18-600 Foundations of Computer Systems

Lecture 7:
"Machine-Level Programming III: Data & Program"

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September 21, 2016

- Required Reading Assignment:
  - **Chapter 3 of CS:APP (3rd edition) by Randy Bryant & Dave O'Hallaron**
- Assignments for This Week:
  - Lab 2

Electrical & Computer ENGINEERING

Today

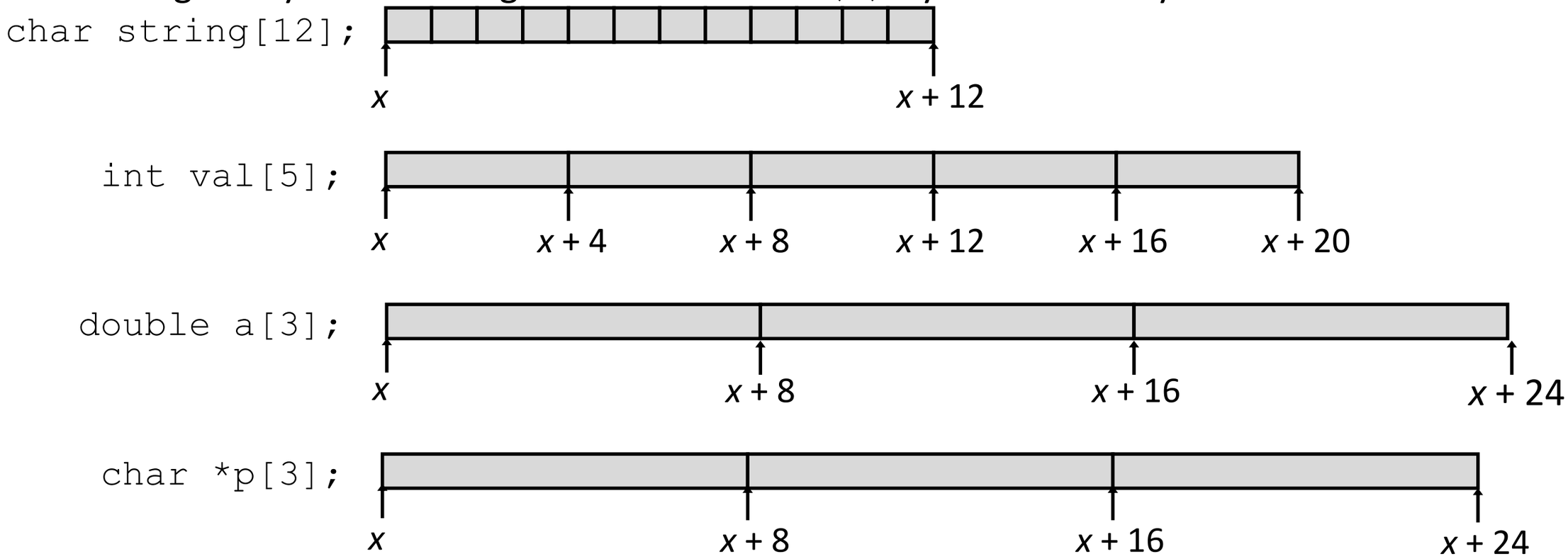
- Data
  - Arrays
  - Structures
  - Unions
  - Floating Point and SIMD operations
- Buffer Overflow
  - Memory Layout
  - Vulnerability and Protection

Array Allocation

- Basic Principle

  T **`A[`***L***`];`**

  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **`sizeof`**`(`*T*`)` bytes in memory

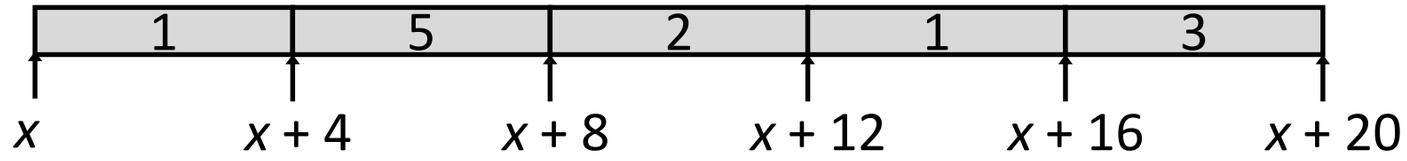


Array Access

- Basic Principle

  T **A[***L***];**
  - Array of data type *T* and length *L*
  - Identifier **A** can be used as a pointer to array element 0: Type *T**

```
int val[5];
```



