photo by unsplash.com user @tabithabrooke

COMP201

Computer Systems & Programming

Lecture #19 – Security Vulnerabilities

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Spring 2021

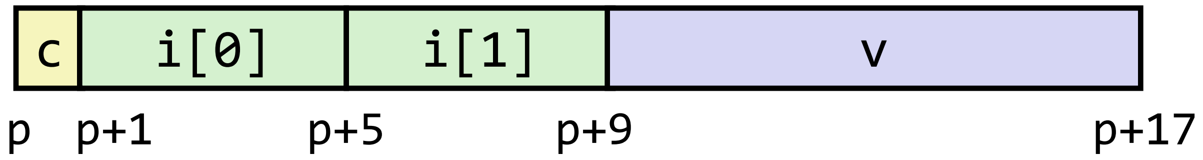
Recap

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

Recap: Structures & Alignment

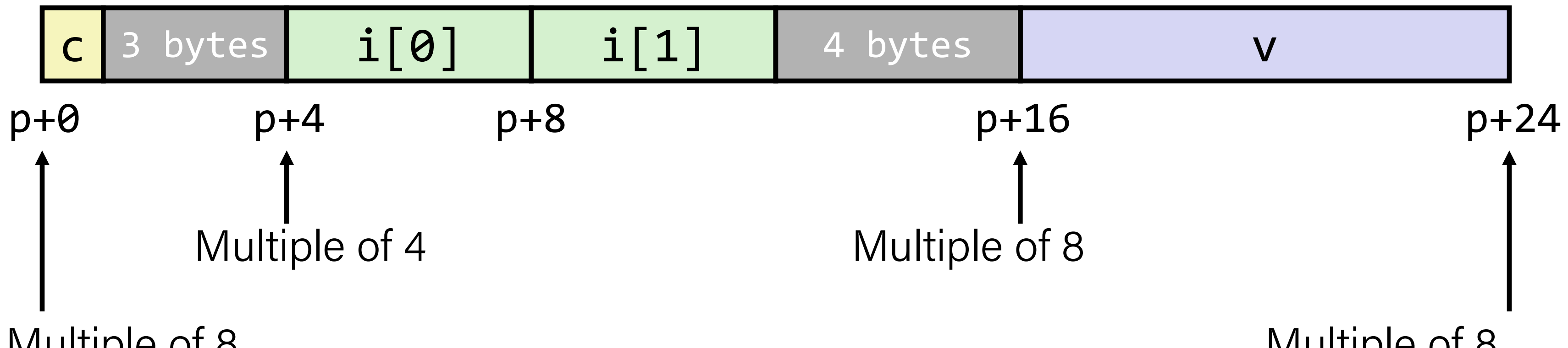
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

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

Satisfying Alignment with Structures

Within structure:

- Must satisfy each element's alignment requirement

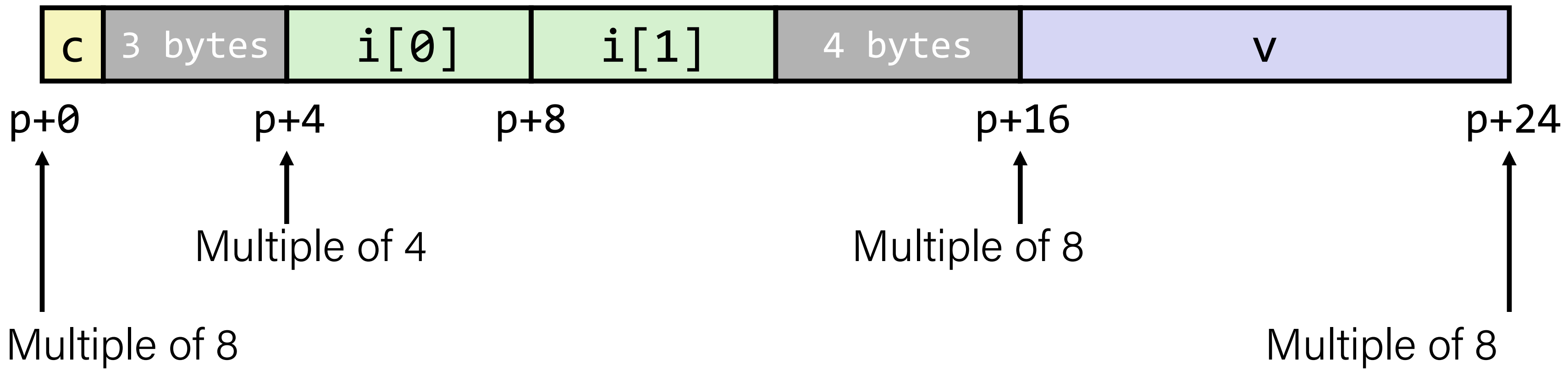
Overall structure placement

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

Example:

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

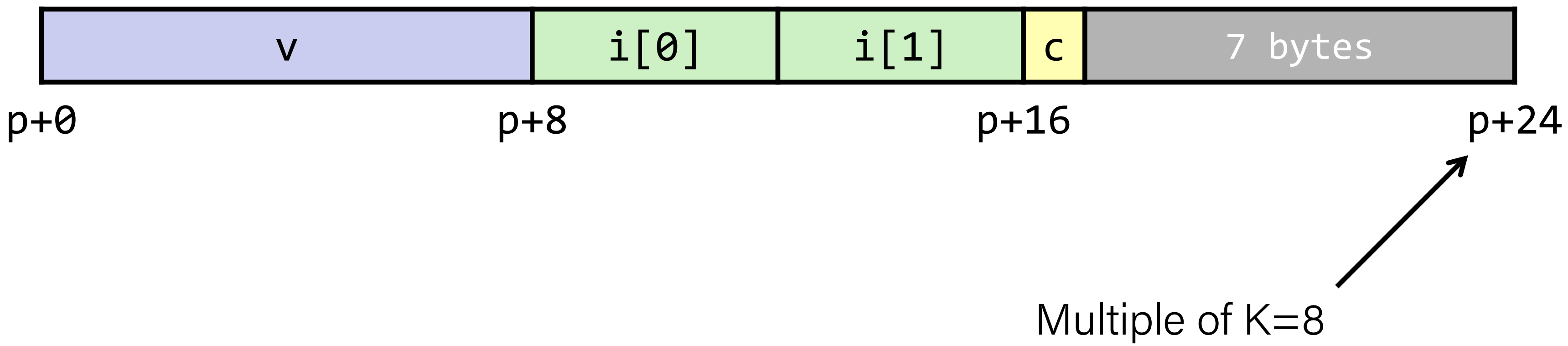
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



