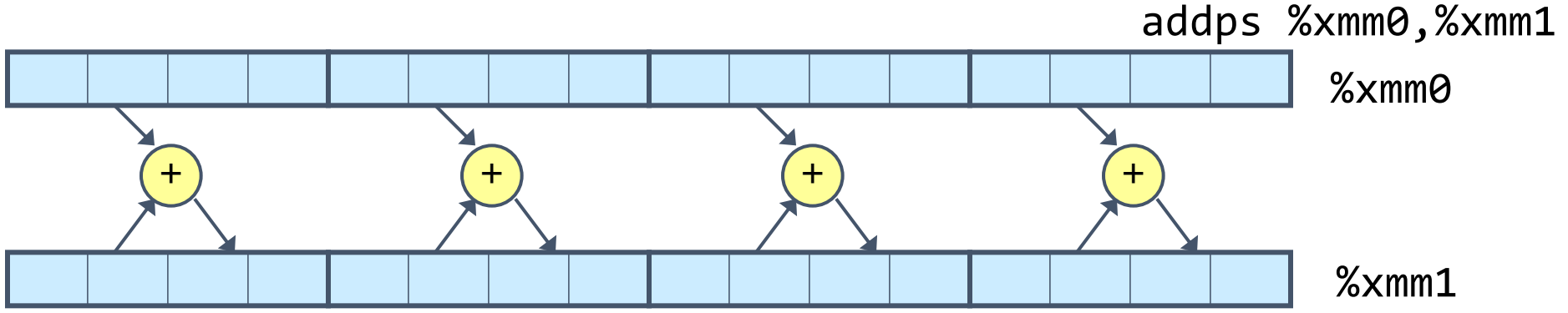
- 1 double-precision float

Scalar & SIMD Operations

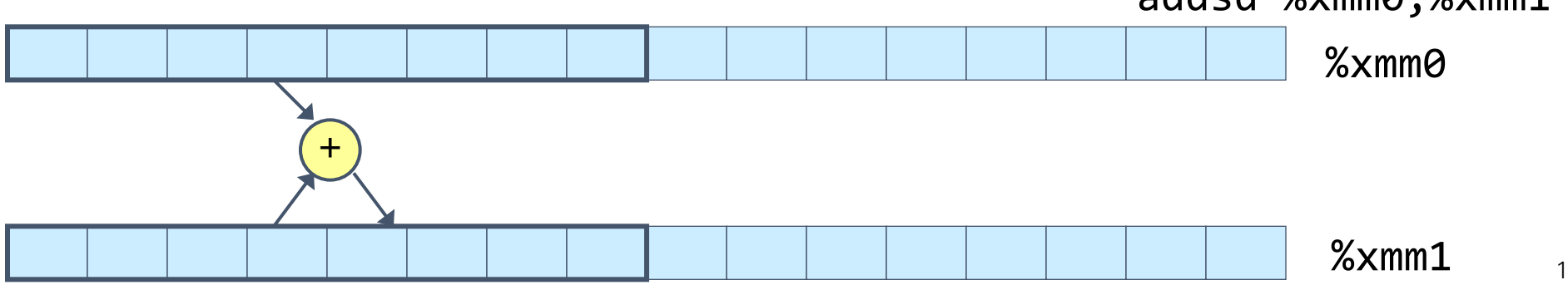
- Scalar Operations: Single Precision



- SIMD Operations: Single Precision



- Scalar Operations: Double Precision



FP Basics

- Arguments passed in `%xmm0`, `%xmm1`, …
- Result returned in `%xmm0`
- All XMM registers caller-saved

```
float fadd(float x, float y) {
    return x + y;
}
```

```
# x in %xmm0, y in %xmm1
addss   %xmm1, %xmm0
ret
```

```
double dadd(double x, double y) {
    return x + y;
}
```

```
# x in %xmm0, y in %xmm1
addsd   %xmm1, %xmm0
ret
```

FP Memory Referencing

- Integer (and pointer) arguments passed in regular registers
- FP values passed in XMM registers
- Different `mov` instructions to move between XMM registers, and between memory and XMM registers

```
double dincr(double *p, double v)
{
    double x = *p;
    *p = x + v;
    return x;
}
```

```
# p in %rdi, v in %xmm0
movapd  %xmm0, %xmm1   # Copy v
movsd   (%rdi), %xmm0  # x = *p
addsd   %xmm0, %xmm1   # t = x + v
movsd   %xmm1, (%rdi)  # *p = t
ret
```

Other Aspects of FP Code

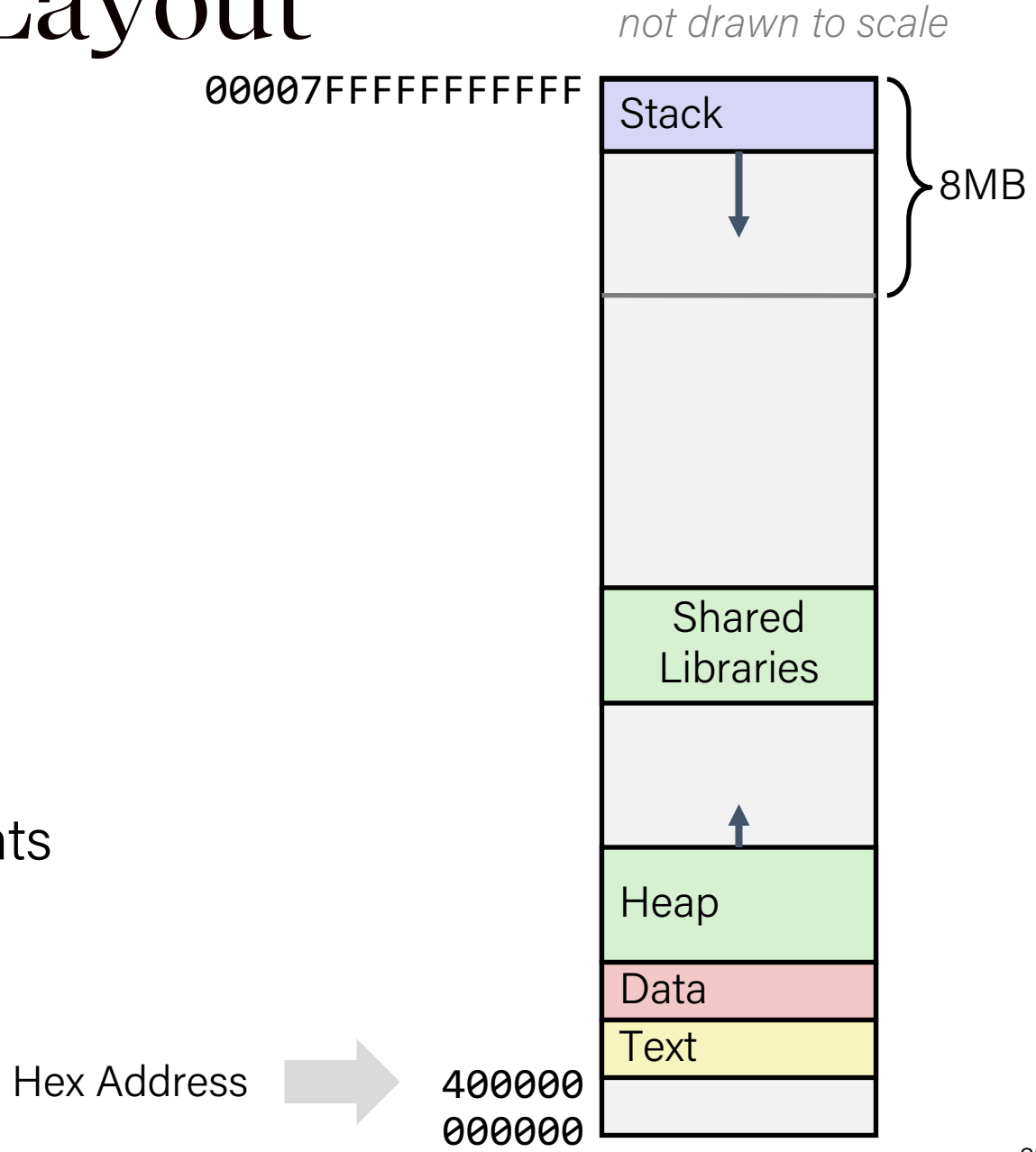
- Lots of instructions
  - Different operations, different formats, …
- Floating-point comparisons
  - Instructions `ucomiss` and `ucomisd`
  - Set condition codes `CF`, `ZF`, and `PF`
- Using constant values
  - Set XMM0 register to 0 with instruction `xorpd %xmm0, %xmm0`
  - Others loaded from memory

