CS330 - Computer Organization and Assembly Language Programming

Lecture 16

-Floating Points -

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Agenda

- Floating Points
- Combining Control and Data in Machine Level Programs
- Security Vulnerabilities
  - Buffer Overflow
- Union in C

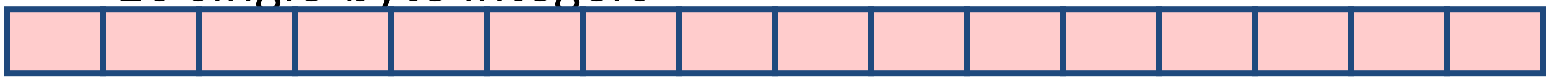
Floating Point: Background

- History
  - x87 FP
    - Legacy, very ugly
  - SSE FP
    - Special case use of vector instructions
  - AVX FP
    - Newest version
    - Similar to SSE
    - Documented in book

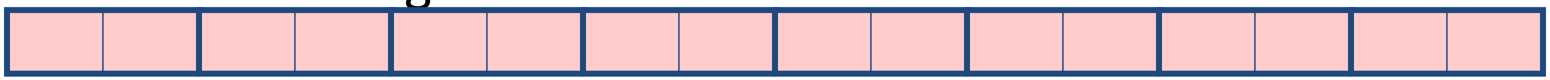
Programming with SSE3

XMM Registers

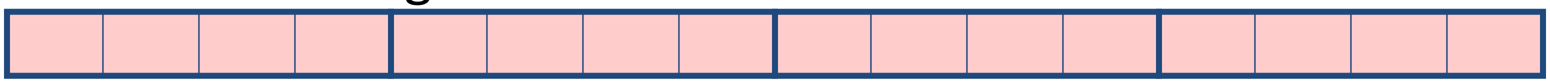
- 16 total, each 16 bytes
- 16 single-byte integers



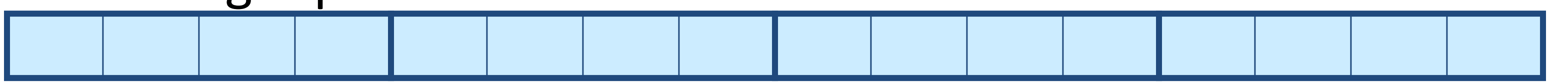
- 8 16-bit integers



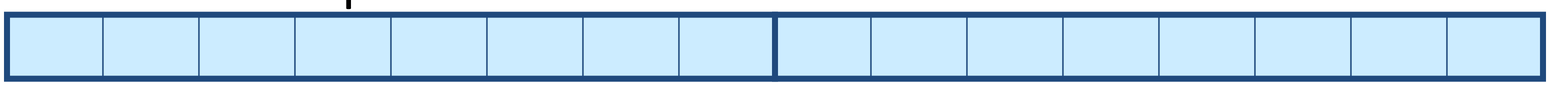
- 4 32-bit integers



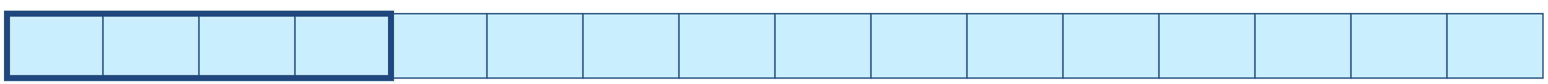
- 4 single-precision floats



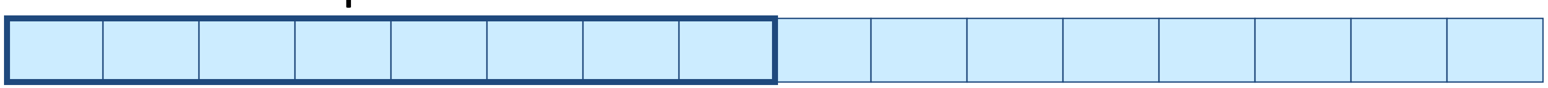
- 2 double-precision floats



- 1 single-precision float

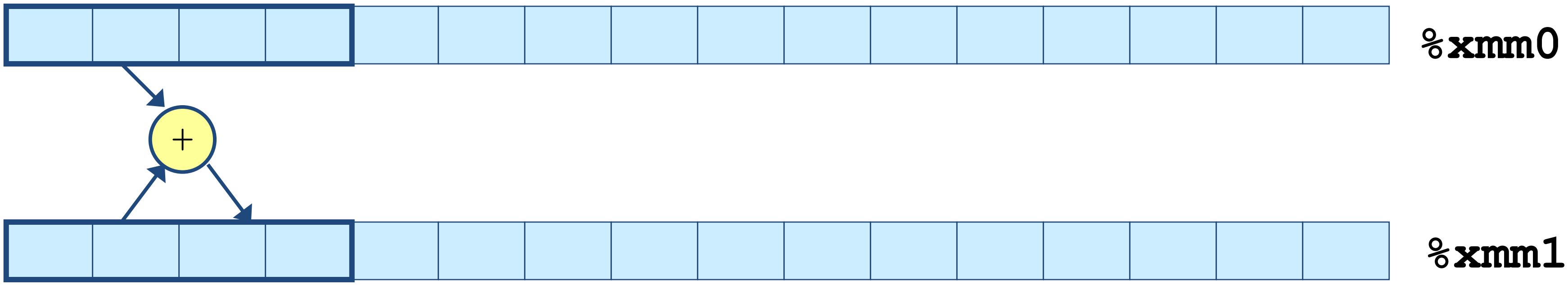


- 1 double-precision float

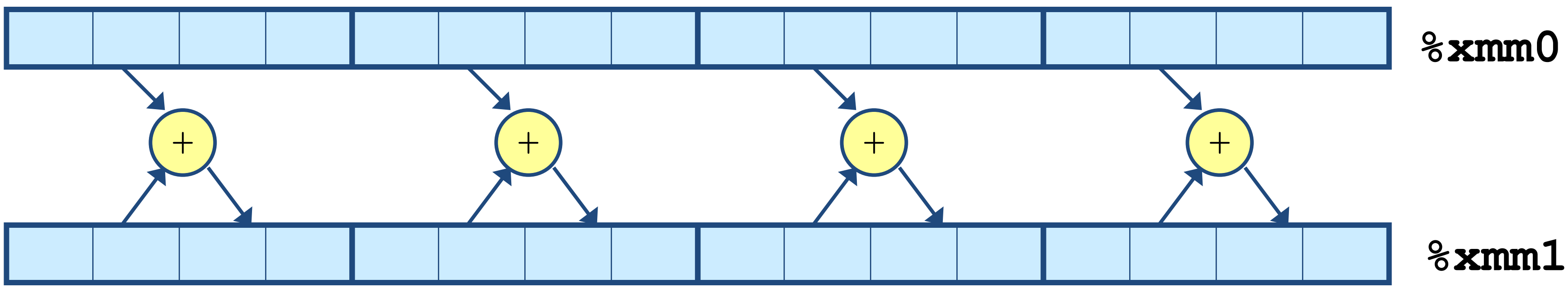


Scalar & SIMD Operations

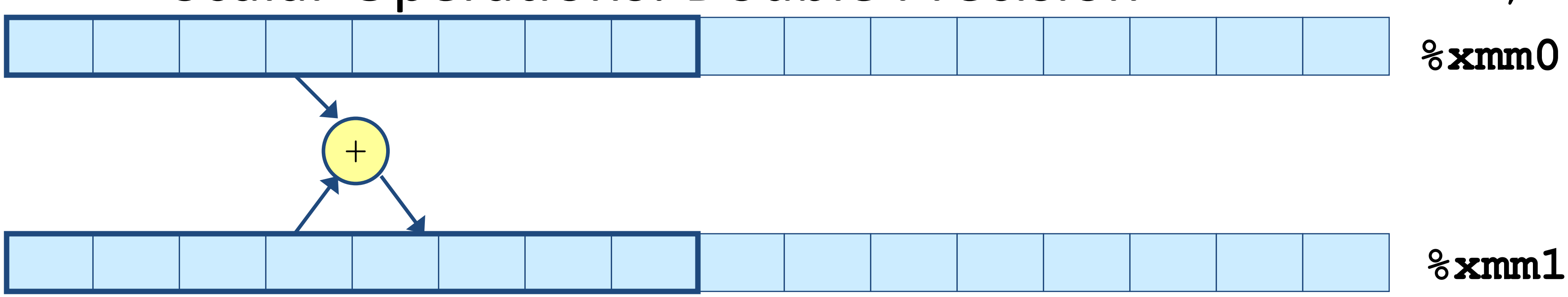
- **Scalar Operations: Single Precision** `addss %xmm0,%xmm1`