Meeting Overall Alignment Requirement

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

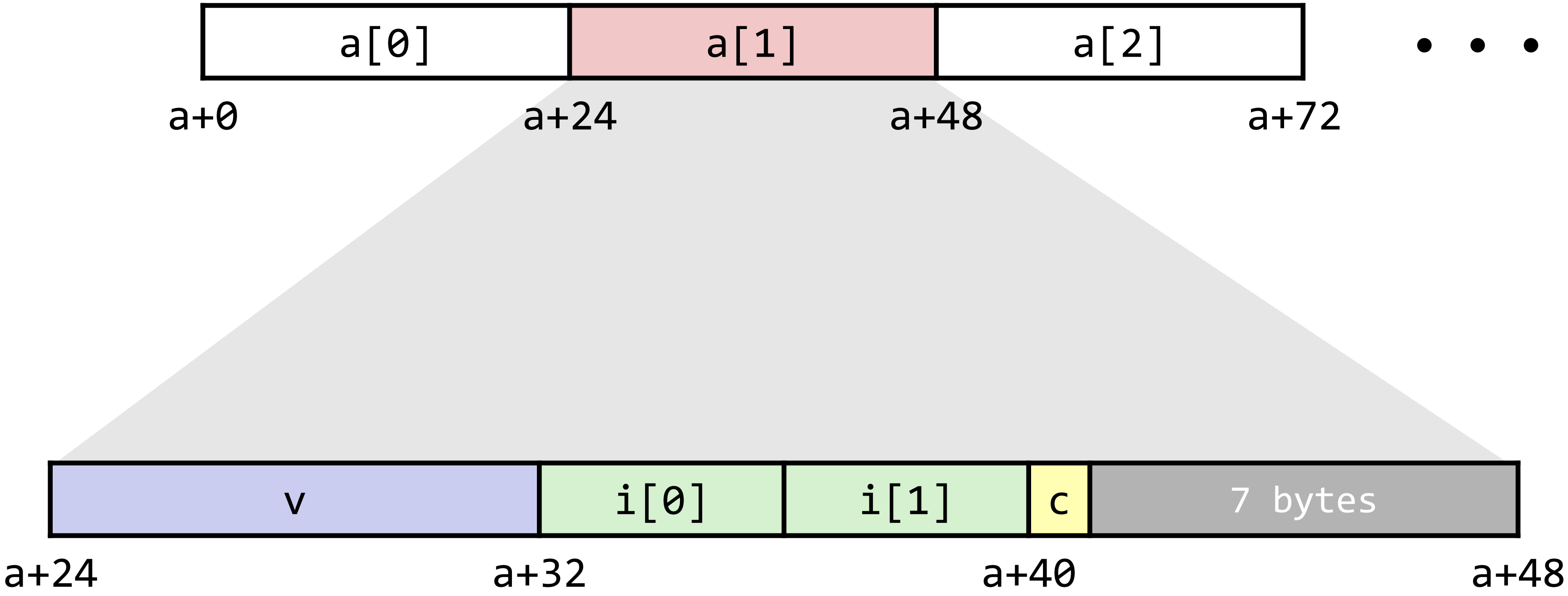
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

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

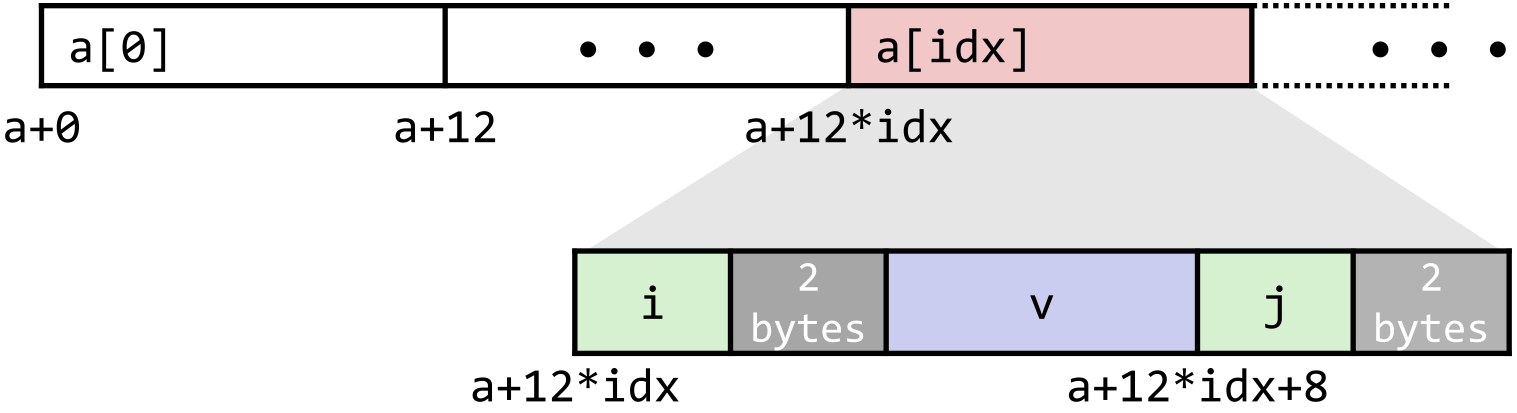
- Overall structure length multiple of K
- Satisfy alignment requirement for every element



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
```

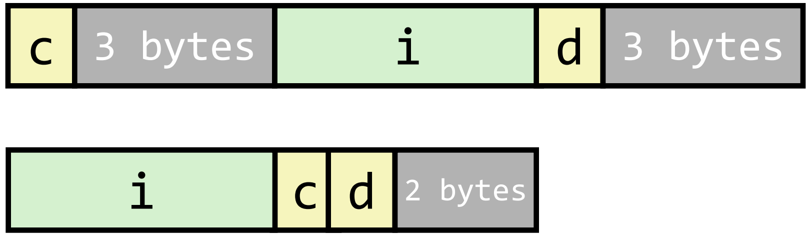
Saving Space

- Put large data types first