Lecture Plan

- Floating Point
- Memory Layout
- Buffer Overflow

x86-64 Linux Memory Layout

- Stack
  - Runtime stack (8MB limit)
  - E. g., local variables
- Heap
  - Dynamically allocated as needed
  - When call `malloc()`, `calloc()`, `new()`
- Data
  - Statically allocated data
  - E.g., global vars, static vars, string constants
- Text / Shared Libraries
  - Executable machine instructions
  - Read-only



Memory Allocation Example

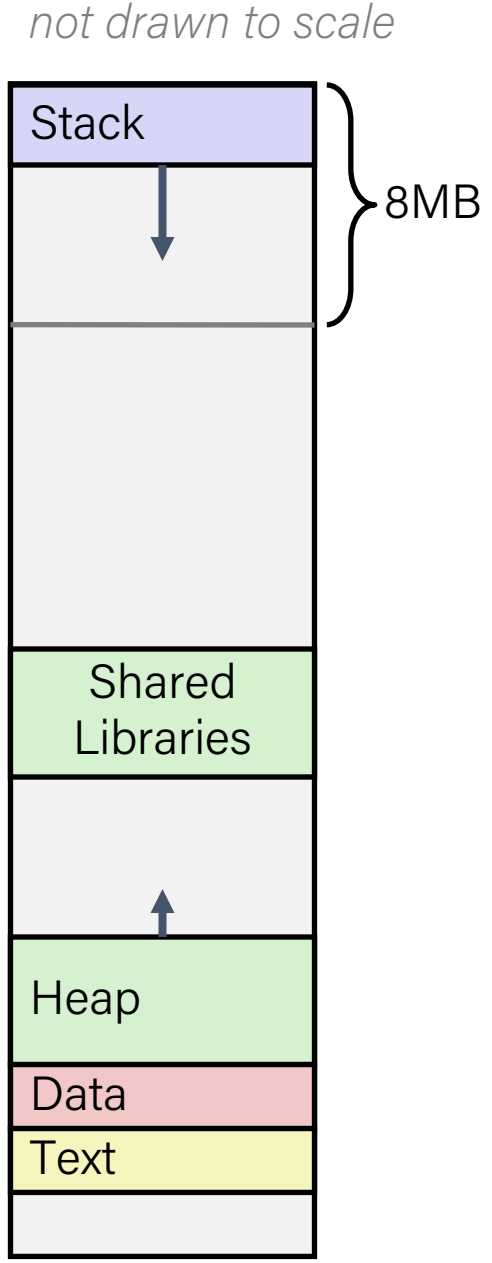
```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

int global = 0;

int useless() { return 0; }

int main ()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
 /* Some print statements ... */
}
```

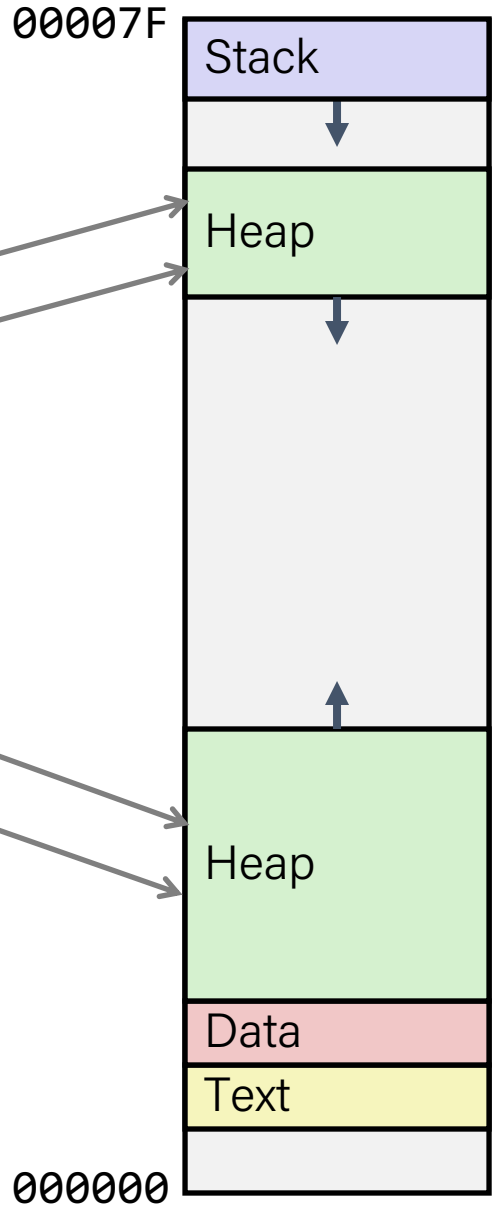
- Where does everything go?



x86-64 Example Addresses

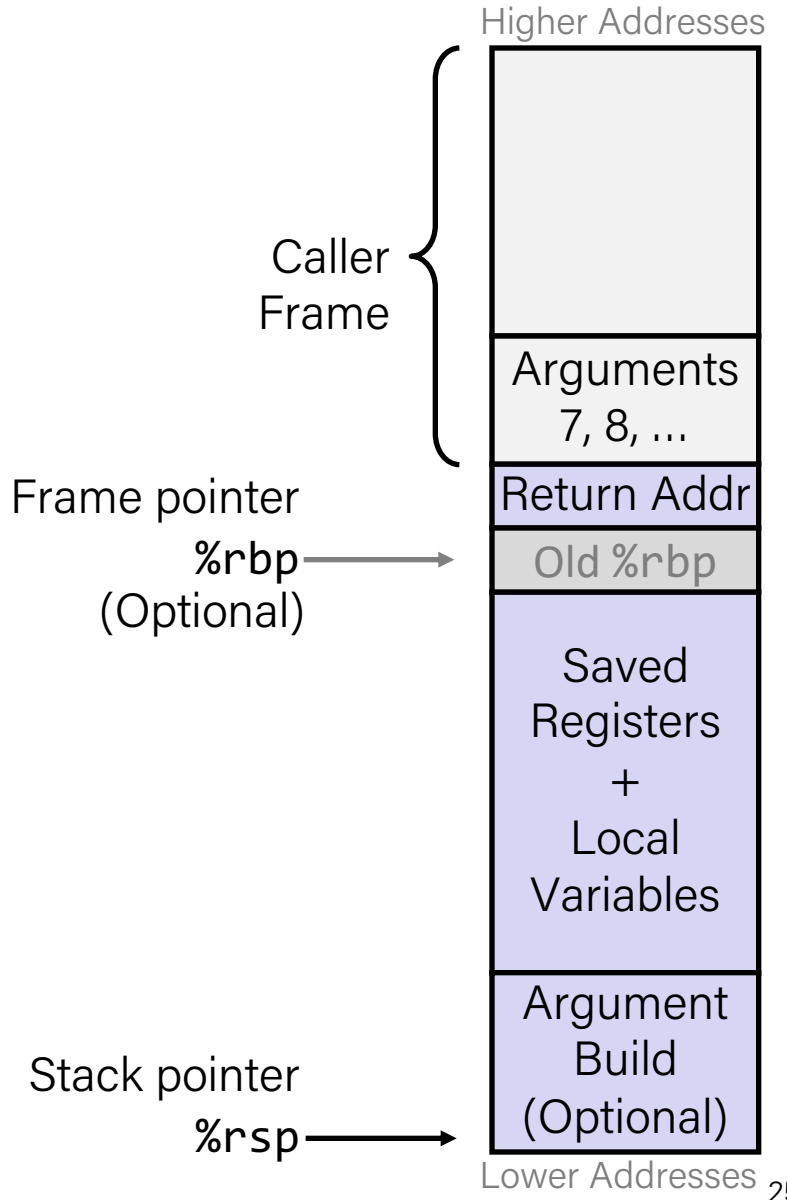
address range ~2^{47}

local	0x00007ffe4d3be87c
p1	0x00007f7262a1e010
p3	0x00007f7162a1d010
p4	0x00000008359d120
p2	0x00000008359d010
big_array	0x00000080601060
huge_array	0x00000000601060
main()	0x00000000040060c
useless()	0x00000000400590