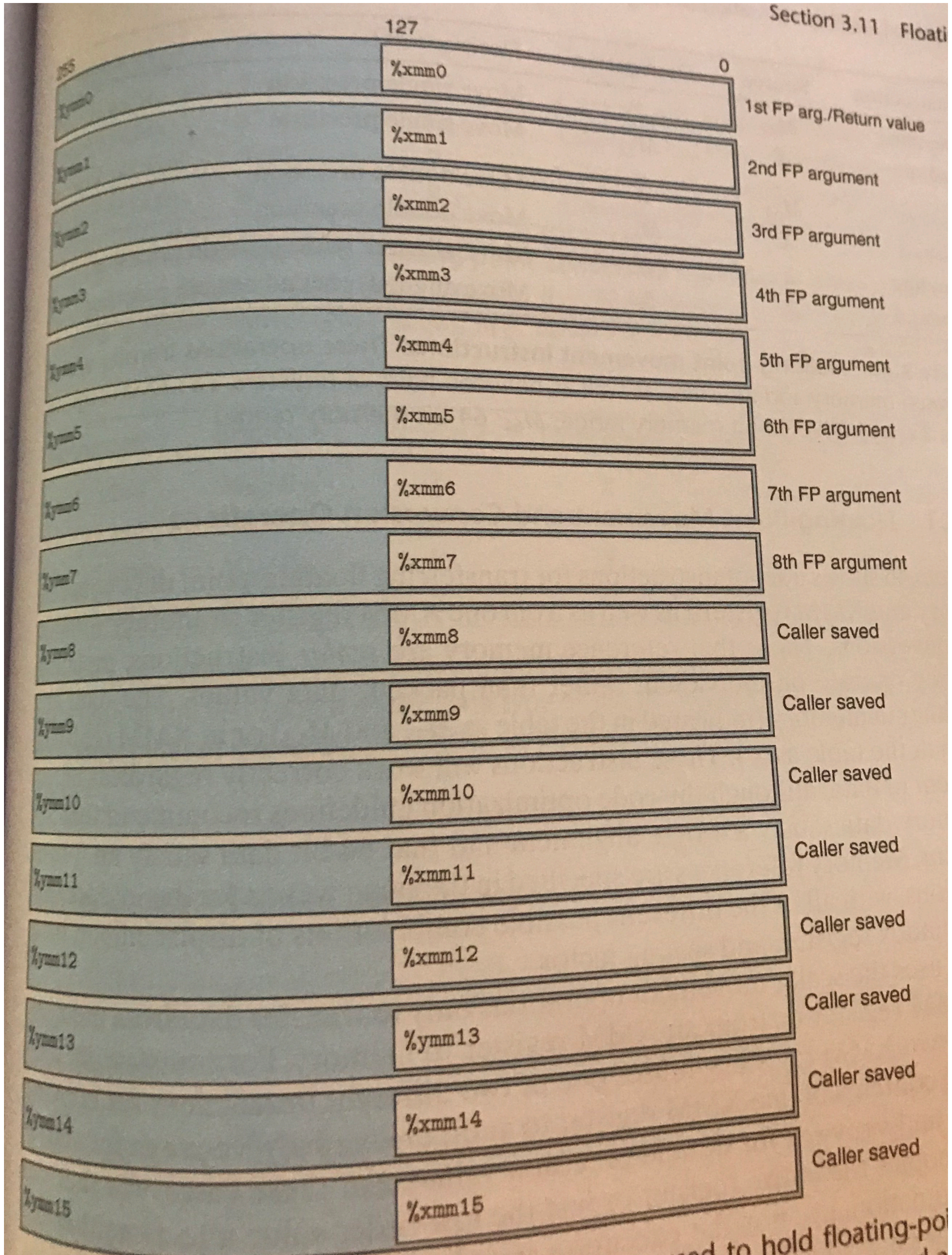


- **SIMD Operations: Single Precision** `addps %xmm0,%xmm1`



- **Scalar Operations: Double Precision** `addsd %xmm0,%xmm1`




Section 3.11
127
0
255
%xmm0
1st FP arg./Return value
%xmm1
2nd FP argument
%xmm2
3rd FP argument
%xmm3
4th FP argument
%xmm4
5th FP argument
%xmm5
6th FP argument
%xmm6
7th FP argument
%xmm7
8th FP argument
%xmm8
Caller saved
%xmm9
Caller saved
%xmm10
Caller saved
%xmm11
Caller saved
%xmm12
Caller saved
%ymm13
Caller saved
%xmm14
Caller saved
%xmm15
Caller saved
%ymm10
%ymm11
%ymm12
%ymm13
%ymm14
%ymm15

- ss: single precision
- sd: double precision
- aps: aligned, packed single precision
- apd: aligned packed 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;
}
```

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

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

```
 # 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

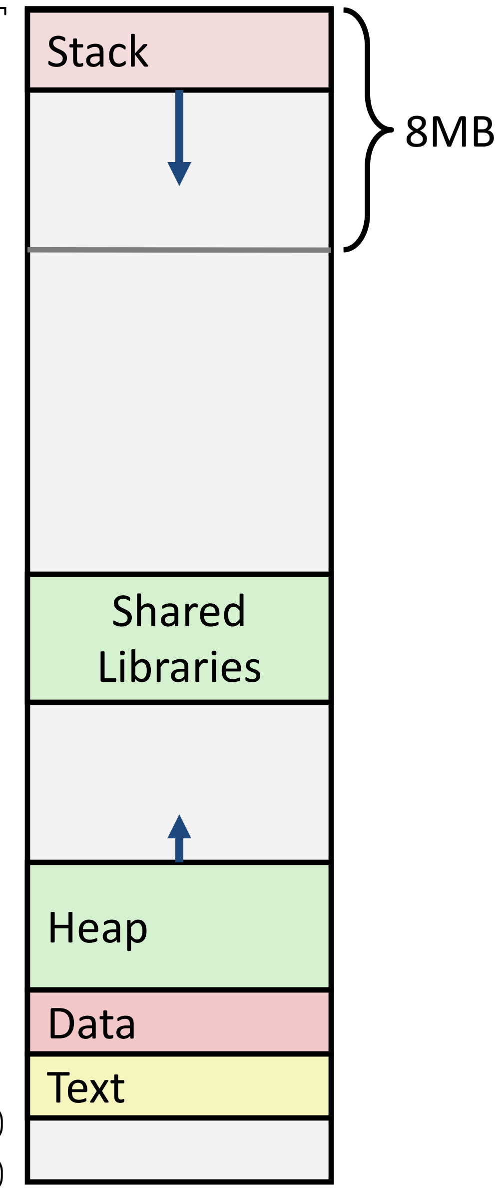
Summary

- Arrays
  - Elements packed into contiguous region of memory
  - Use index arithmetic to locate individual elements
- Structures
  - Elements packed into single region of memory
  - Access using offsets determined by compiler
  - Possible require internal and external padding to ensure alignment
- Combinations
  - Can nest structure and array code arbitrarily
- Floating Point
  - Data held and operated on in XMM registers