```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```

```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```

- Effect (K=4)



Practice 3: Alignment

slido

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	36		

4 bytes padded to satisfy 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

Lecture Plan

- Floating Point
- Memory Layout
- Buffer Overflow

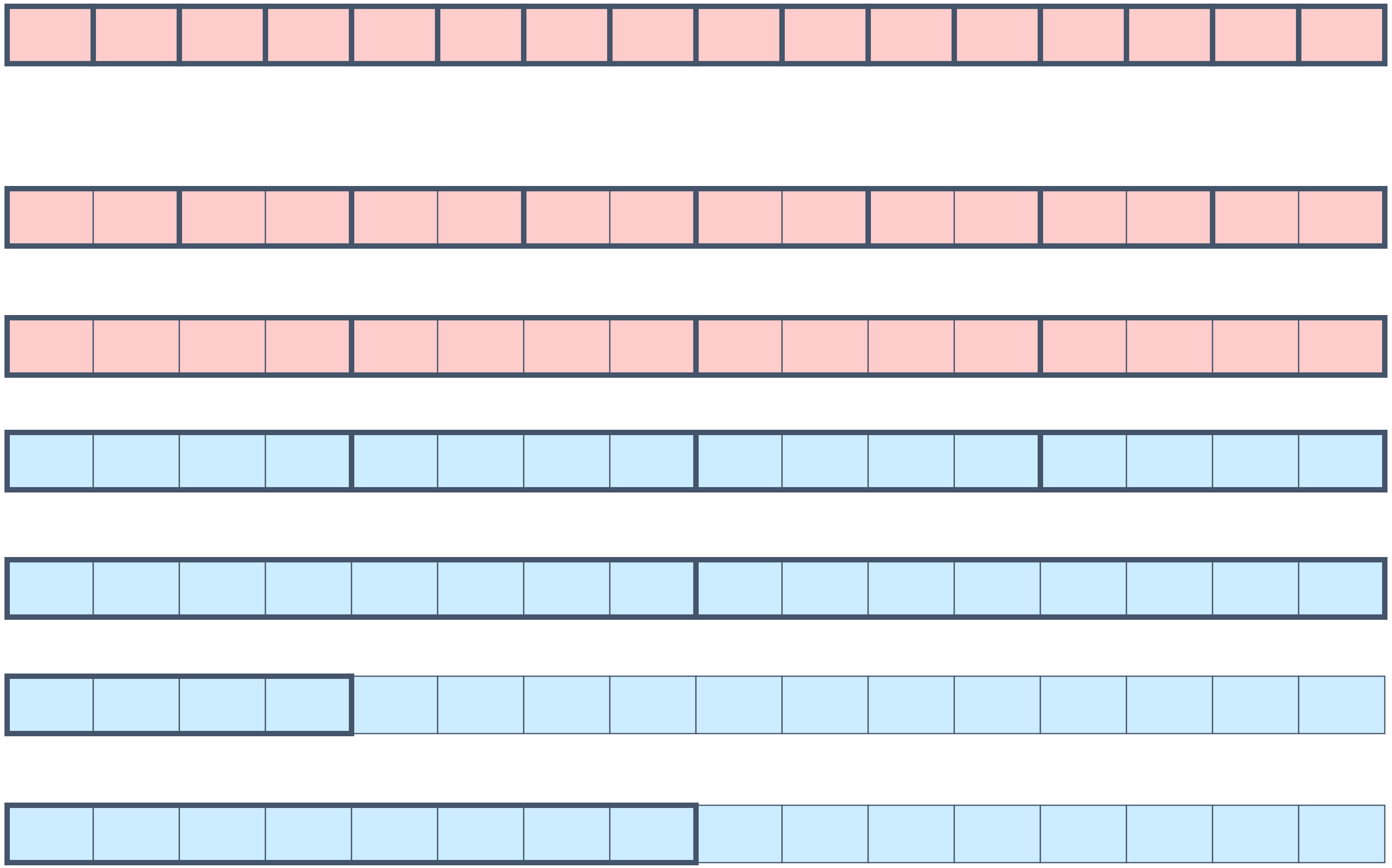
Background

- 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

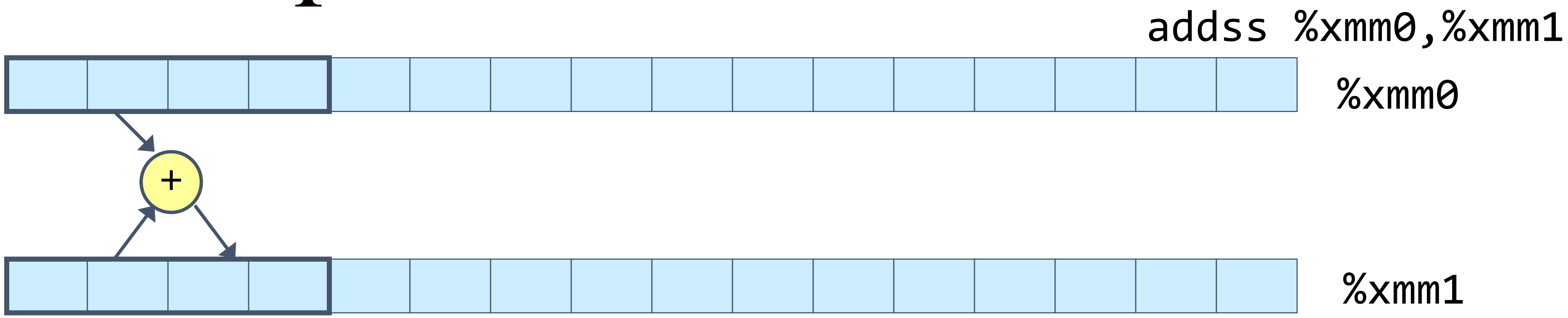
XMM Registers

- 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

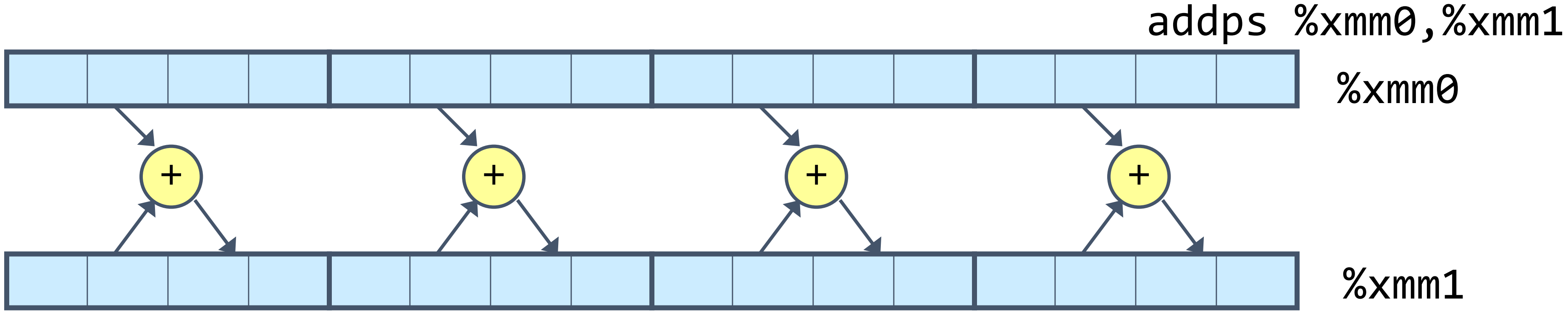


Scalar & SIMD Operations

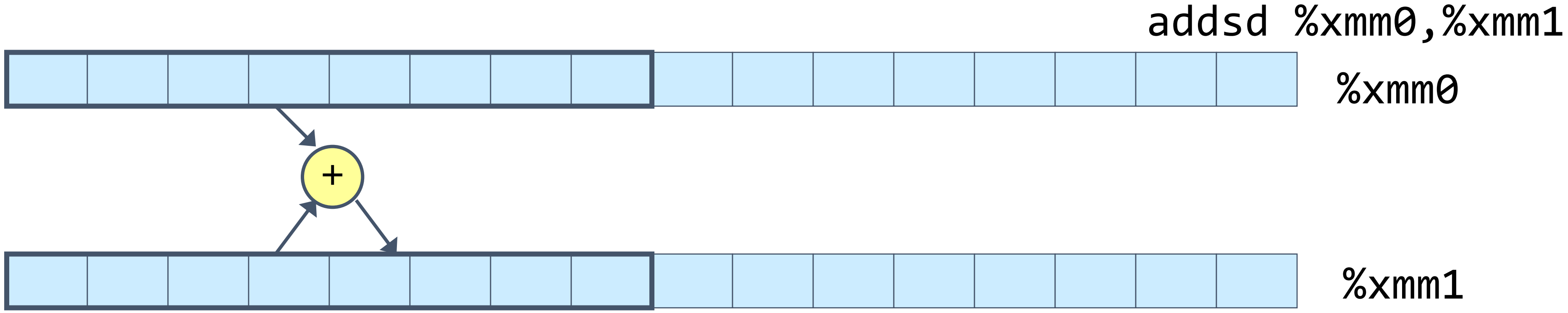
- Scalar Operations: Single Precision



- SIMD Operations: Single Precision



- Scalar Operations: Double Precision



FP Basics

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

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

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