Reminder: x86-64/Linux Stack Frame

- **Caller's Stack Frame**
  - Arguments (if > 6 args) for this call
- **Current/ Callee Stack Frame**
  - Return address
    - Pushed by `call` instruction
  - Old frame pointer (optional)
  - Caller-saved pushed before setting up arguments for a function call
  - Callee-saved pushed before using long-term registers
  - Local variables (if can't be kept in registers)
  - "Argument build" area (Need to call a function with >6 arguments? Put them here)



Lecture Plan

- Floating Point
- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection

Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;

double fun(int i) {
  volatile struct_t s;
  s.d = 3.14;
  s.a[i] = 1073741824; /* Possibly out of bounds */
  return s.d;
}
```

```
fun(0) → 3.14
fun(1) → 3.14
fun(2) → 3.1399998664856
fun(3) → 2.00000061035156
fun(4) → 3.14
fun(6) → Segmentation fault
```

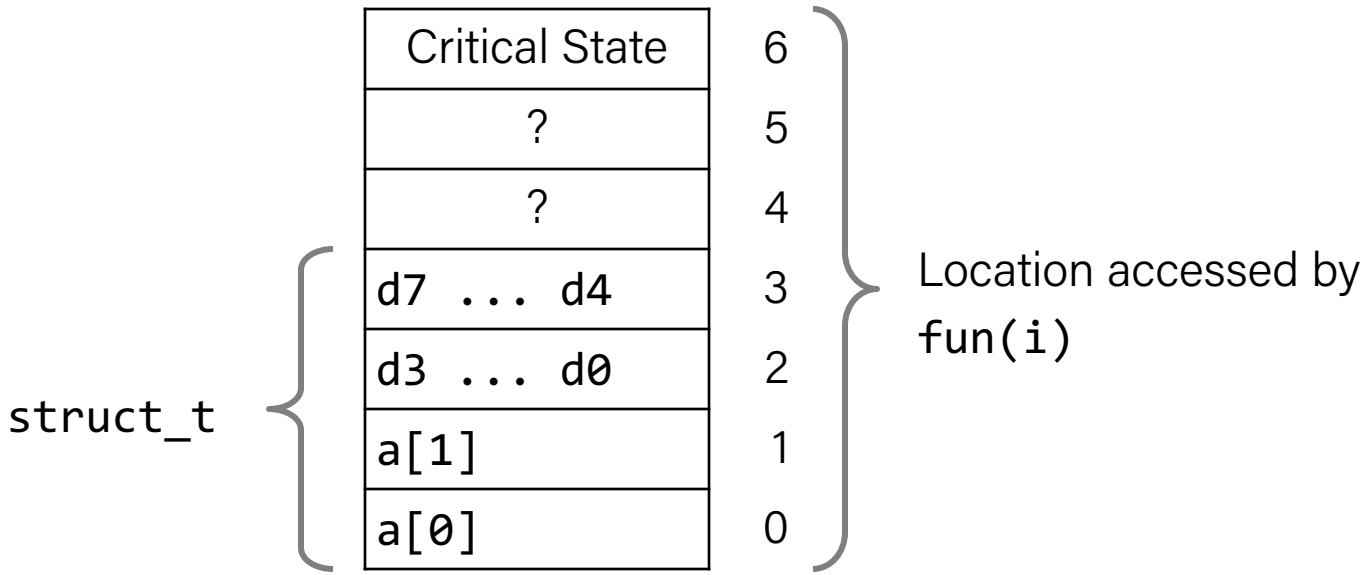
Result is system specific

Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;
```

```
fun(0) → 3.14
fun(1) → 3.14
fun(2) → 3.1399998664856
fun(3) → 2.0000061035156
fun(4) → 3.14
fun(6) → Segmentation fault
```

Explanation:



Buffer Overflow in a Nutshell

- C does not check array bounds
  - Many Unix/Linux/C functions don't check argument sizes
  - Allows overflowing (writing past the end) of buffers (arrays)

- "Buffer Overflow" = Writing past the end of an array

- Characteristics of the traditional Linux memory layout provide opportunities for malicious programs
  - Stack grows "backwards" in memory
  - Data and instructions both stored in the same memory

String Library Code

- Implementation of Unix function `gets()`

```
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getchar();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

- No way to specify limit on number of characters to read
- Similar problems with other library functions
  - `strcpy`, `strcat`: Copy strings of arbitrary length
  - `scanf`, `fscanf`, `sscanf`, when given `%s` conversion specification

Vulnerable Buffer Code

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}


void call_echo() {
    echo();
}
```

btw, how big is big enough?

```
unix>./bufdemo-nsp
Type a string:
0123456789012345678901230123456789012345678901230123456789012345678901234
Segmentation Fault
```

Buffer Overflow Disassembly

echo:

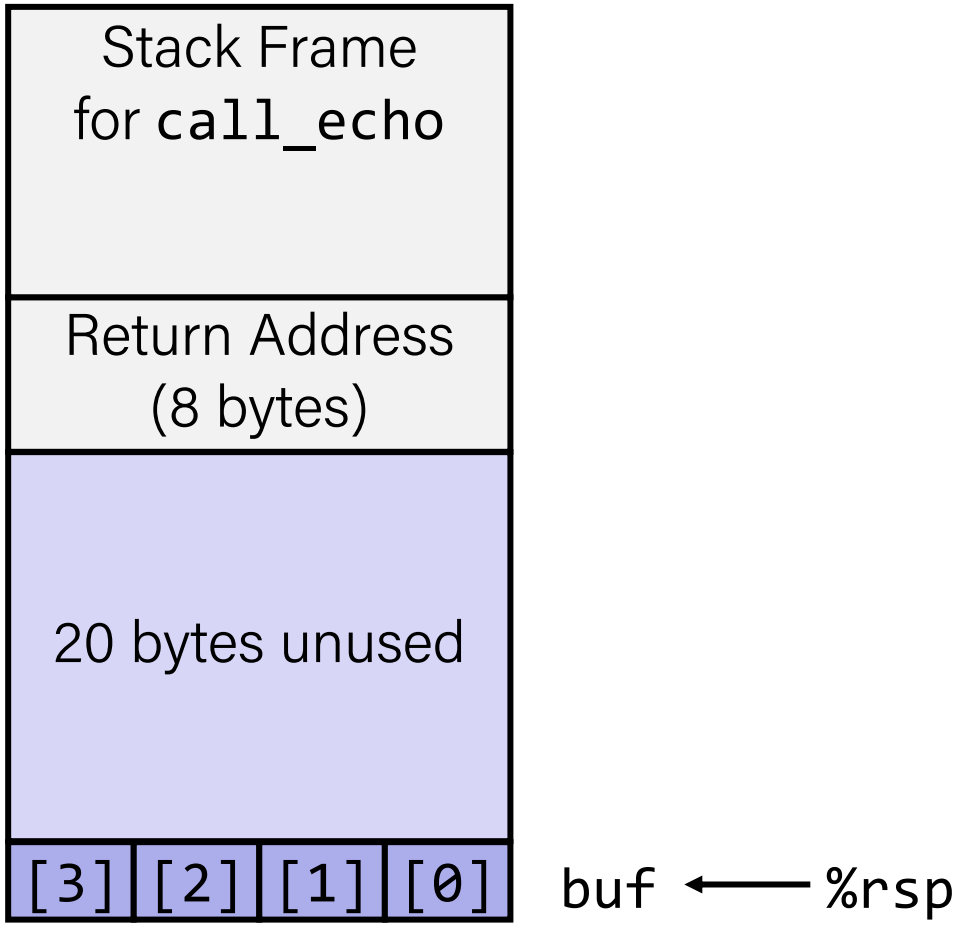
```
0000000004006cf <echo>:
 4006cf: 48 83 ec 18          sub    $0x18,%rsp
 4006d3: 48 89 e7             mov    %rsp,%rdi
 4006d6: e8 a5 ff ff ff       callq  400680 <gets>
 4006db: 48 89 e7             mov    %rsp,%rdi
 4006de: e8 3d fe ff ff       callq  400520 <puts@plt>
 4006e3: 48 83 c4 18          add    $0x18,%rsp
 4006e7: c3                   retq
```