x86-64 Linux Memory Layout

not drawn to scale

- 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

not drawn to scale

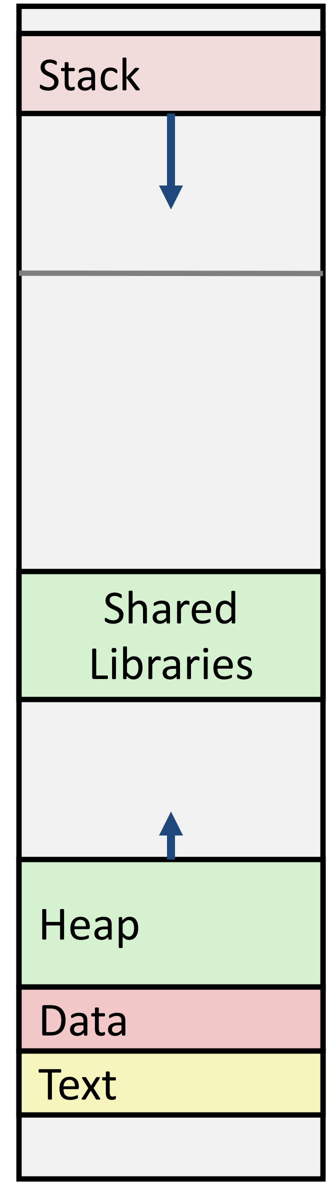
```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

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?

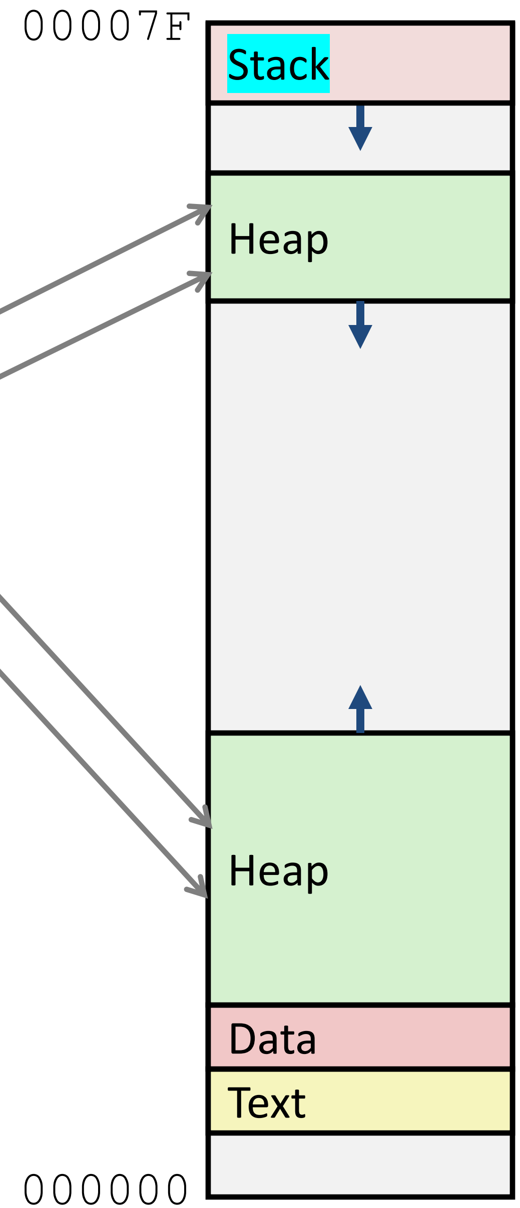


x86-64 Example Addresses

not drawn to scale

address range ~2^{47}

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



Recall: 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

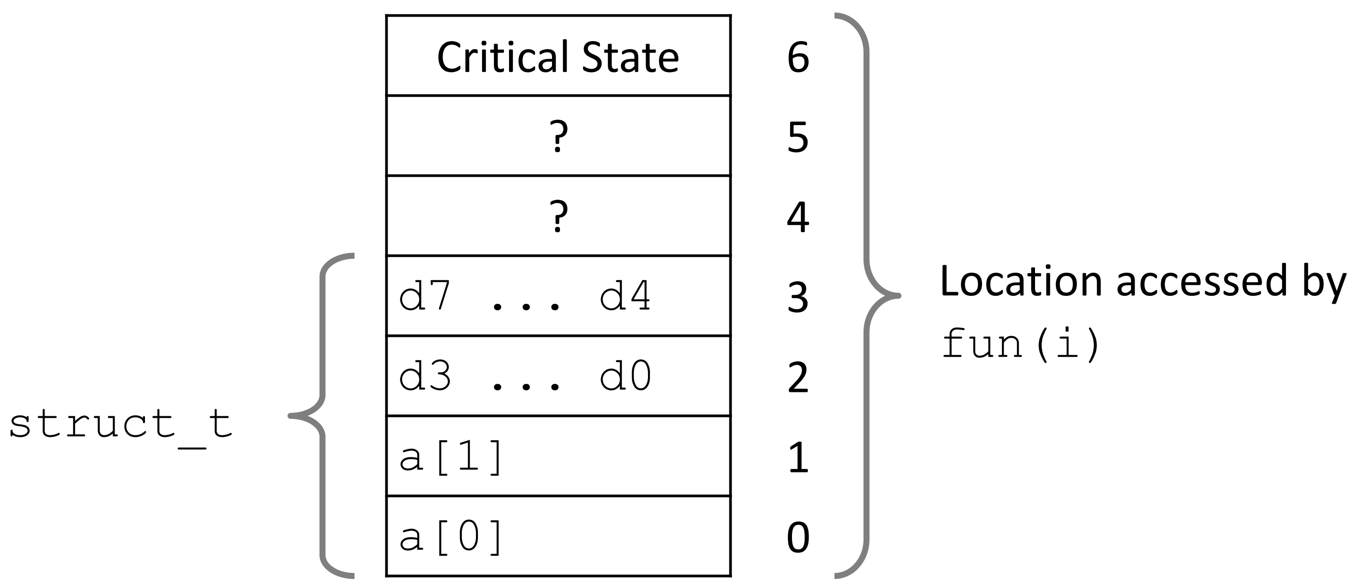
– Result is system specific

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

Vulnerable Buffer Code

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

← btw, how big is big enough?

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

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

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

Buffer Overflow Disassembly

echo:

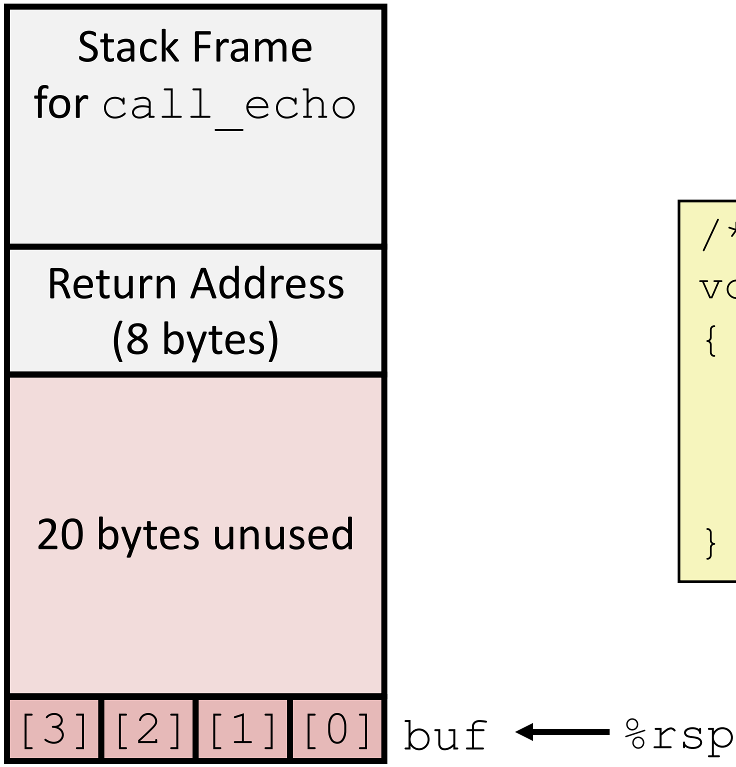
```
0000000004006cf <echo>:
 4006cf:  48 83 ec 18              sub    $0x18,%rsp
 4006d3:  48 89 e7                 mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff           callq  400680 <gets>
 4006db:  48 89 e7                 mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff           callq  400520 <puts@plt>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