- Reference

Type	Value
val[4]	**int**	3
val	**int ***	*x*
val+1	**int ***	*x* + 4
&val[2]	**int ***	*x* + 8
val[5]	**int**	??
***(val+1)**	**int**	5
val + *i*	**int ***	*x* + 4 *i*

Multidimensional (Nested) Arrays

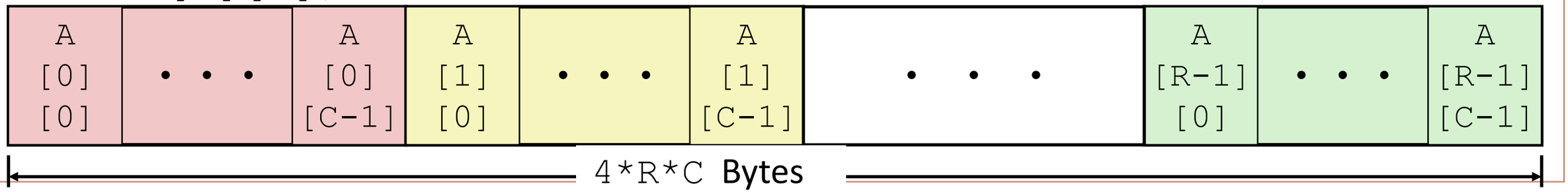
- Declaration

  T **A**[*R*][*C*];

  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes
- Array Size
  - *R* * *C* * *K* bytes
- Arrangement
  - Row-Major Ordering

$$\begin{bmatrix} A[0][0] & \cdots & A[0][C-1] \\ \vdots & & \vdots \\ A[R-1][0] & \cdots & A[R-1][C-1] \end{bmatrix}$$

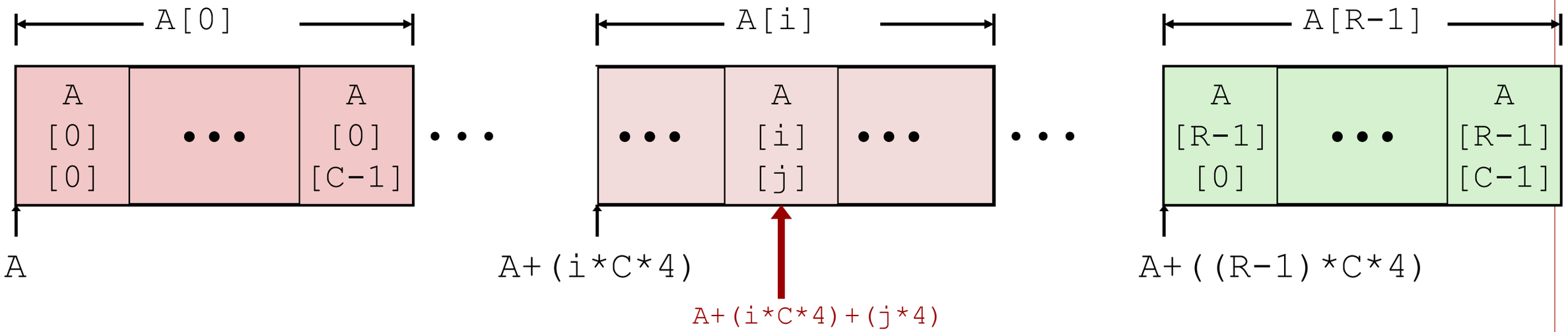
`int A[R][C];`



Nested Array Access

- **Row Vectors**
  - **`A[i]`** is array of *C* elements
  - Each element of type *T* requires *K* bytes
  - Starting address **`A`** **`+`** *i* * (*C* * *K*)
- Array Elements
  - **`A[i][j]`** is element of type *T,* which requires *K* bytes
  - Address **`A`** **`+`** *i* * (*C* * *K*) + *j* * *K* = *A* + (*i* * *C* + *j*)* *K*

```
int A[R][C];
```