call_echo:

```
 4006e8: 48 83 ec 08          sub    $0x8,%rsp
 4006ec: b8 00 00 00 00       mov    $0x0,%eax
 4006f1: e8 d9 ff ff ff       callq  4006cf <echo>
 4006f6: 48 83 c4 08          add    $0x8,%rsp
 4006fa: c3                   retq
```

Buffer Overflow Stack

Before call to gets

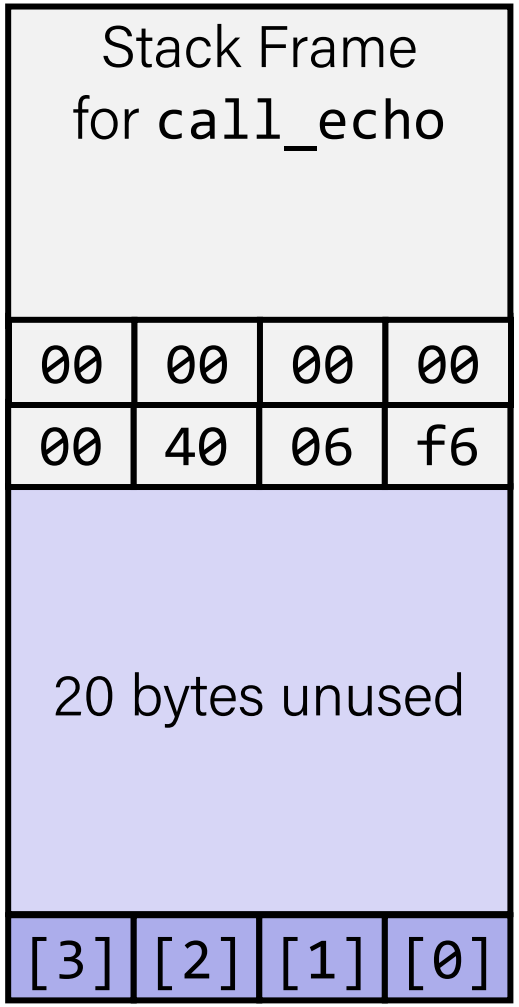



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

Buffer Overflow Stack Example

Before call to gets




```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

```
echo:
   subq   $24, %rsp
   movq   %rsp,
%rdi
   call   gets
   . . .
```

```
call_echo:
   . . .
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
   . . .
```

Buffer Overflow Stack Example #1

After call to gets

Stack Frame for `call_echo`

00	00	00	00
00	40	06	f6
00	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

buf ⟵ %rsp

```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

```
echo:
   subq   $24, %rsp
   movq   %rsp,
%rdi
   call   gets
   . . .
```

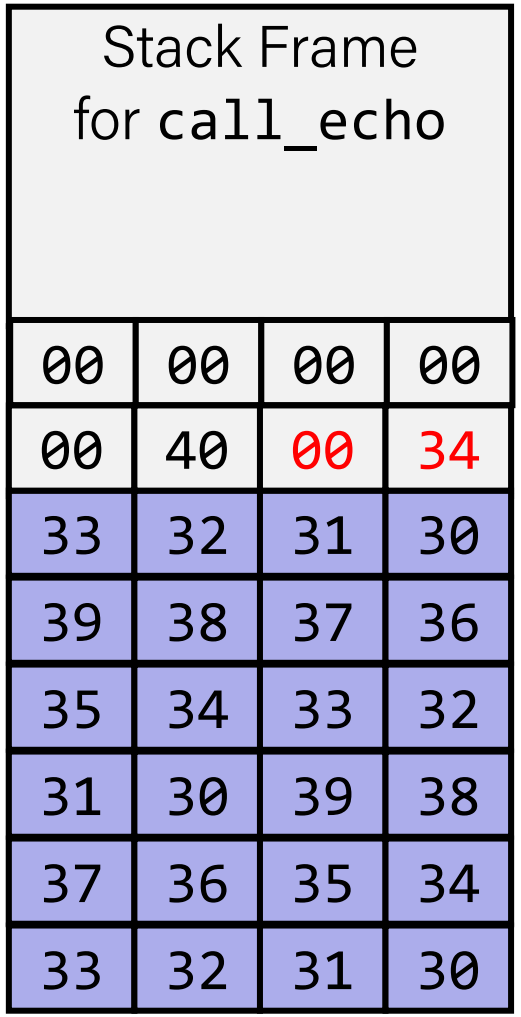
```
call_echo:
   . . .
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
   . . .
```

```
unix>./bufdemo-nsp
Type a string:
012345678901234567890123
012345678901234567890123
```

Overflowed buffer, but did not corrupt state

Buffer Overflow Stack Example #2

After call to gets




```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

```
echo:
   subq   $24, %rsp
   movq   %rsp,
%rdi
   call   gets
   . . .
```

```
call_echo:
   . . .
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
   . . .
```

```
unix>./bufdemo-nspunix>./bufdemo-nsp
Type a string:
012345678901234567890123
Segmentation Fault
```

Overflowed buffer and corrupted return pointer

Buffer Overflow Stack Example #3

After call to gets

Stack Frame for `call_echo`

00	00	00	00
00	40	06	00
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

buf ⟵ %rsp

```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

```
echo:
   subq   $24, %rsp
   movq   %rsp,
%rdi
   call   gets
   . . .
```

```
call_echo:
   . . .
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
   . . .
```

```
unix>./bufdemo-nsp
Type a string:
012345678901234567890123
012345678901234567890123
```

Overflowed buffer, corrupted return pointer, but program seems to work!

Buffer Overflow Stack Example #3 Explained

After call to gets

Stack Frame for `call_echo`			
00	00	00	00
00	40	06	00
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

`buf` ⟵ `%rsp`

```
register_tm_clones:
    . . .
    400600: mov    %rsp,%rbp
    400603: mov    %rax,%rdx
    400606: shr    $0x3f,%rdx
    40060a: add    %rdx,%rax
    40060d: sar    %rax
    400610: jne    400614
    400612: pop    %rbp
    400613: retq
```

"Returns" to unrelated code

Lots of things happen, without modifying critical state

Eventually executes `retq` back to main

Why is buffer overflow a big deal?