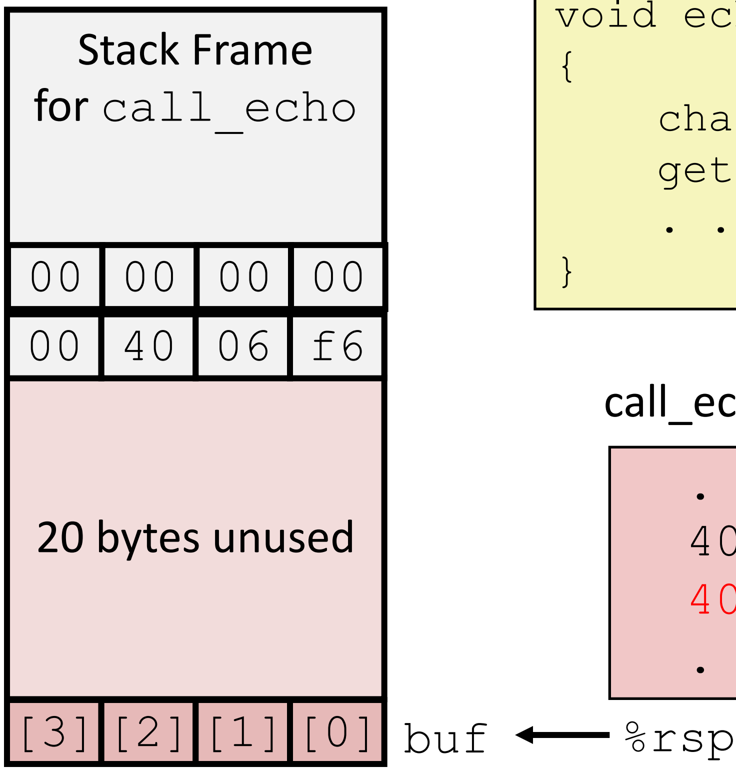



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

Buffer Overflow Stack Example

Before call to gets




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

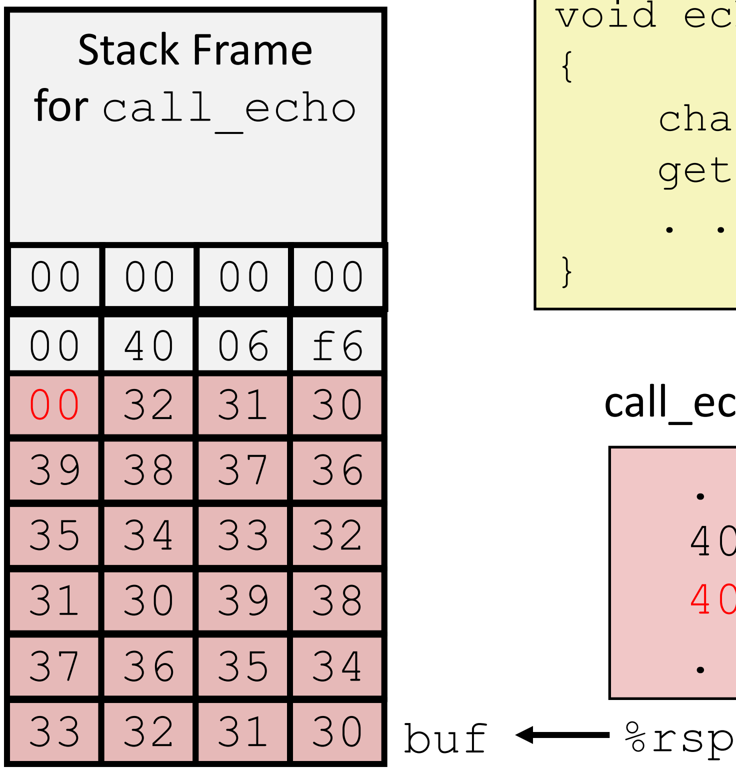
```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

call_echo:

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

Buffer Overflow Stack Example #1

After call to gets




```
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-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:

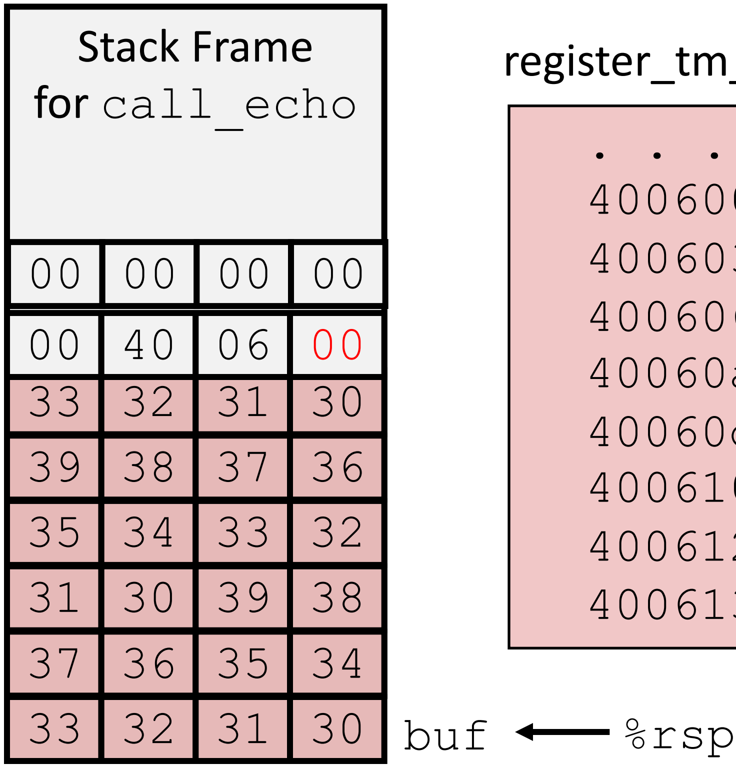
```
   . . .
   4006f1:  callq   4006cf <echo>
   4006f6:  add     $0x8,%rsp
   . . .
```