```c
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

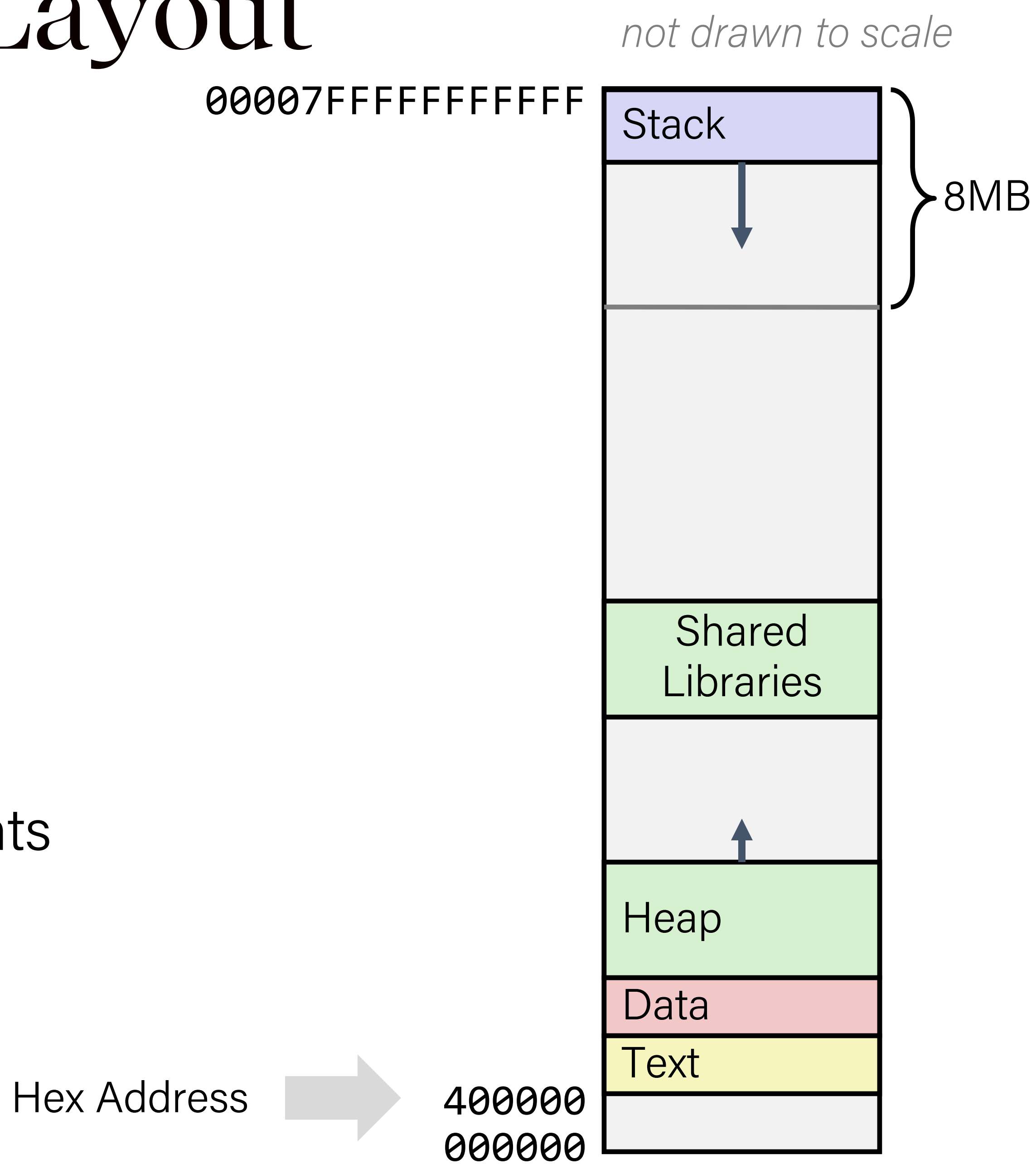
- Lots of instructions
  - Different operations, different formats, …
- Floating-point comparisons
  - Instructions `ucomiss` and `ucomisd`
  - Set condition codes `CF`, `ZF`, and `PF`
- Using constant values
  - Set XMM0 register to 0 with instruction `xorpd %xmm0, %xmm0`
  - Others loaded from memory