16 X 16 Matrix Access

- **Array Elements**
  - Address **`A`** + *i* * (*C* * *K*) + *j* * *K*
  - C = 16, K = 4

```
/* Get element a[i][j] */
int fix_ele(fix_matrix a, size_t i, size_t j) {
  return a[i][j];
}
```

```
  # a in %rdi, i in %rsi, j in %rdx
  salq    $6, %rsi                # 64*i
  addq    %rsi, %rdi              # a + 64*i
  movl    (%rdi,%rdx,4), %eax     # M[a + 64*i + 4*j]
  ret
```

n X n Matrix Access

- **Array Elements**
  - Address **`A`** **`+`** $i * (C * K) + j * K$
  - C = n, K = 4
  - Must perform integer multiplication

```
/* Get element a[i][j] */
int var_ele(size_t n, int a[n][n], size_t i, size_t j) {
  return a[i][j];
}
```

```
  # n in %rdi, a in %rsi, i in %rdx, j in %rcx
  imulq   %rdx, %rdi              # n*i
  leaq    (%rsi,%rdi,4), %rax     # a + 4*n*i
  movl    (%rax,%rcx,4), %eax     # a + 4*n*i + 4*j
  ret
```

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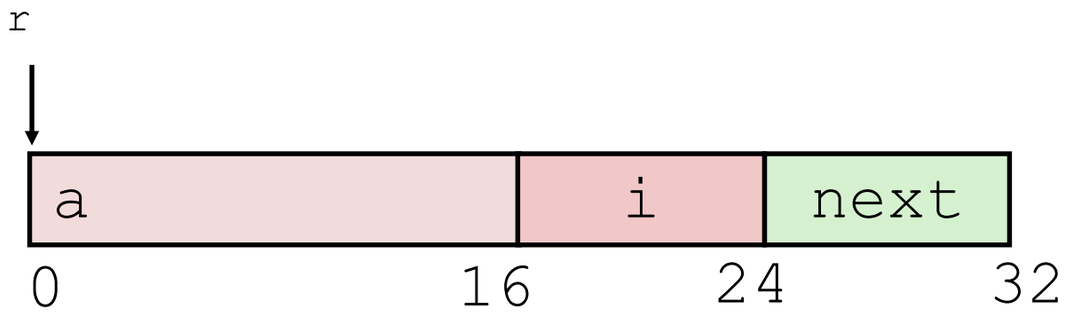
Structure Representation

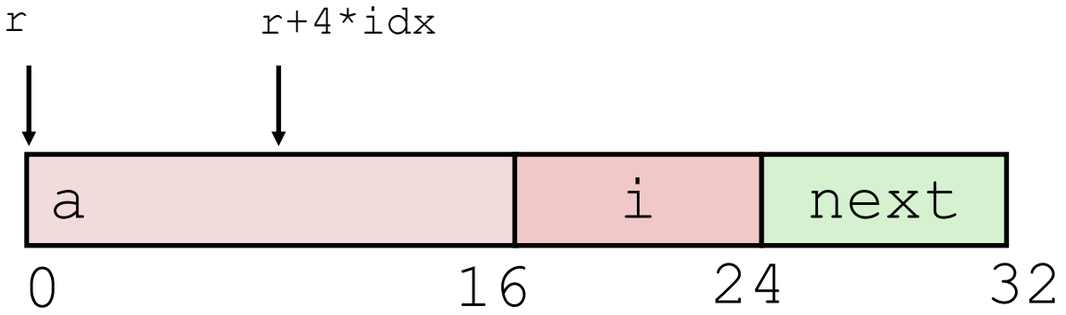
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- Structure represented as block of memory
  - **Big enough to hold all of the fields**
- Fields ordered according to declaration
  - **Even if another ordering could yield a more compact representation**
- Compiler determines overall size + positions of fields
  - **Machine-level program has no understanding of the structures in the source code**

Generating Pointer to Structure Member

```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- Generating Pointer to Array Element
  - Offset of each structure member determined at compile time
  - Compute as **`r + 4*idx`**