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

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

Buffer Overflow Stack Example #3 Explained

After call to gets



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`

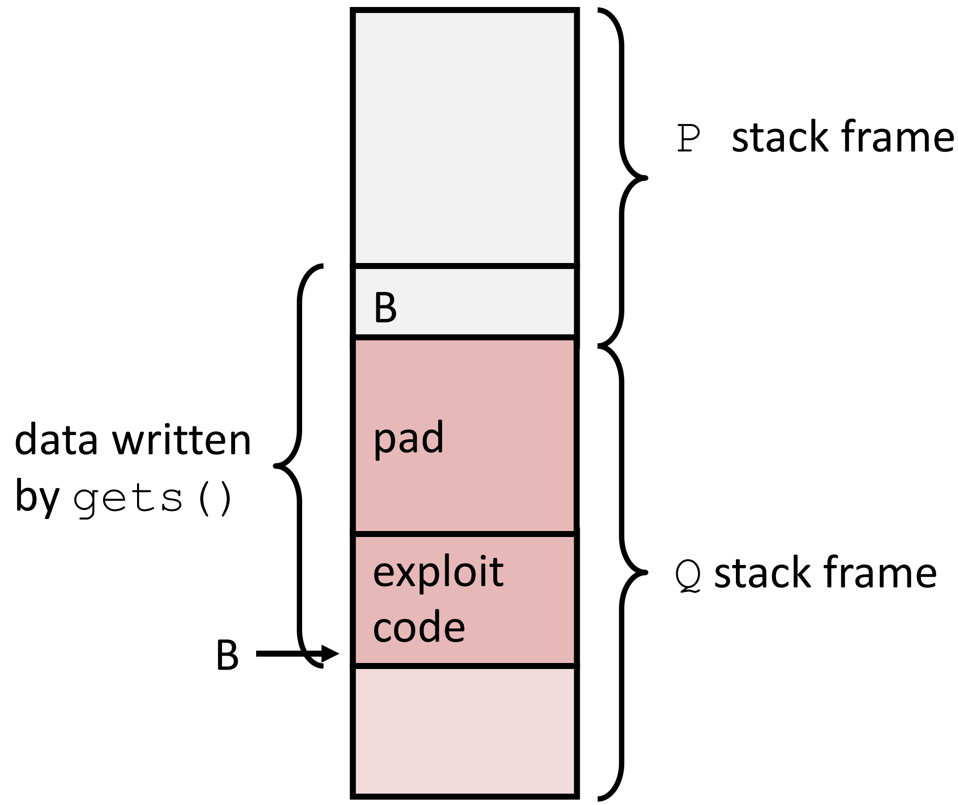
Code Injection Attacks

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

return address A

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

Stack after call to `gets()`



- 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

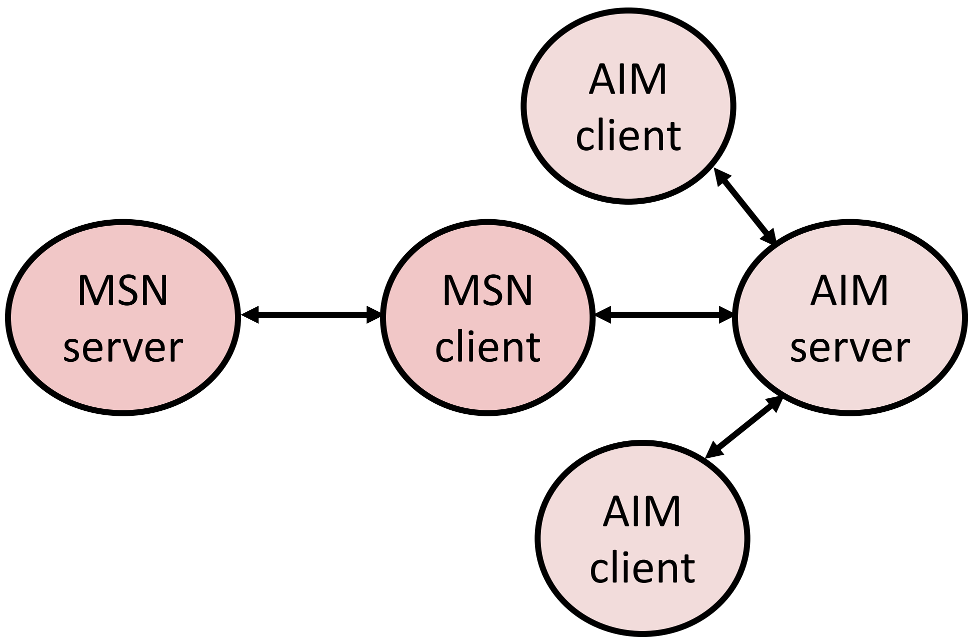
- *Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines*
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original "Internet worm" (1988)
  - "IM wars" (1999)
  - Twilight hack on Wii (2000s)
  - … and many, many more

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 unan@uab.edu`**
  - 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… still 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”

- Lets talk about each…

1. Avoid Overflow Vulnerabilities in Code (!)

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

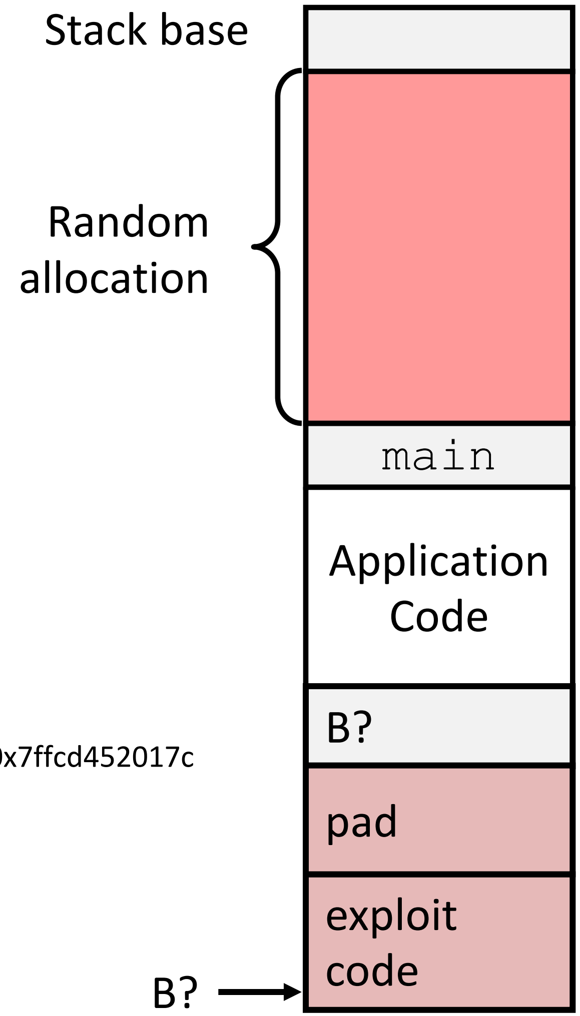
- For example, use library routines that limit string lengths
  - **`fgets`** instead of **`gets`**
  - **`strncpy`** instead of **`strcpy`**
  - Don't use **`scanf`** with **`%s`** conversion specification
    - Use **`fgets`** to read the string
    - Or use **`%ns`** where **`n`** is a suitable integer

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

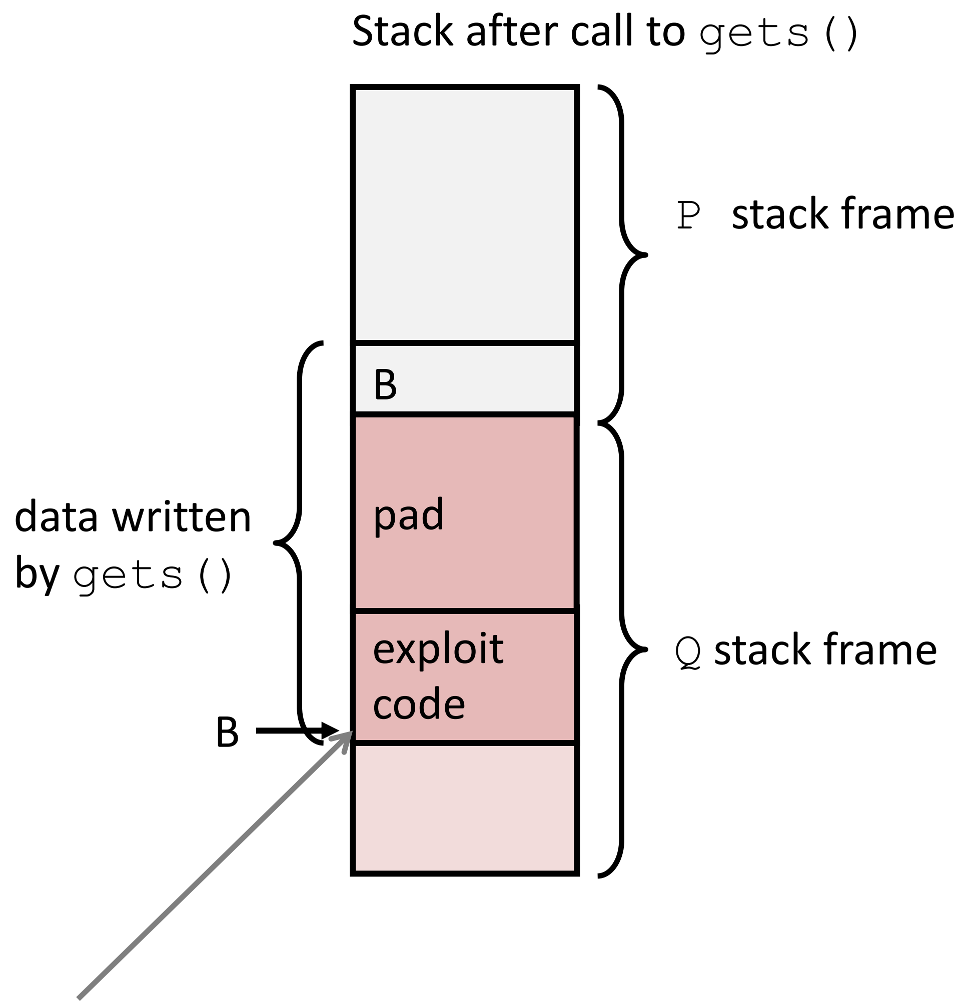
local	0x7ffe4d3be87c	0x7fff75a4f9fc	0x7ffeadb7c80c	0x7ffeaea2fdac	0x7ffcd452017c