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

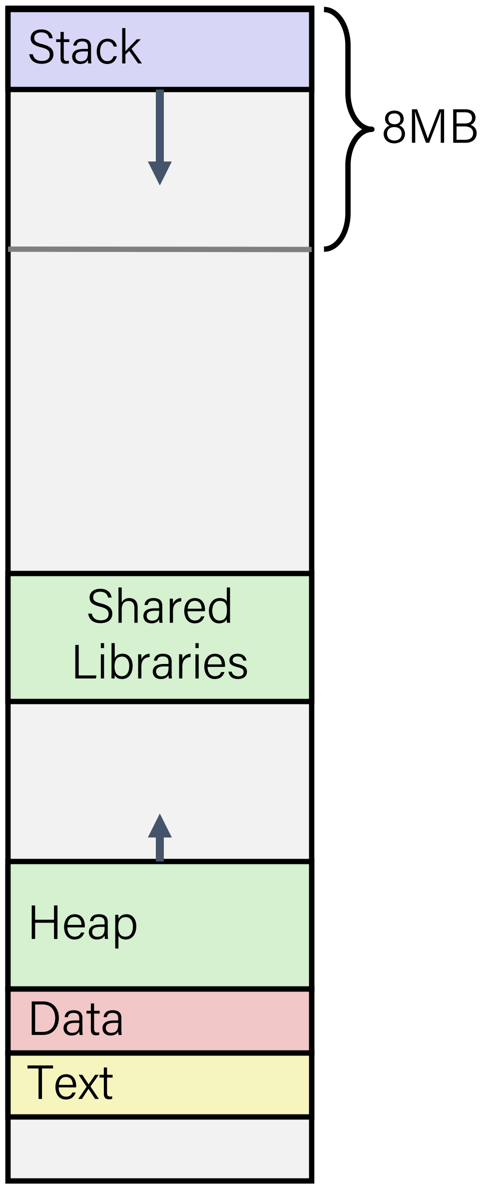


Memory Allocation Example

```
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?

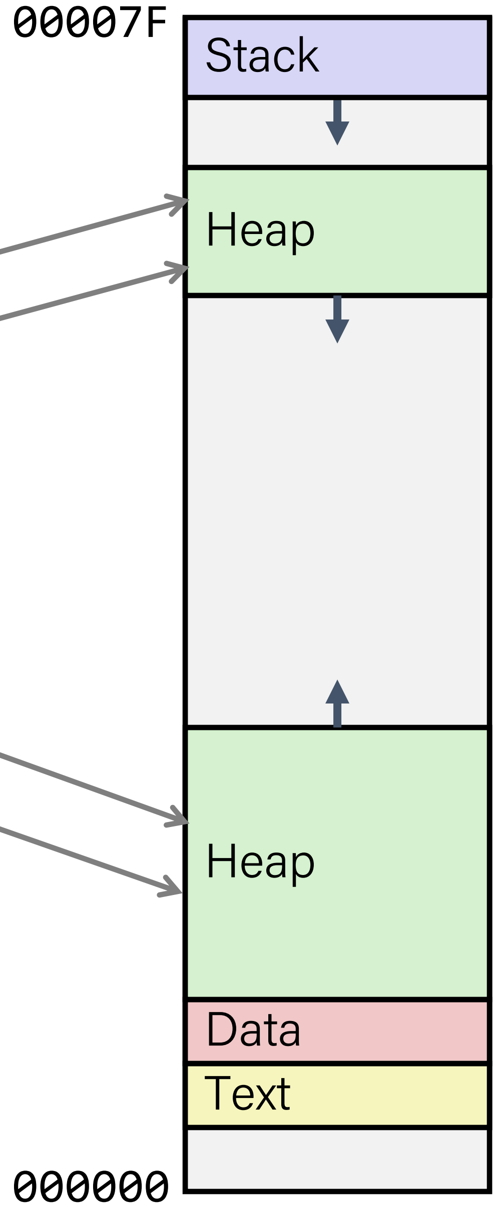
not drawn to scale



x86-64 Example Addresses

address range ~2^{47}

`local`	`0x00007ffe4d3be87c`
`p1`	`0x00007f7262a1e010`
`p3`	`0x00007f7162a1d010`
`p4`	`0x000000008359d120`
`p2`	`0x000000008359d010`
`big_array`	`0x0000000080601060`
`huge_array`	`0x0000000000601060`
`main()`	`0x000000000040060c`
`useless()`	`0x0000000000400590`



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
```

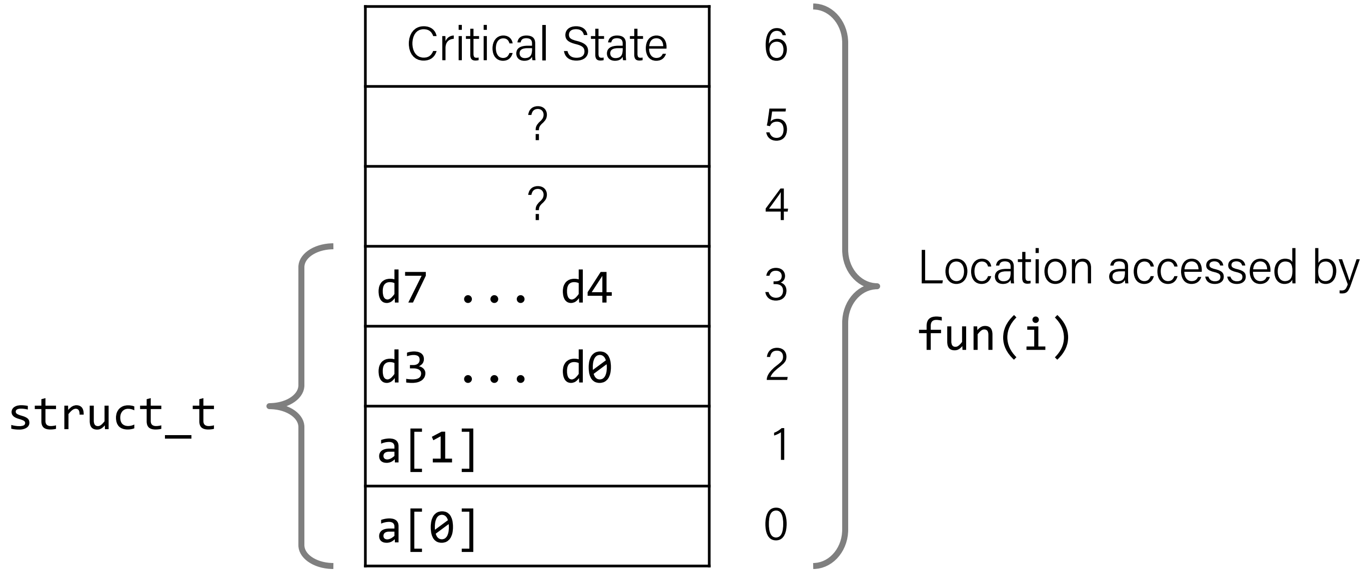
Result is system specific

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) → 2.00000061035156
fun(4) → 3.14
```
`fun(6)` → Segmentation fault

Explanation:



Such problems are a BIG deal

- Generally called a **buffer overflow**
  - when exceeding the memory size allocated for an array
- Why a big deal?
  - It's the #1 technical cause of security vulnerabilities
    - #1 overall cause is social engineering / user ignorance
- Most common form
  - Unchecked lengths on string inputs
  - Particularly for bounded character arrays on the stack
    - sometimes referred to as stack smashing

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

Demo: Bufdemo

`bufdemo.c`

https://godbolt.org/z/vE5zWrzfr

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:
012345678901234567890123
012345678901234567890123
```

```
unix>./bufdemo-nsp
Type a string:
0123456789012345678901234
Segmentation Fault
```

Buffer Overflow Disassembly

echo:

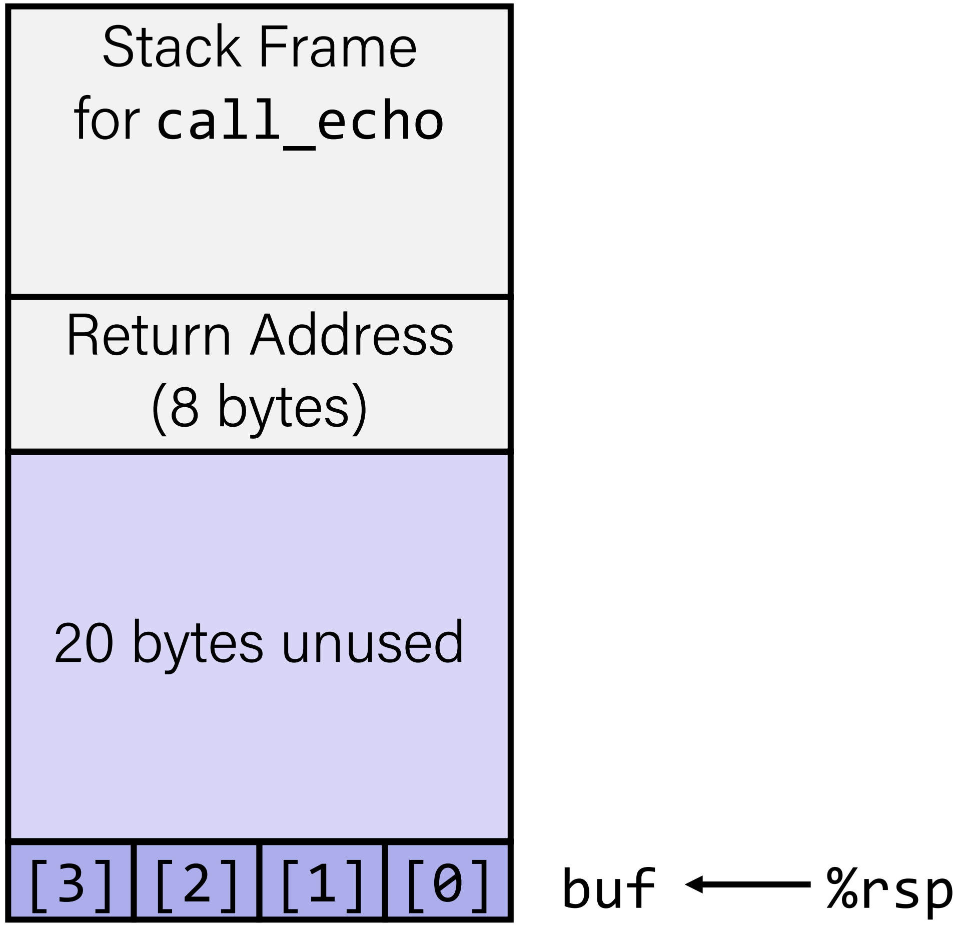
```
00000000004006cf <echo>:
 4006cf: 48 83 ec 18              sub    $0x18,%rsp
 4006d3: 48 89 e7                 mov    %rsp,%rdi
 4006d6: e8 a5 ff ff ff           callq  400680 <gets>
 4006db: 48 89 e7                 mov    %rsp,%rdi
 4006de: e8 3d fe ff ff           callq  400520 <puts@plt>
 4006e3: 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

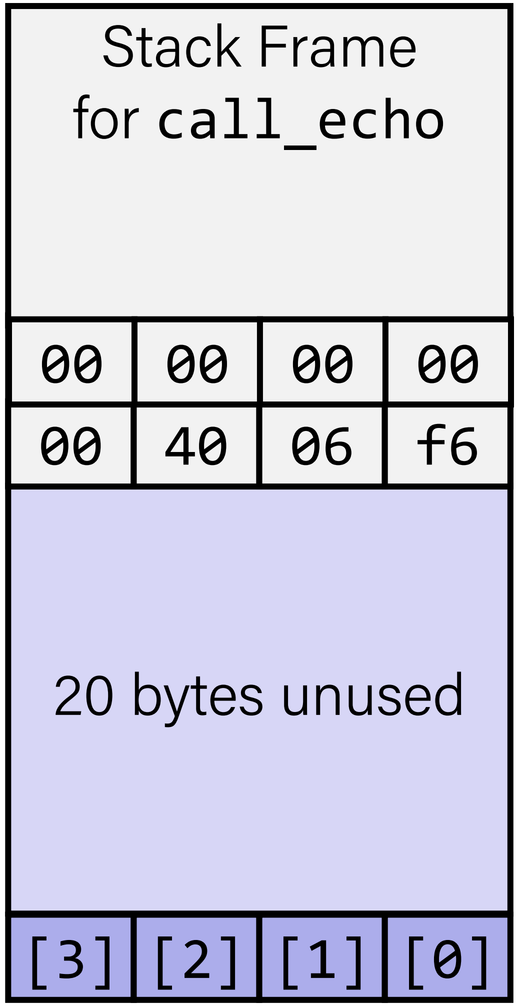



```c
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

Buffer Overflow Stack Example

Before call to gets



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
   . . .
```

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:
01234567890123456789012
01234567890123456789012
```

Overflowed buffer, but did not corrupt state

Buffer Overflow Stack Example #2

After call to gets

Stack Frame for `call_echo`			
00	00	00	00
00	40	00	34
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-nspunix>./bufdemo-nsp
Type a string:
012345678901234567890123 4
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:
01234567890123456789012
01234567890123456789012
```

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

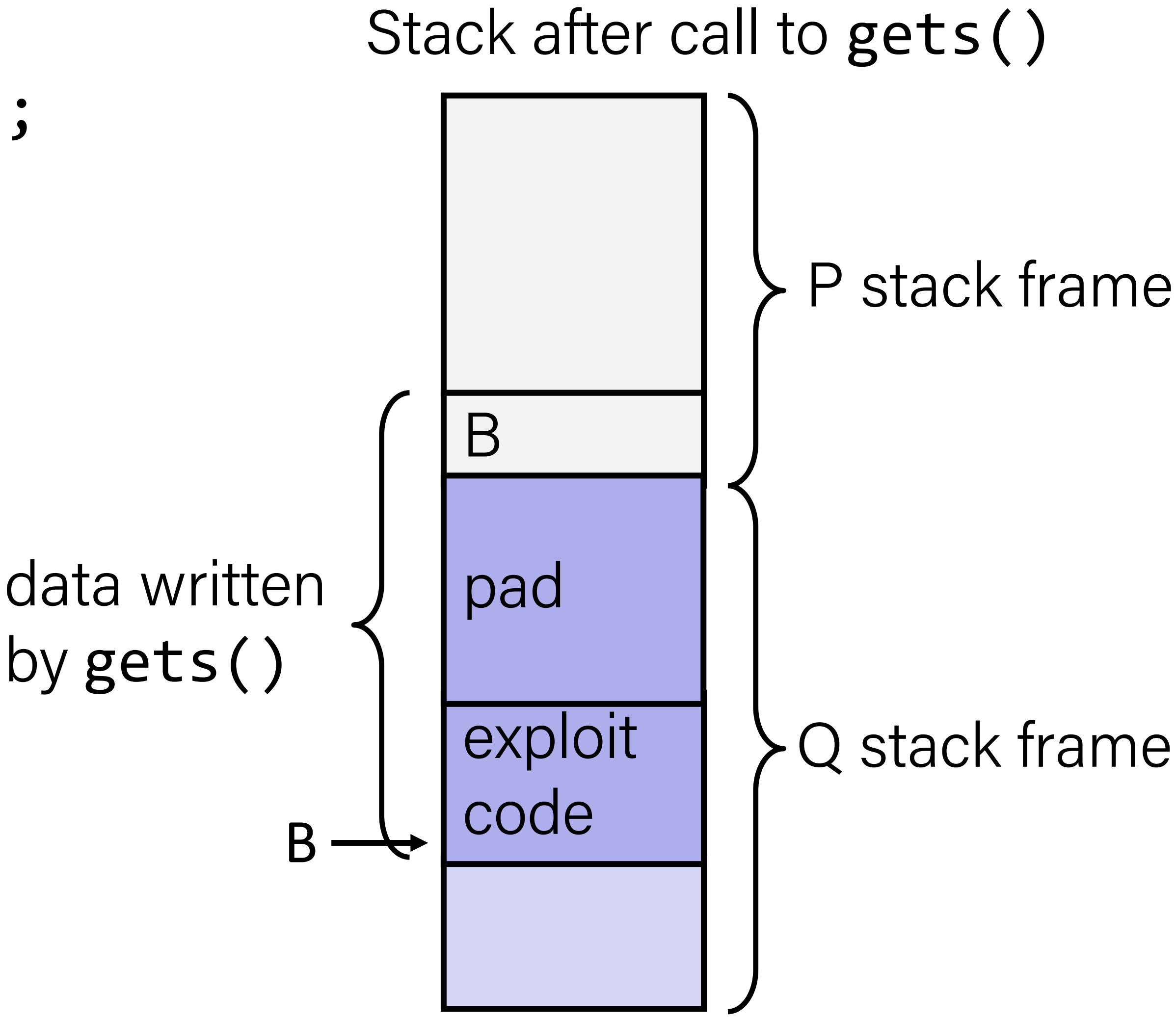
Code Injection Attacks

```
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



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)
  - ... and many, many more
- You will learn some of the tricks in Assignment 5
  - Hopefully to convince you to never leave such holes in your programs!!