```
int *get_ap
  (struct rec *r, size_t idx)
{
  return &r->a[idx];
}
```

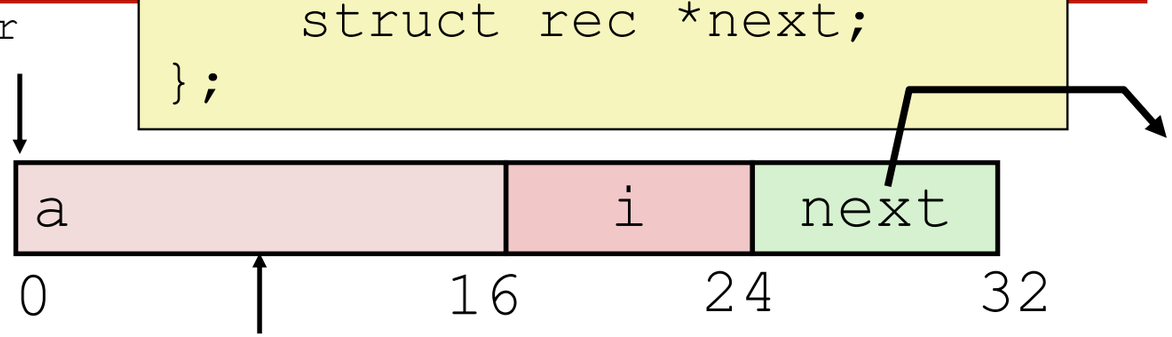
```
  # r in %rdi, idx in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

Following Linked List

```
struct rec {
    int a[4];
    int i;
    struct rec *next;
};
```

- C Code

```
void set_val
  (struct rec *r, int val)
{
  while (r) {
    int i = r->i;
    r->a[i] = val;
    r = r->next;
  }
}
```



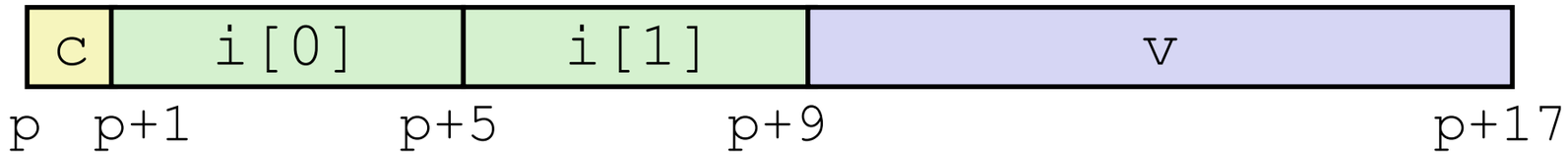
Element i

Register	Value
%rdi	r
%rsi	val

```
.L11:                                  # loop:
  movslq  16(%rdi), %rax               #   i = M[r+16]
  movl    %esi, (%rdi,%rax,4)          #   M[r+4*i] = val
  movq    24(%rdi), %rdi               #   r = M[r+24]
  testq   %rdi, %rdi                   #   Test r
  jne     .L11                         #   if !=0 goto loop
```