  - 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 ***
```

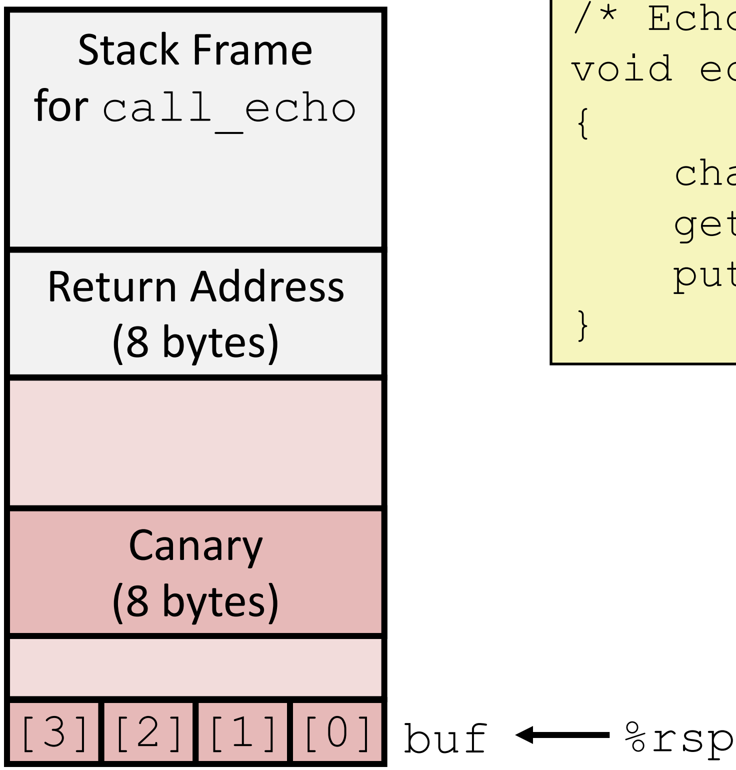
Protected Buffer Disassembly

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

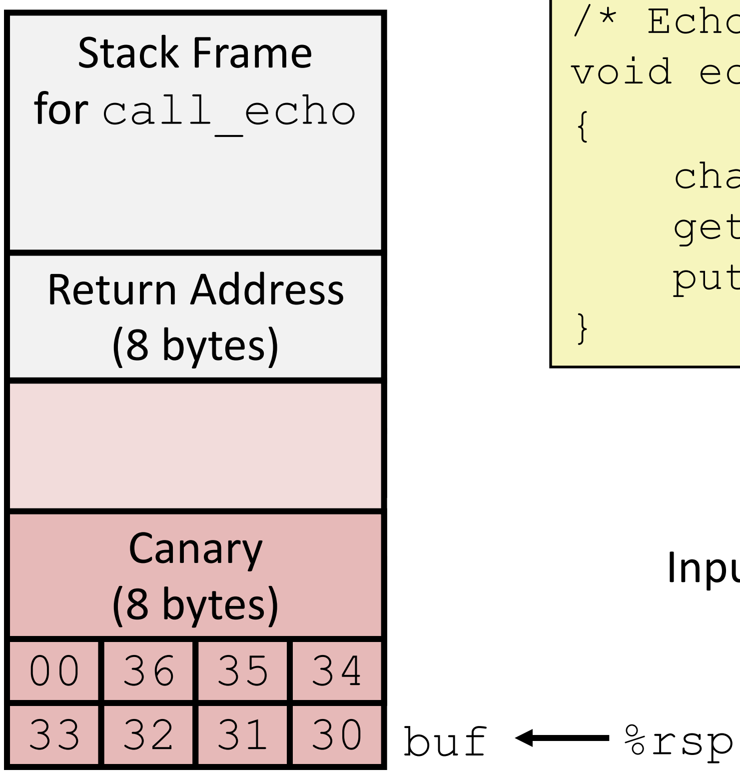



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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: . . .
```

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`

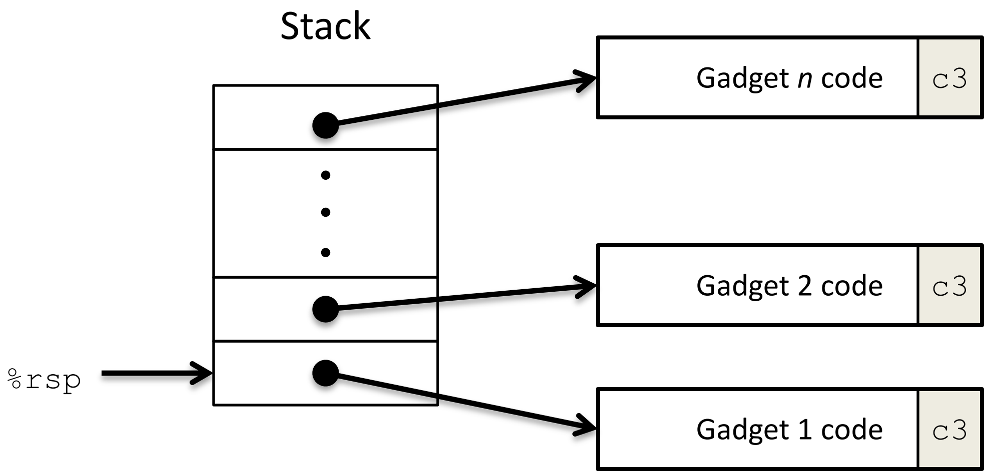
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl   $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

rdi ← rax

Gadget address = `0x4004dc`

- Repurpose byte codes

ROP Execution

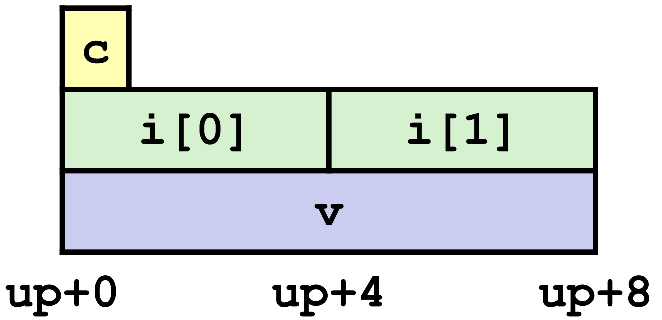


- Trigger with `ret` instruction
  - Will start executing Gadget 1
- Final `ret` in each gadget will start next one

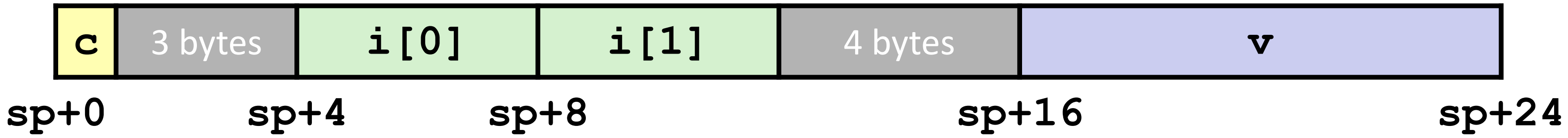
Union Allocation

- Allocate according to largest element
- Can only use one field at a time

```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```

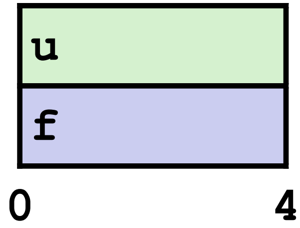



```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```



Using Union to Access Bit Patterns

```
typedef union {
  float f;
  unsigned u;
} bit_float_t;
```




```
float bit2float(unsigned u)
{
  bit_float_t arg;
  arg.u = u;
  return arg.f;
}
```

```
unsigned float2bit(float f)
{
  bit_float_t arg;
  arg.f = f;
  return arg.u;
}
```

Same as **`(float) u`** ?

Same as **`(unsigned) f`** ?

Byte Ordering Revisited

- Idea
  - Short/long/quad words stored in memory as 2/4/8 consecutive bytes
  - Which byte is most (least) significant?
  - Can cause problems when exchanging binary data between machines
- Big Endian
  - Most significant byte has lowest address
  - Sparc
- Little Endian
  - Least significant byte has lowest address
  - Intel x86, ARM Android and IOS
- Bi Endian
  - Can be configured either way
  - ARM

Byte Ordering Example

```
union {
  unsigned char c[8];
  unsigned short s[4];
  unsigned int i[2];
  unsigned long l[1];
} dw;
```

32-bit

<table>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="4">l[0]</td><td colspan="4"></td></tr>
</table>

64-bit

<table>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="8">l[0]</td></tr>
</table>

Byte Ordering Example (Cont).

```
int j;
for (j = 0; j < 8; j++)
    dw.c[j] = 0xf0 + j;

printf("Characters 0-7 ==
[0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x]\n",
    dw.c[0], dw.c[1], dw.c[2], dw.c[3],
    dw.c[4], dw.c[5], dw.c[6], dw.c[7]);

printf("Shorts 0-3 == [0x%x,0x%x,0x%x,0x%x]\n",
    dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

printf("Ints 0-1 == [0x%x,0x%x]\n",
    dw.i[0], dw.i[1]);

printf("Long 0 == [0x%lx]\n",
    dw.l[0]);
```

Byte Ordering on IA32

Little Endian

<table>
<tr><td>f0</td><td>f1</td><td>f2</td><td>f3</td><td>f4</td><td>f5</td><td>f6</td><td>f7</td></tr>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="4">l[0]</td><td colspan="4"></td></tr>
</table>