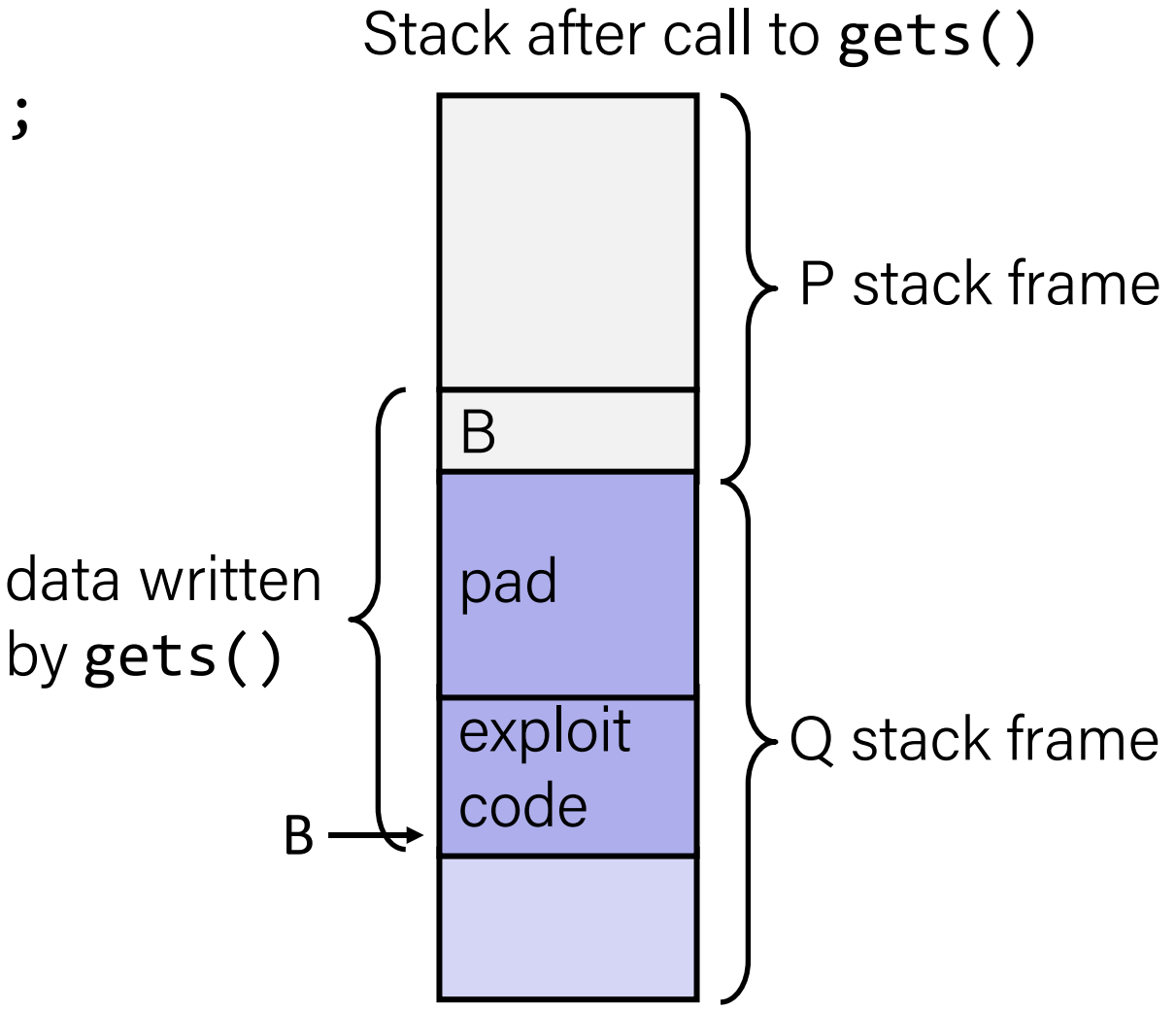
- Buffer overflows on the stack can overwrite "interesting" data
  - Attackers just choose the right inputs
- Simplest form (sometimes called "stack smashing")
  - Unchecked length on string input into bounded array causes overwriting of stack data
  - Try to change the return address of the current procedure
- Why is this a big deal?
  - It was the #1 *technical* cause of security vulnerabilities
    - #1 *overall* cause is social engineering / user ignorance

Code Injection Attacks

```
void P(){
  Q();
  ...
}
```

return address A

```
int Q() {
  char buf[64];
  gets(buf);
  ...
  return ...;
}
```



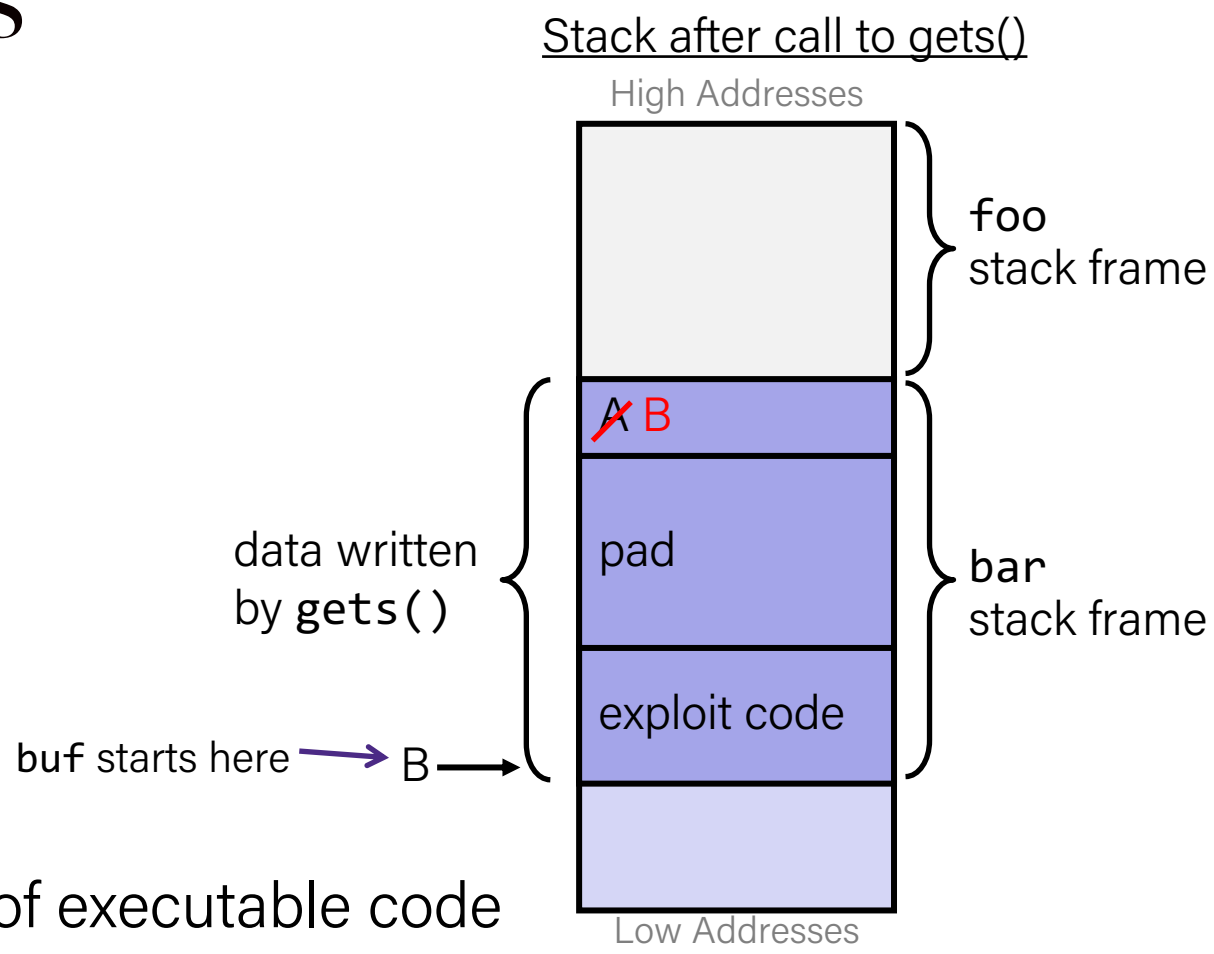
- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When Q executes `ret`, will jump to exploit code