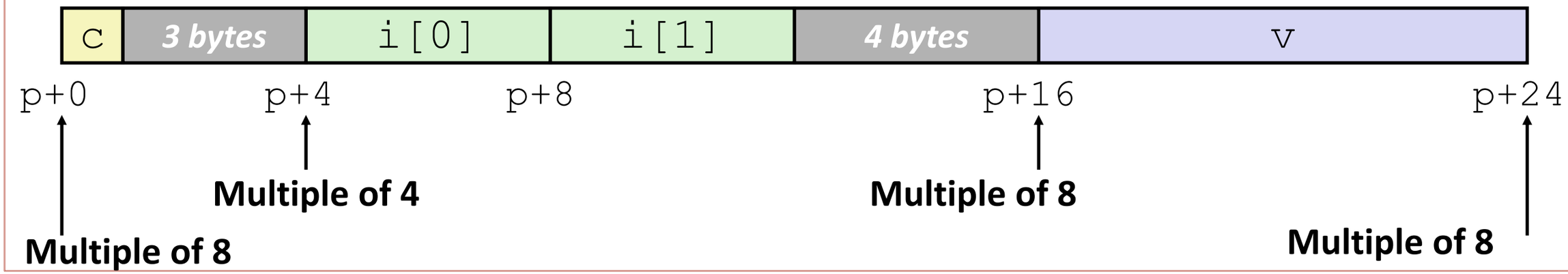
Structures & Alignment

- Unaligned Data




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

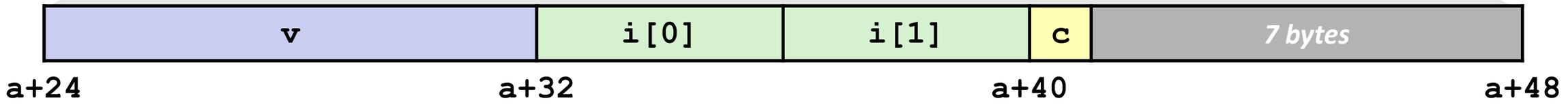
- Aligned Data
  - Primitive data type requires ***K*** bytes
  - Address must be multiple of ***K***
  - Required on some machines; advised on x86-64
  - Motivation: Inefficient to load/store datum that spans word boundaries



Arrays of Structures

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

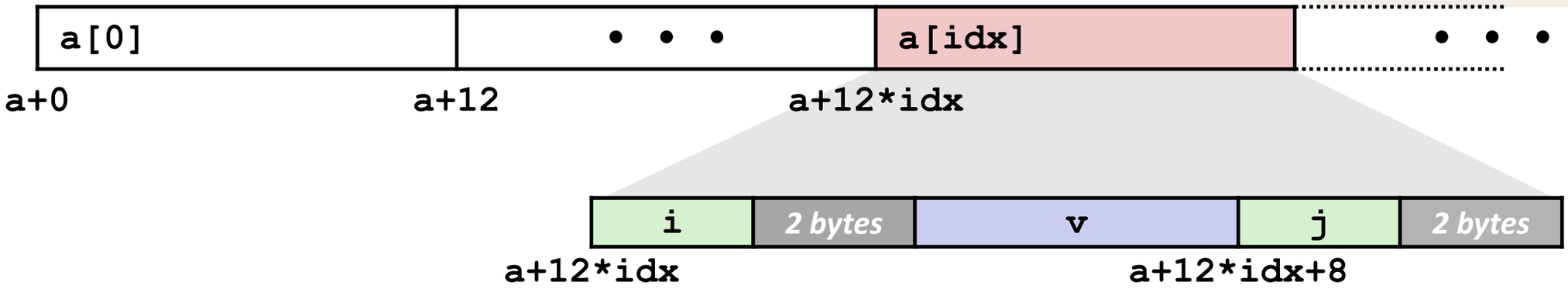
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

- 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

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




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

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

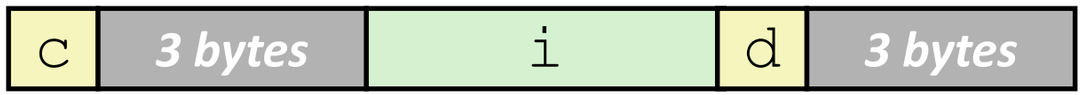
Saving Space

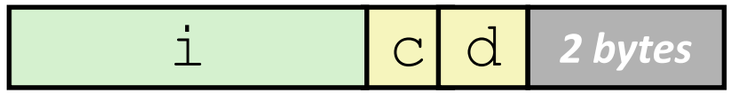
- Put large data types first

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

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

- Effect (K=4)





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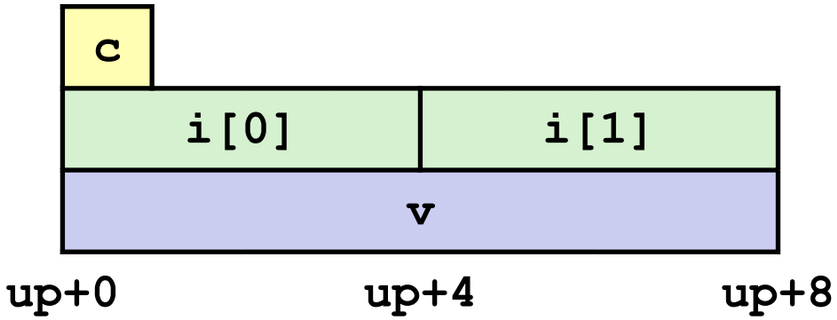
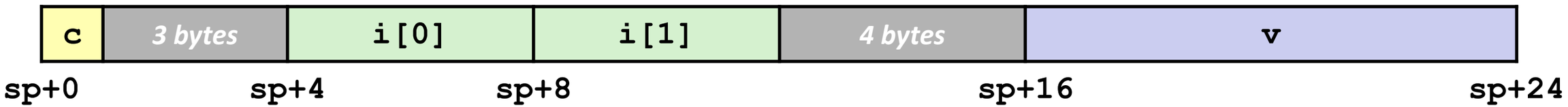
Union Allocation