LSB MSB LSB MSB

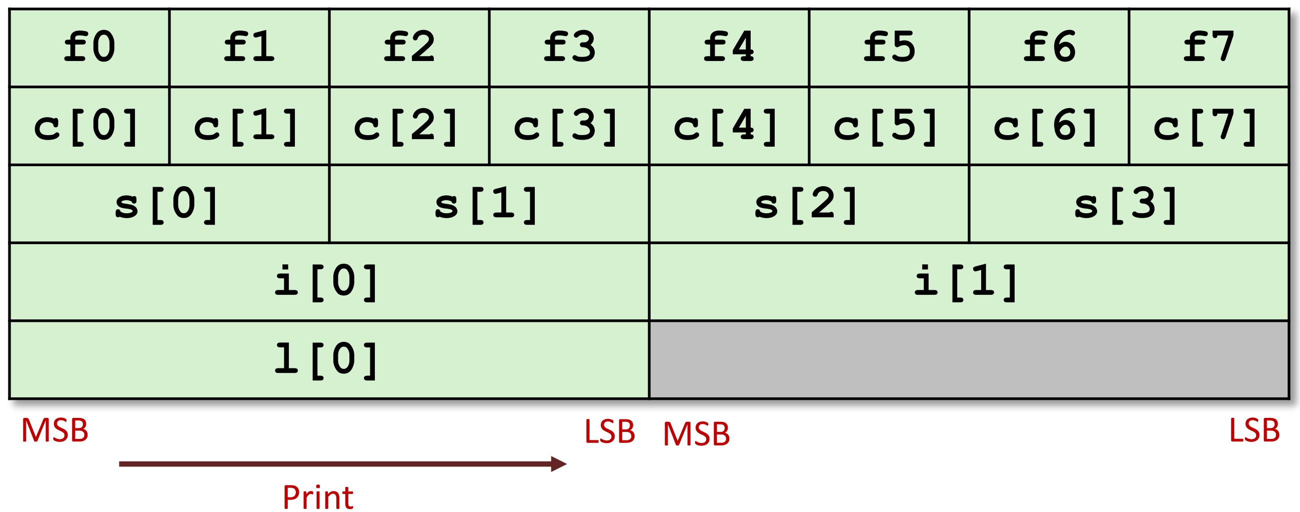
Print

Output:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]
Ints       0-1 == [0xf3f2f1f0,0xf7f6f5f4]
Long       0   == [0xf3f2f1f0]
```

Byte Ordering on Sun

Big Endian

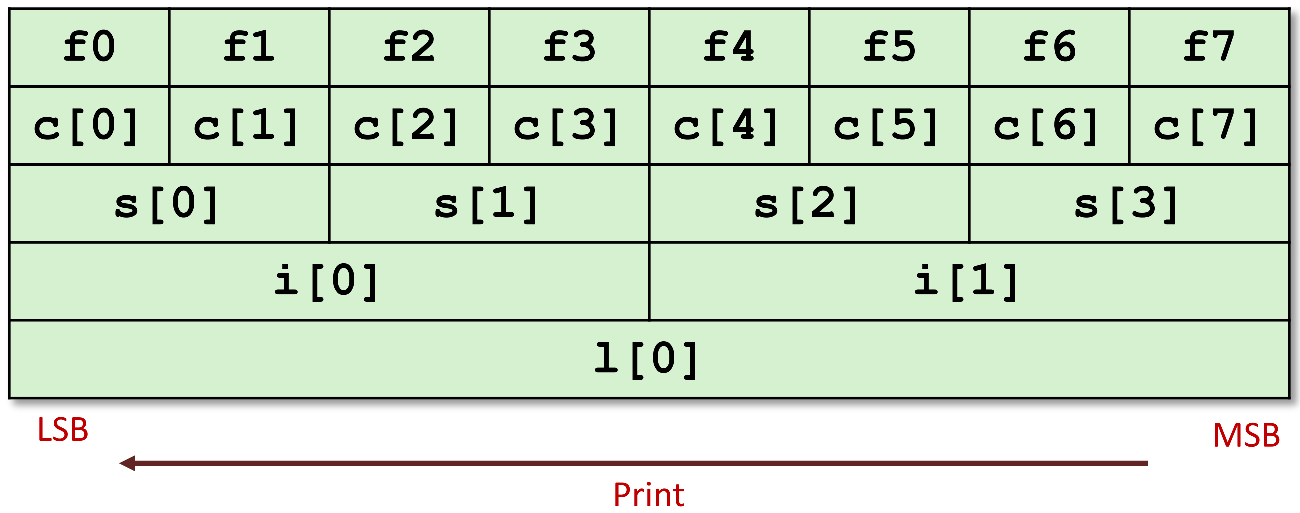


Output on Sun:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf0f1,0xf2f3,0xf4f5,0xf6f7]
Ints       0-1 == [0xf0f1f2f3,0xf4f5f6f7]
Long       0   == [0xf0f1f2f3]
```