Malicious Use of Buffer Overflow: Code Injection Attacks

```
void foo(){
  bar();
A:...
}
```

return address A

```
int bar() {
  char buf[64];
  gets(buf);
  ...
  return ...;
}
```

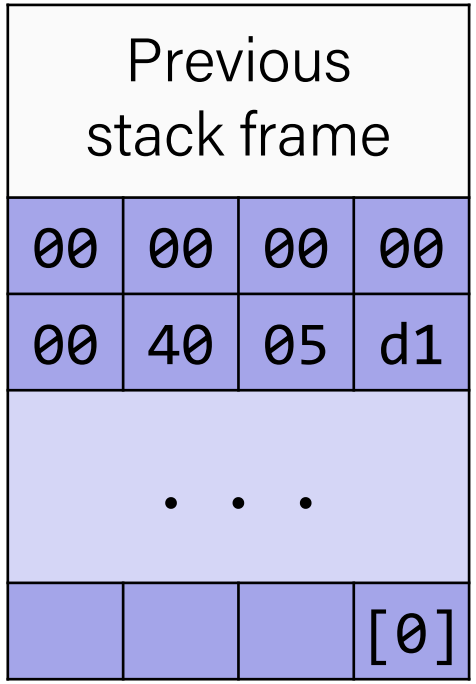


- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When `bar()` executes `ret`, will jump to exploit code

Question

- `smash_me` is vulnerable to stack smashing!
- What is the minimum number of characters that `gets` must read in order for us to change the return address to a stack address?
  - For example: (`0x00 00 7f ff CA FE F0 0D`)

Always 0's



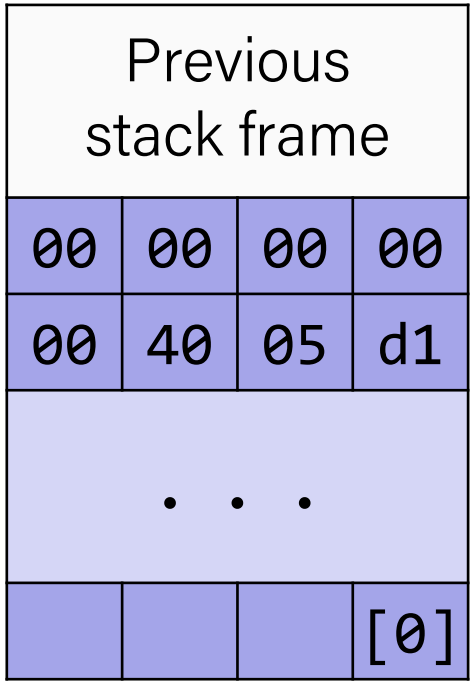

```
smash_me:
   subq   $0x40, %rsp
    ...
   leaq   16(%rsp), %rdi
   call   gets
    ...
```

A. 27
B. 30
C. 51
D. 54
E. We're lost...

Question

- `smash_me` is vulnerable to stack smashing!
- What is the minimum number of characters that `gets` must read in order for us to change the return address to a stack address?
  - For example: (`0x00 00 7f ff CA FE F0 0D`)

Always 0's




```
smash_me:
   subq   $0x40, %rsp
    ...
   leaq   16(%rsp), %rdi
   call   gets
    ...
```

A. 27
B. 30
C. 51
D. 54 = 64 – 16 + 6
E. We're lost...

Exploits Based on Buffer Overflows

- **Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines**
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹️
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original "Internet worm" (1988)
  - "IM wars" (1999)
  - Twilight hack on Wii (2000s)
  - Hacking embedding devices (e.g. cars, smart homes, planes)
- You will learn some of the tricks in Assignment 5
  - Hopefully to convince you to never leave such holes in your programs!!

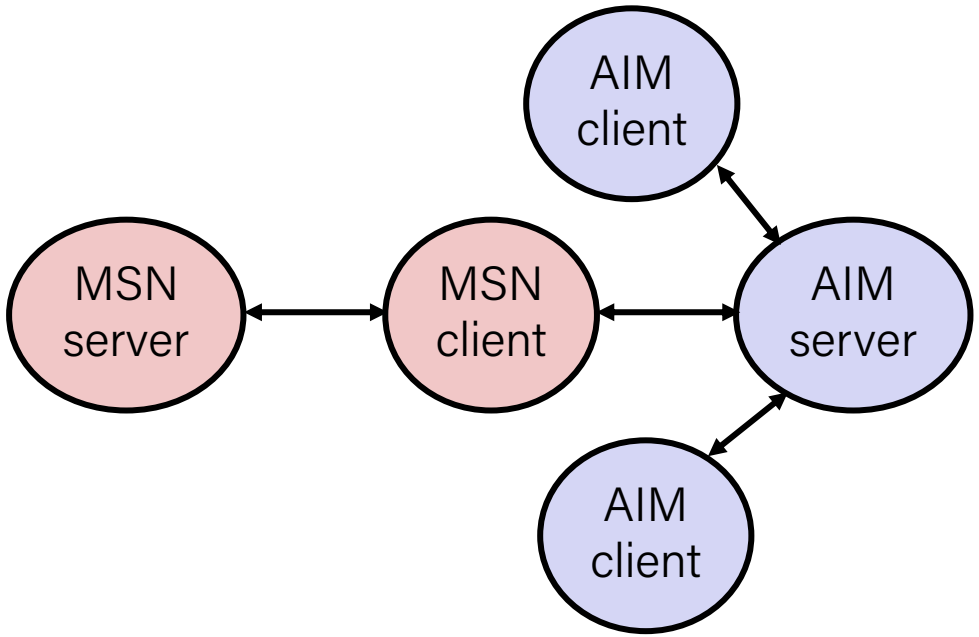
Example: the original Internet worm (1988)

- Exploited a few vulnerabilities to spread
  - Early versions of the finger server (fingerd) used `gets()` to read the argument sent by the client:
    - `finger droh@linuxpool.ku.edu.tr`
  - Worm attacked fingerd server by sending phony argument:
    - `finger “exploit-code padding new-return-address”`
    - exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker.
- Once on a machine, scanned for other machines to attack
  - invaded ~6000 computers in hours (10% of the Internet 🙂)
    - see June 1989 article in Comm. of the ACM
  - the young author of the worm was prosecuted…
  - and CERT was formed… homed at CMU

Example 2: IM War

July 1999:

- Microsoft launches MSN Messenger (instant messaging system).
- Messenger clients can access popular AOL Instant Messaging Service (AIM) servers



IM War (cont.)

August 1999:

- Mysteriously, Messenger clients can no longer access AIM servers
- Microsoft and AOL begin the IM war:
  - AOL changes server to disallow Messenger clients
  - Microsoft makes changes to clients to defeat AOL changes
  - At least 13 such skirmishes
- What was really happening?
  - AOL had discovered a buffer overflow bug in their own AIM clients
  - They exploited it to detect and block Microsoft: the exploit code returned a 4-byte signature (the bytes at some location in the AIM client) to server
  - When Microsoft changed code to match signature, AOL changed signature location

Date: Wed, 11 Aug 1999 11:30:57 -0700 (PDT)
From: Phil Bucking <philbucking@yahoo.com>
Subject: AOL exploiting buffer overrun bug in their own software!
To: rms@pharlap.com

Mr. Smith,

I am writing you because I have discovered something that I think you might find interesting because you are an Internet security expert with experience in this area. I have also tried to contact AOL but received no response.

I am a developer who has been working on a revolutionary new instant messaging client that should be released later this year.
...
It appears that the AIM client has a buffer overrun bug. By itself this might not be the end of the world, as MS surely has had its share. But AOL is now *exploiting their own buffer overrun bug* to help in its efforts to block MS Instant Messenger.
....
Since you have significant credibility with the press I hope that you can use this information to help inform people that behind AOL's friendly exterior they are nefariously compromising peoples' security.

Sincerely,
Phil Bucking
Founder, Bucking Consulting
philbucking@yahoo.com

It was later determined that this email originated from within Microsoft!