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

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

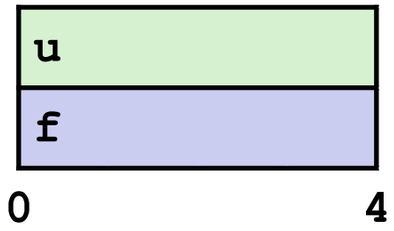



```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```



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;
}
```

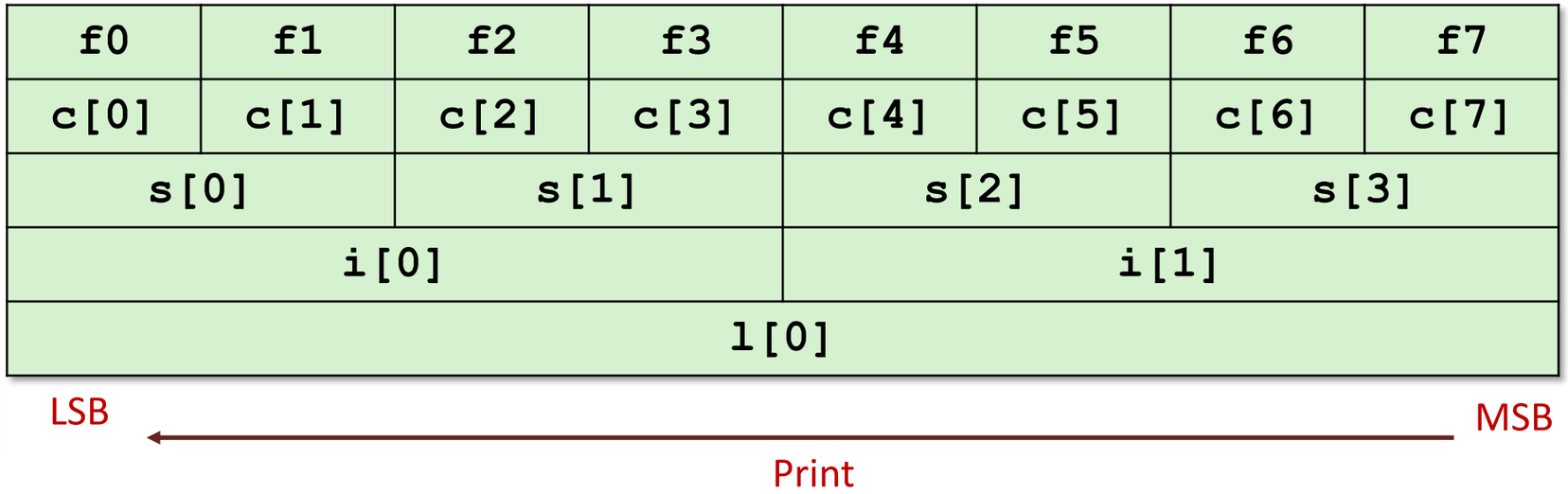
Same as (float) u ?

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

Same as (unsigned) f ?

Byte Ordering Example on x86-64

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



Output on x86-64 (little endian):

```
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]
```

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Background

- History
  - x87 FP
    - Legacy, very ugly
  - SSE FP
    - Supported by Shark machines
    - 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