Byte Ordering on x86-64

Little Endian



Output on x86-64:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]
Ints       0-1 == [0xf3f2f1f0,0xf7f6f5f4]
Long       0   == [0xf7f6f5f4f3f2f1f0]
```

Summary of Compound Types in C

- Arrays
  - Contiguous allocation of memory
  - Aligned to satisfy every element’s alignment requirement
  - Pointer to first element
  - No bounds checking
- Structures
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- Unions
  - Overlay declarations
  - Way to circumvent type system

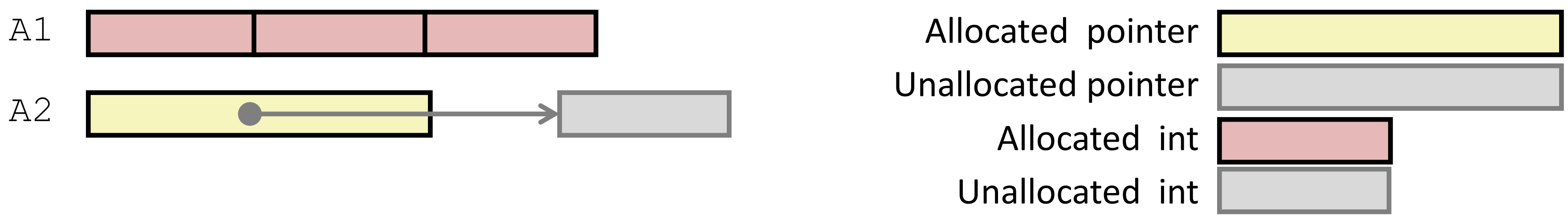
Understanding Pointers & Arrays #1

Decl	*An*			**An*		
	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3]`						
`int *A2`						

- Cmp: Compiles (Y/N)
- Bad: Possible bad pointer reference (Y/N)
- Size: Value returned by `sizeof`

Understanding Pointers & Arrays #1

Decl	*An*			***An*		
	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3]`	**Y**	**N**	**12**	**Y**	**N**	**4**
`int *A2`	**Y**	**N**	**8**	**Y**	**Y**	**4**



- Cmp: Compiles (Y/N)
- Bad: Possible bad pointer reference (Y/N)
- Size: Value returned by `sizeof`

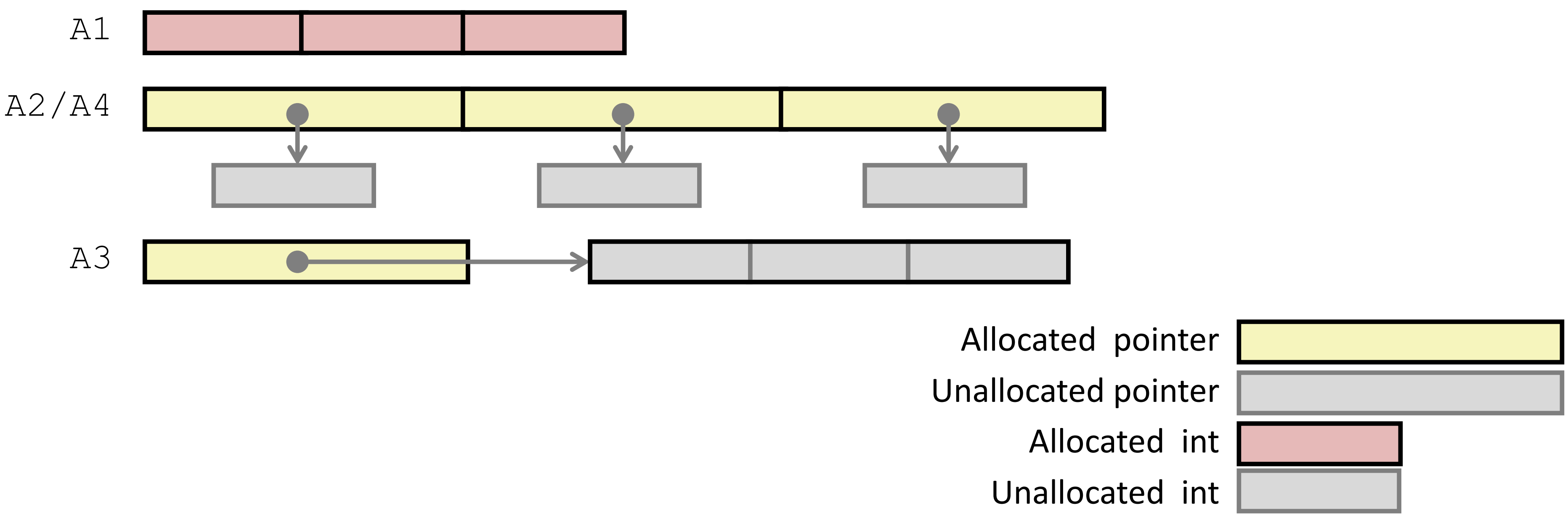
Understanding Pointers & Arrays #2

Decl	*An*			**An*			***An*		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3]`									
`int *A2[3]`									
`int (*A3)[3]`									
`int (*A4[3])`									

- Cmp: Compiles (Y/N)
- Bad: Possible bad pointer reference (Y/N)
- Size: Value returned by `sizeof`

Understanding Pointers & Arrays #2

Decl	An			*An			**An		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3]`	Y	N	12	Y	N	4	N	-	-
`int *A2[3]`	Y	N	24	Y	N	8	Y	Y	4
`int (*A3)[3]`	Y	N	8	Y	Y	12	Y	Y	4
`int (*A4[3])`	Y	N	24	Y	N	8	Y	Y	4

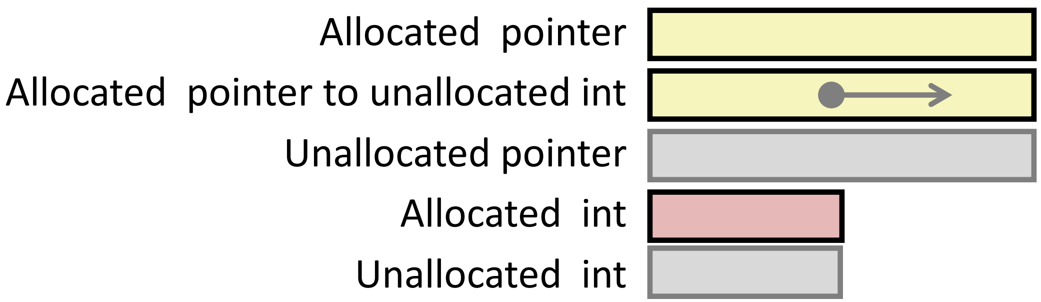


Understanding Pointers & Arrays #3

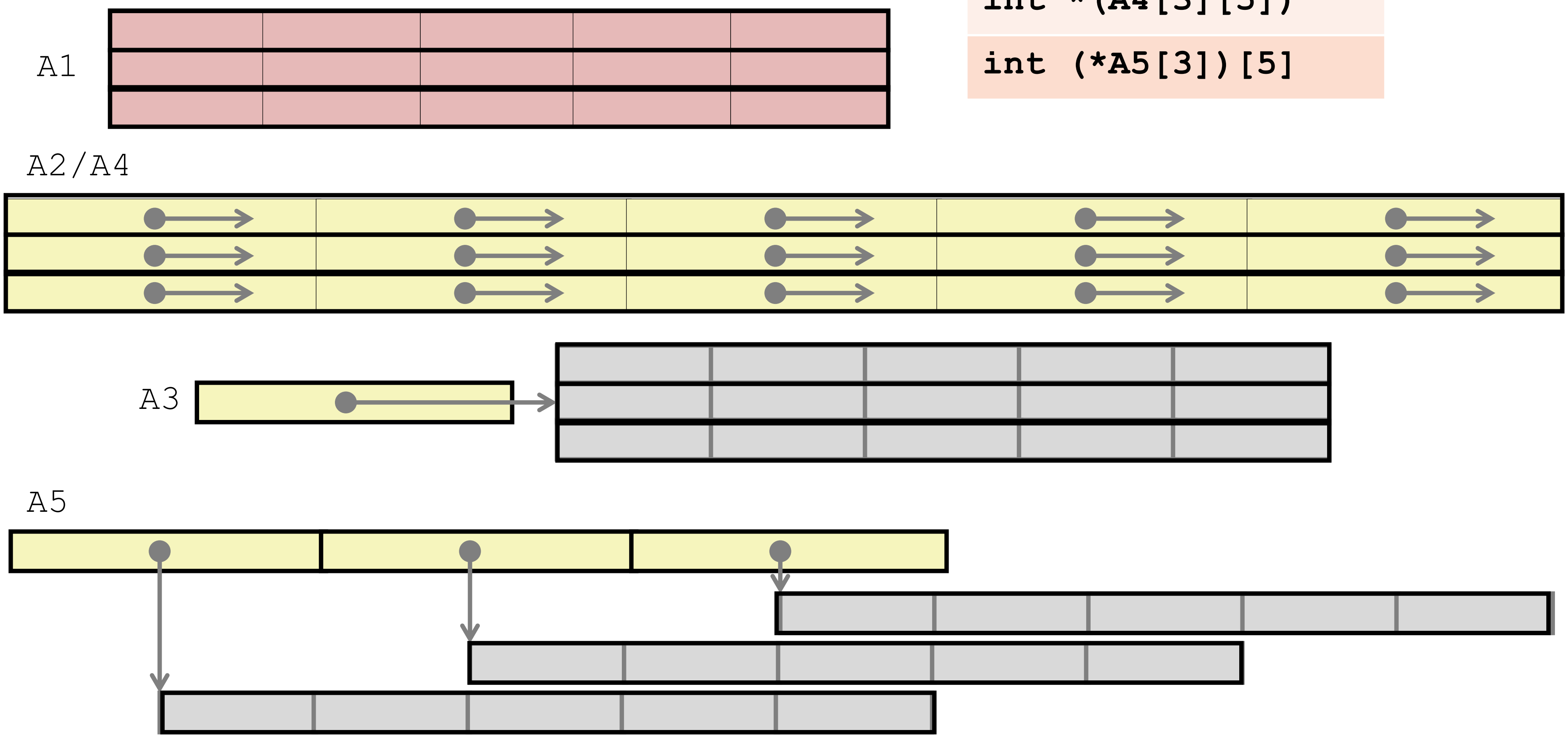
Decl	**A*n***			***A*n***			****A*n***		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
int A1[3][5]									
int *A2[3][5]									
int (*A3)[3][5]									
int *(A4[3][5])									
int (*A5[3])[5]									

Decl	*****A*n***		
	Cmp	Bad	Size
int A1[3][5]			
int *A2[3][5]			
int (*A3)[3][5]			
int *(A4[3][5])			
int (*A5[3])[5]			

- Cmp: Compiles (Y/N)
- Bad: Possible bad pointer reference (Y/N)
- Size: Value returned by `sizeof`



Declaration
`int A1[3][5]`
`int *A2[3][5]`
`int (*A3)[3][5]`
`int *(A4[3][5])`
`int (*A5[3])[5]`



Understanding Pointers & Arrays #3

Decl	*An*			**An*			***An*		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3][5]`	Y	N	60	Y	N	20	Y	N	4
`int *A2[3][5]`	Y	N	120	Y	N	40	Y	N	8
`int (*A3)[3][5]`	Y	N	8	Y	Y	60	Y	Y	20
`int *(A4[3][5])`	Y	N	120	Y	N	40	Y	N	8
`int (*A5[3])[5]`	Y	N	24	Y	N	8	Y	Y	20

- Cmp: Compiles (Y/N)
- Bad: Possible bad pointer reference (Y/N)
- Size: Value returned by `sizeof`

Decl	****An*		
	Cmp	Bad	Size
`int A1[3][5]`	N	-	-
`int *A2[3][5]`	Y	Y	4
`int (*A3)[3][5]`	Y	Y	4
`int *(A4[3][5])`	Y	Y	4
`int (*A5[3])[5]`	Y	Y	4