Aside: Worms and Viruses

- **Worm:** A program that
  - Can run by itself
  - Can propagate a fully working version of itself to other computers

- **Virus:** Code that
  - Adds itself to other programs
  - Does not run independently

- Both are (usually) designed to spread among computers and to wreak havoc

Hacking Cars

- UW CSE research from 2010 demonstrated wirelessly hacking a car using buffer overflow
- Overwrote the onboard control system's code
  - Disable brakes
  - Unlock doors
  - Turn engine on/off

https://www.youtube.com/watch?v=hB6eY73sLV

OK, what to do about buffer overflow attacks

- Avoid overflow vulnerabilities
- Employ system-level protections
- Have compiler use “stack canaries”

1. Avoid Overflow Vulnerabilities in Code (!)

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

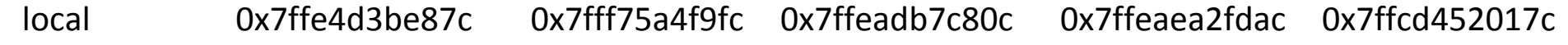
For example, use library routines that limit string lengths

- `fgets` instead of `gets`
- `strncpy` instead of `strcpy`
- Don't use `scanf` with `%s` conversion specification
  - Use `fgets` to read the string
  - Or use `%ns` where `n` is a suitable integer

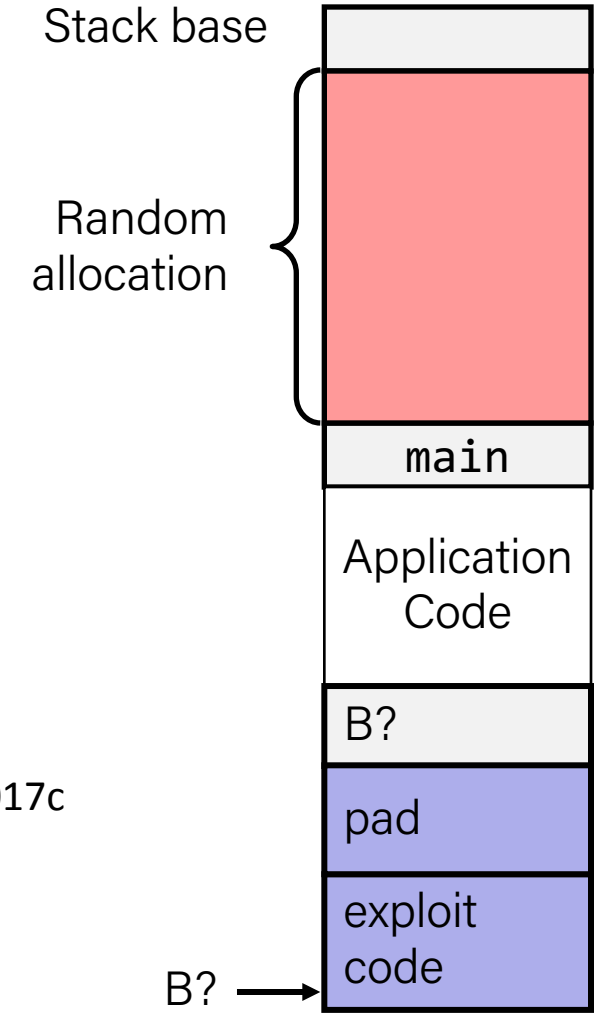
2. System-Level Protections can help

Randomized stack offsets

- At start of program, allocate random amount of space on stack
- Shifts stack addresses for entire program
- Makes it difficult for hacker to predict beginning of inserted code
- E.g.: 5 executions of memory allocation code



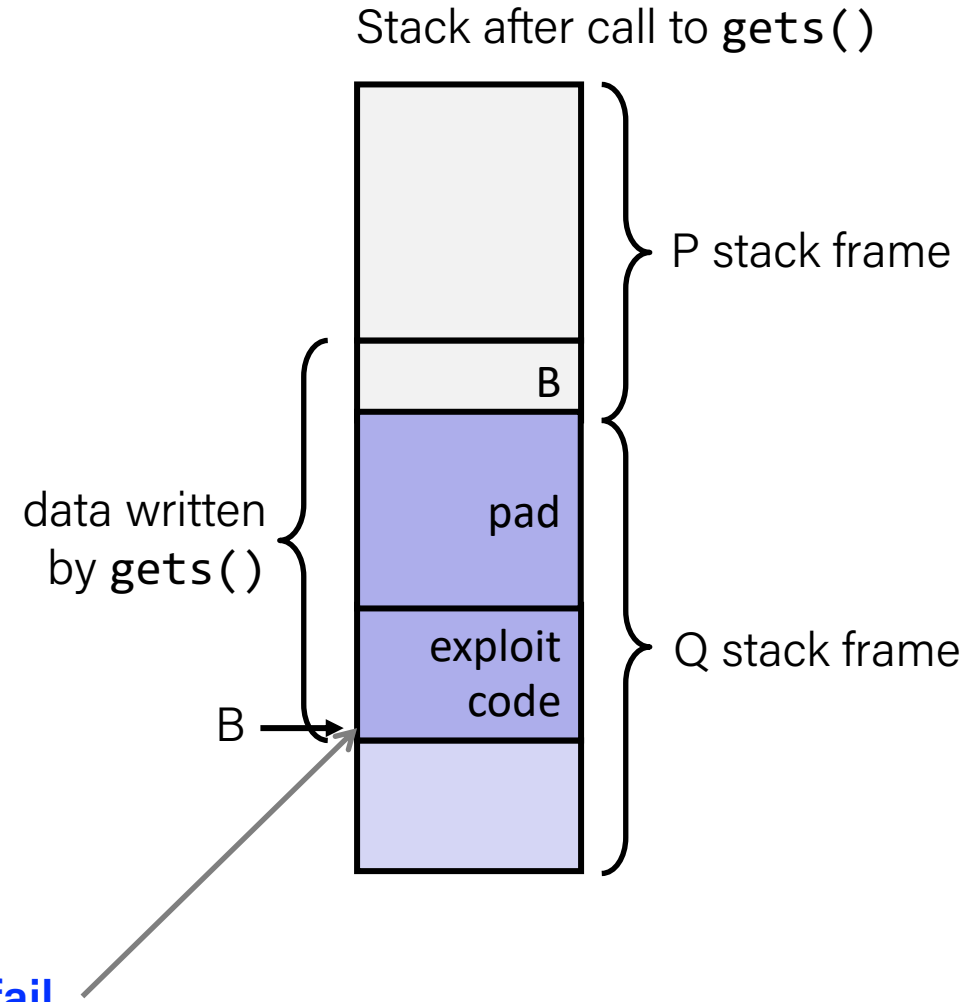
– Stack repositioned each time program executes



2. System-Level Protections can help

Nonexecutable code segments

- In traditional x86, can mark region of memory as either “read-only” or “writeable”
  - Can execute anything readable
- X86-64 added explicit “execute” permission
- Stack marked as non-executable



3. Stack Canaries can help

Idea:

- Place special value (“canary”) on stack just beyond buffer
- Check for corruption before exiting function

GCC Implementation

- `-fstack-protector`
- Now the default (disabled earlier)

```
unix>./bufdemo-sp
Type a string:
0123456
0123456
```