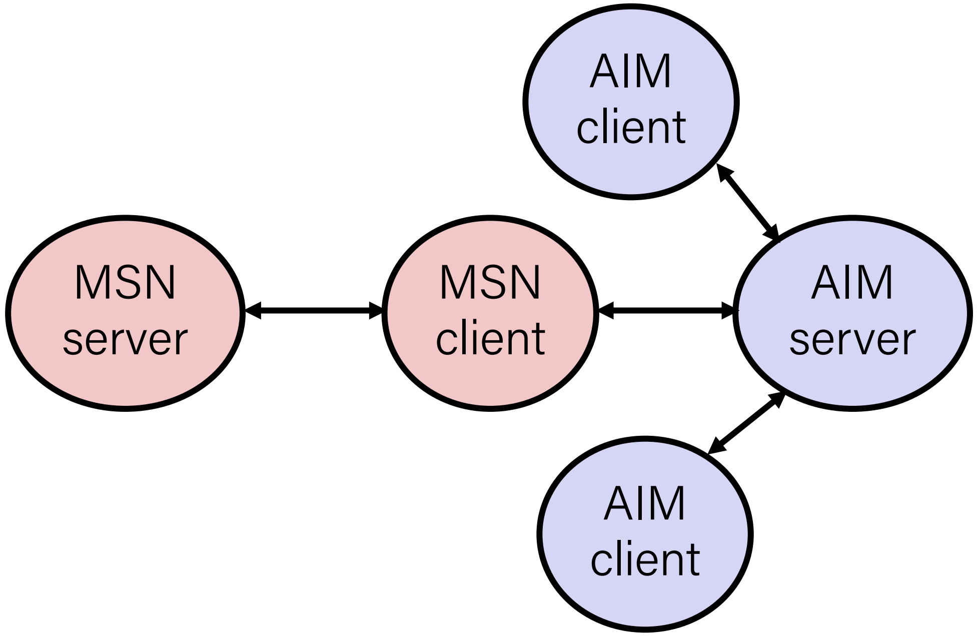
Example: the original Internet worm (1988)

- 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

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

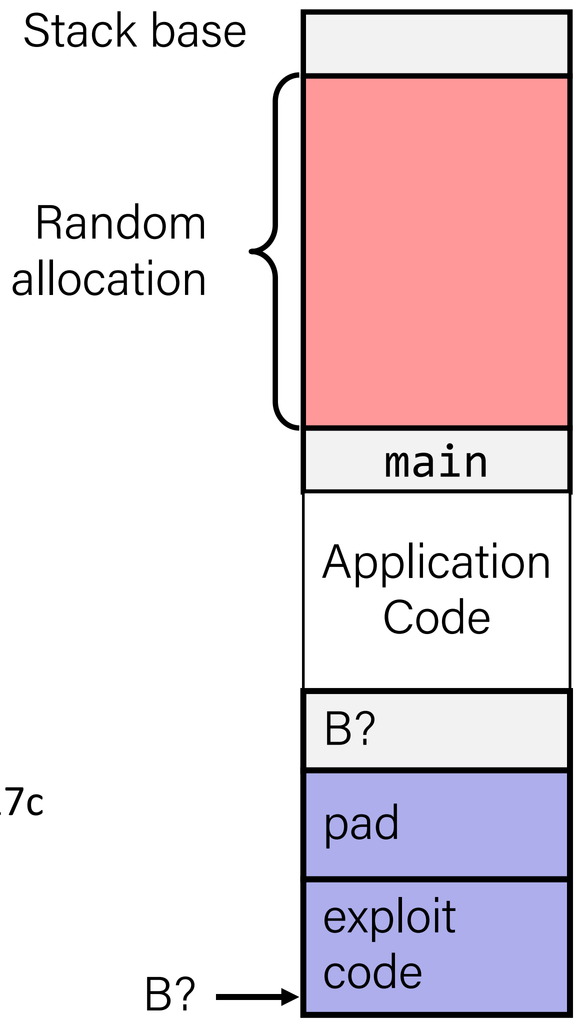
2. System-Level Protections can help

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

local	0x7ffe4d3be87c	0x7fff75a4f9fc	0x7ffeadb7c80c	0x7ffeaea2fdac	0x7ffcd452017c

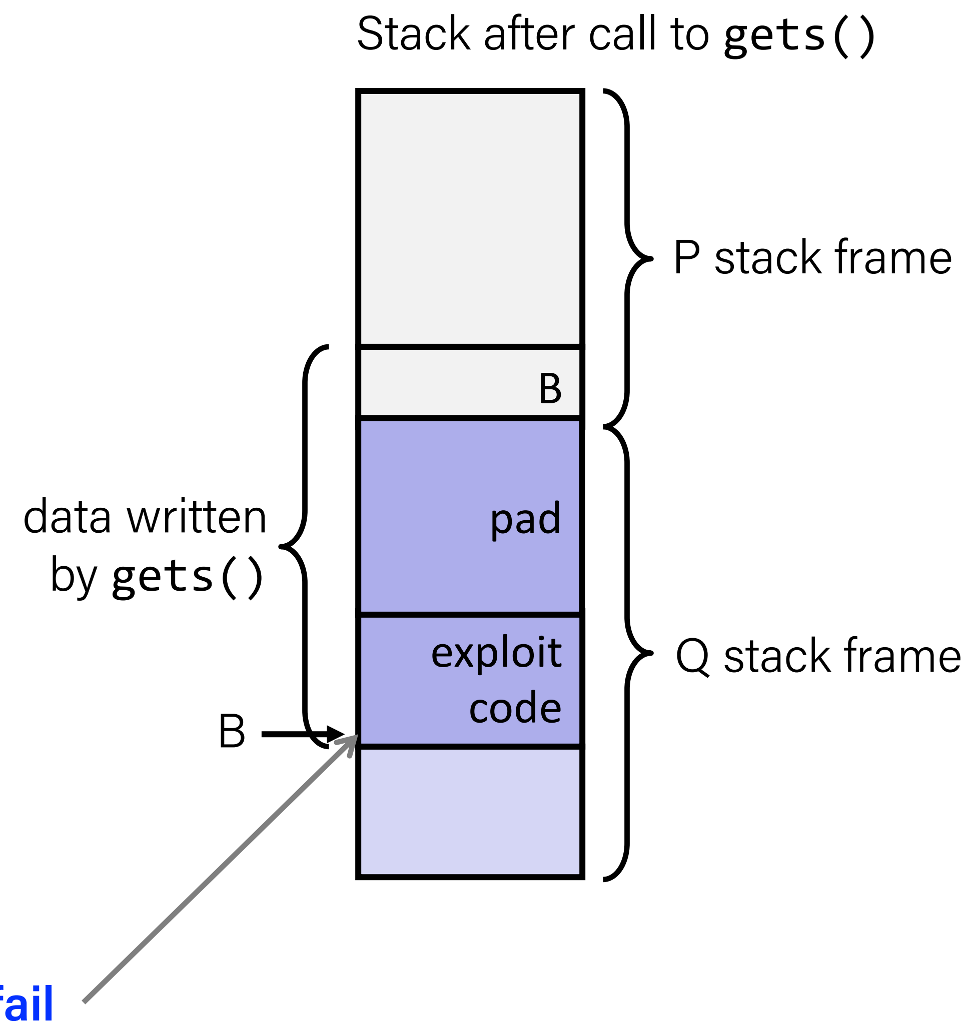
  - Stack repositioned each time program executes



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



Any attempt to execute this code will fail

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
```

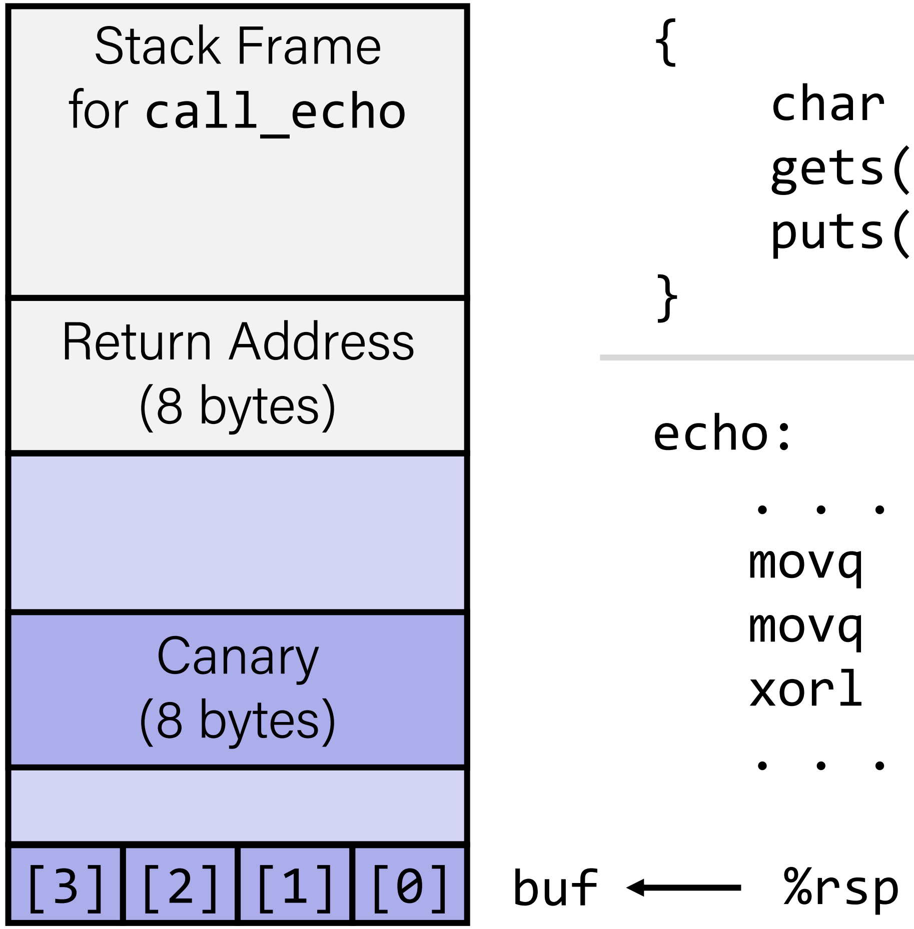
```
unix>./bufdemo-sp
Type a string:
01234567
*** stack smashing detected ***
```

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

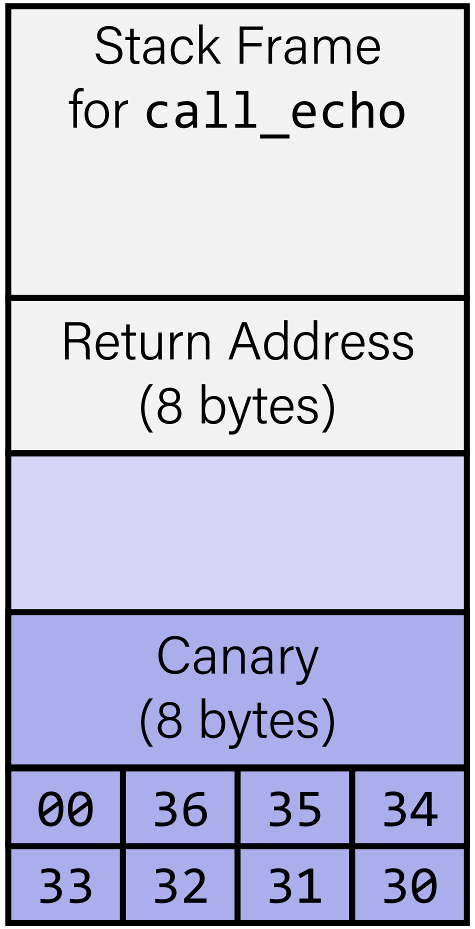



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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:        . . .
```

buf ← %rsp

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;
}
```

```
00000000004004d0 <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
```

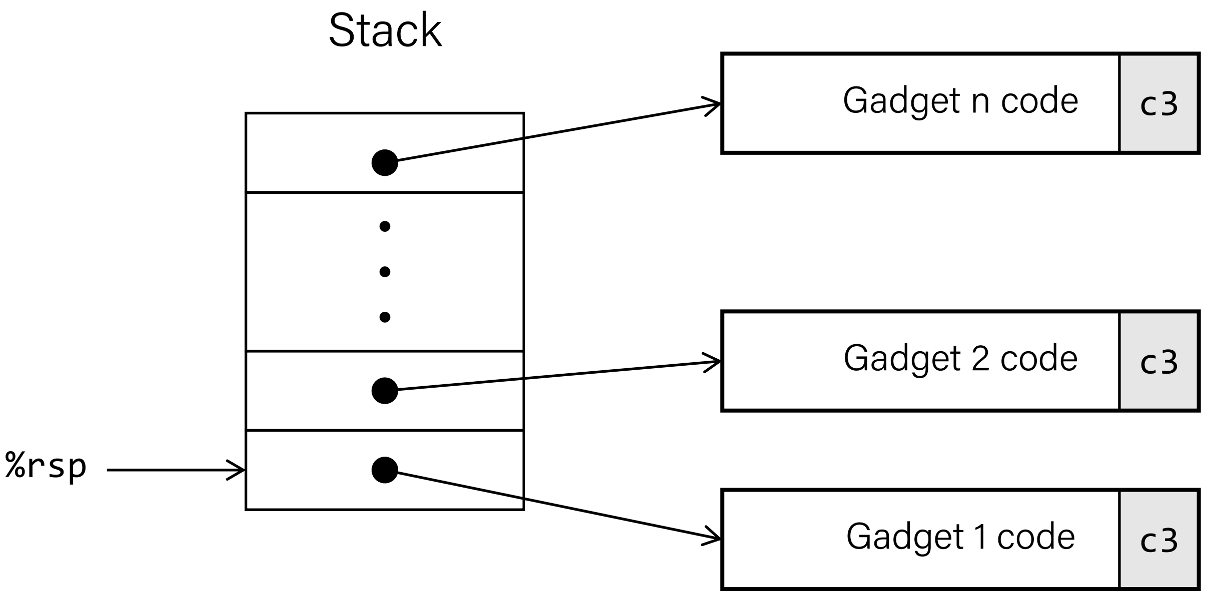
`rdi ← rax`

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