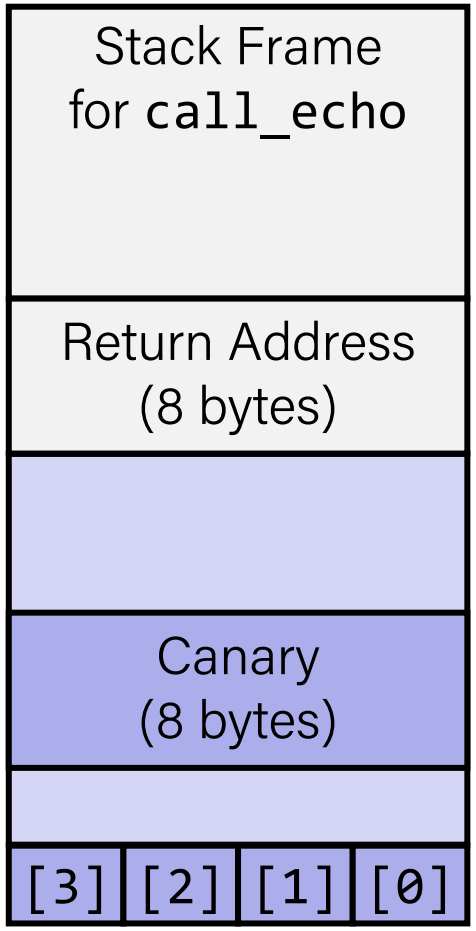
```
unix>./bufdemo-sp
Type a string:
01234567
*** stack smashing detected ***
```

Protected Buffer Disassembly

```
echo:
   40072f: sub    $0x18,%rsp
   400733: mov    %fs:0x28,%rax
   40073c: mov    %rax,0x8(%rsp)
   400741: xor    %eax,%eax
   400743: mov    %rsp,%rdi
   400746: callq  4006e0 <gets>
   40074b: mov    %rsp,%rdi
   40074e: callq  400570 <puts@plt>
   400753: mov    0x8(%rsp),%rax
   400758: xor    %fs:0x28,%rax
   400761: je     400768 <echo+0x39>
   400763: callq  400580 <__stack_chk_fail@plt>
   400768: add    $0x18,%rsp
   40076c: retq
```

Setting Up Canary

Before call to gets

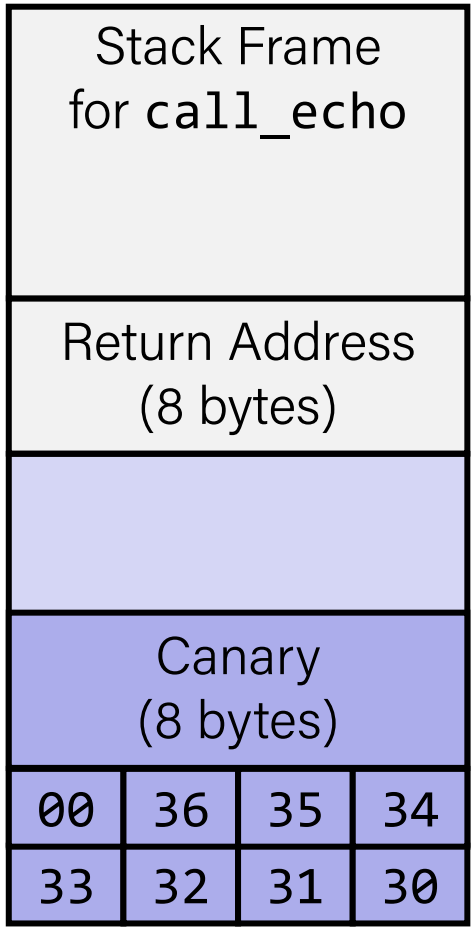



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq    %fs:40, %rax  # Get canary
    movq    %rax, 8(%rsp) # Place on stack
    xorl    %eax, %eax    # Erase canary
    . . .
```

Checking Canary

After call to gets




```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

Input: `0123456`

```
echo:
    . . .
    movq    8(%rsp), %rax     # Retrieve from stack
    xorq    %fs:40, %rax      # Compare to canary
    je      .L6               # If same, OK
    call    __stack_chk_fail  # FAIL
.L6:        . . .
```

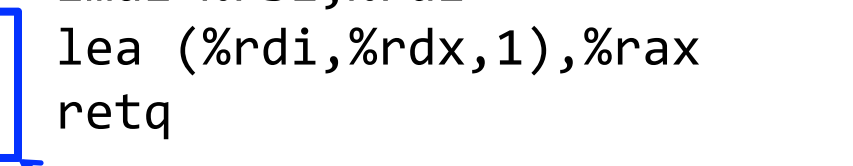
Return-Oriented Programming Attacks

- Challenge (for hackers)
  - Stack randomization makes it hard to predict buffer location
  - Marking stack nonexecutable makes it hard to insert binary code
- Alternative Strategy
  - Use existing code
    - E.g., library code from stdlib
  - String together fragments to achieve overall desired outcome
  - *Does not overcome stack canaries*
- Construct program from gadgets
  - Sequence of instructions ending in `ret`
    - Encoded by single byte `0xc3`
  - Code positions fixed from run to run
  - Code is executable

Gadget Example #1

```
long ab_plus_c
  (long a, long b, long c) {
   return a*b + c;
}
```

```
0000000004004d0 <ab_plus_c>:
  4004d0:  48 0f af fe  imul %rsi,%rdi
  4004d4:  48 8d 04 17  lea (%rdi,%rdx,1),%rax
  4004d8:  c3           retq
```



`rax ← rdi + rdx`

Gadget address = `0x4004d4`

- Use tail end of existing functions

Gadget Example #2

```
void setval(unsigned *p) {
    *p = 3347663060u;
}
```

Encodes `movq %rax, %rdi`

```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl   $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

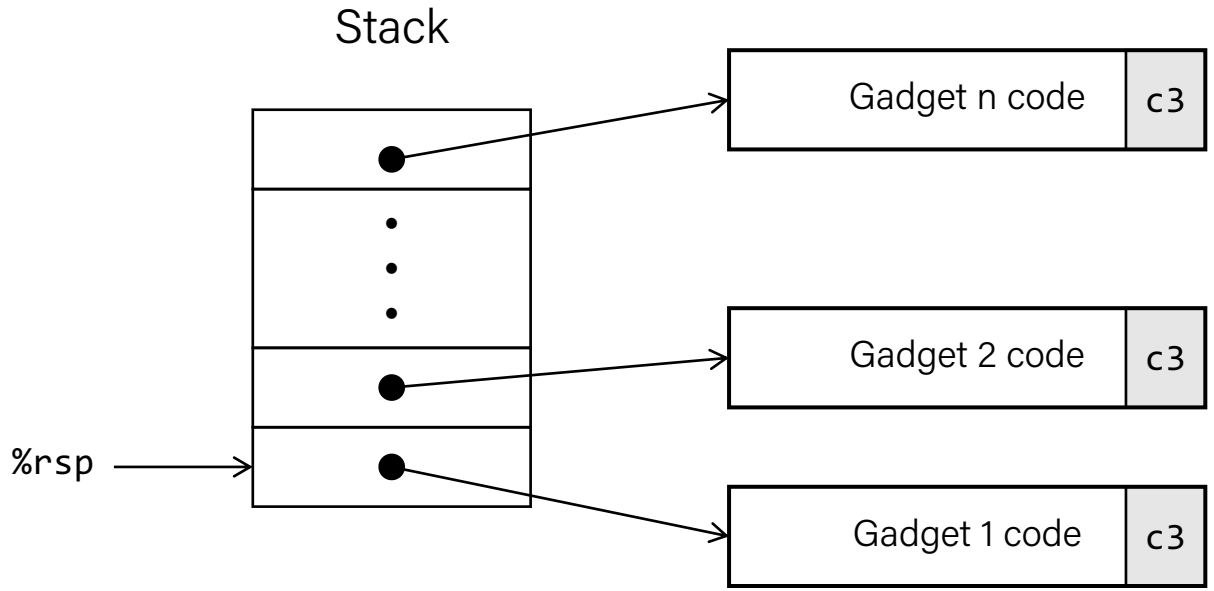
`rdi ← rax`

Gadget address = `0x4004dc`

- Repurpose byte codes

ROP Execution

- Trigger with `ret` instruction
  - Will start executing Gadget 1
- Final `ret` in each gadget will start next one



Recap

- Floating Point
- Memory Layout
- Buffer Overflow

Next time: memory hierarchy