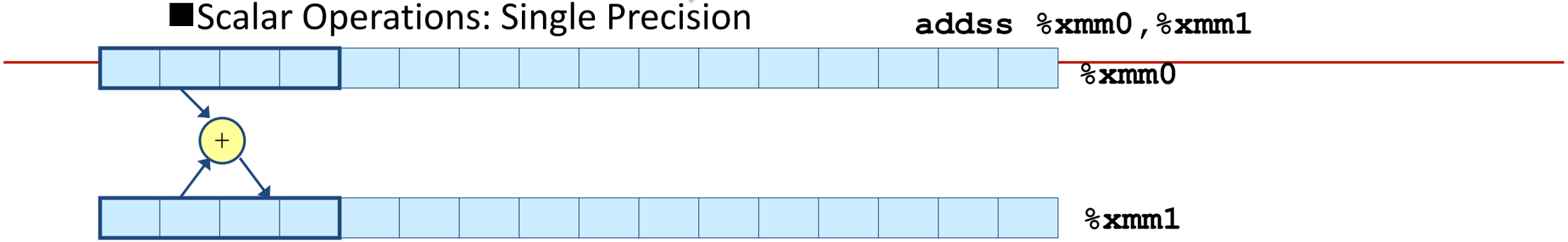
- 2 double-precision floats

- 1 single-precision float

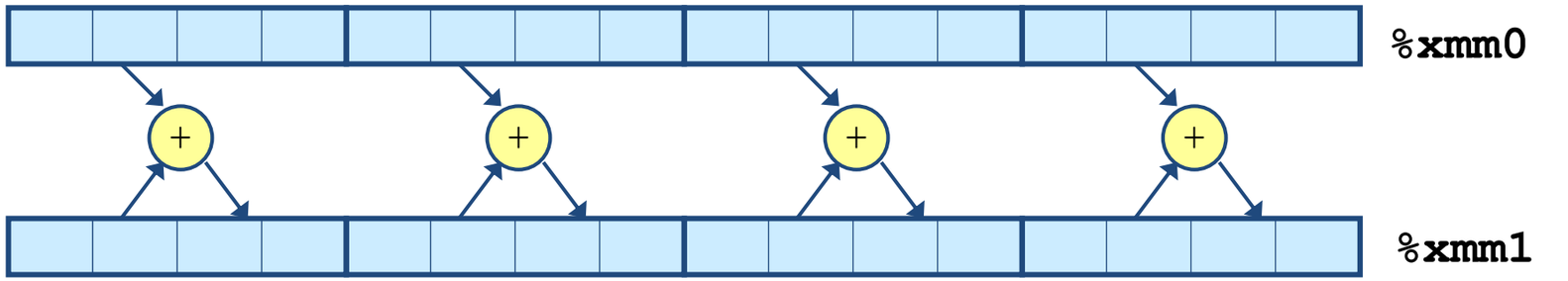
- 1 double-precision float

Scalar & SIMD Operations

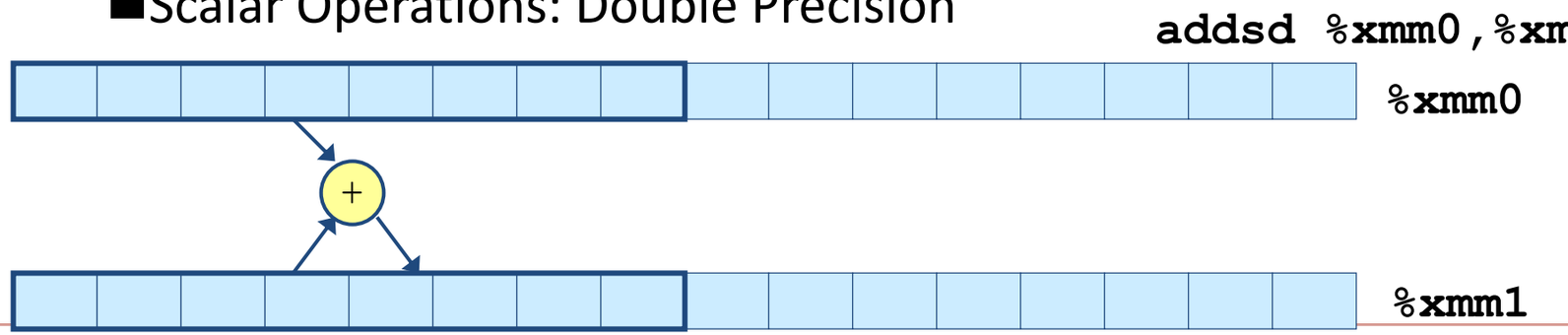
■Scalar Operations: Single Precision



■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
```

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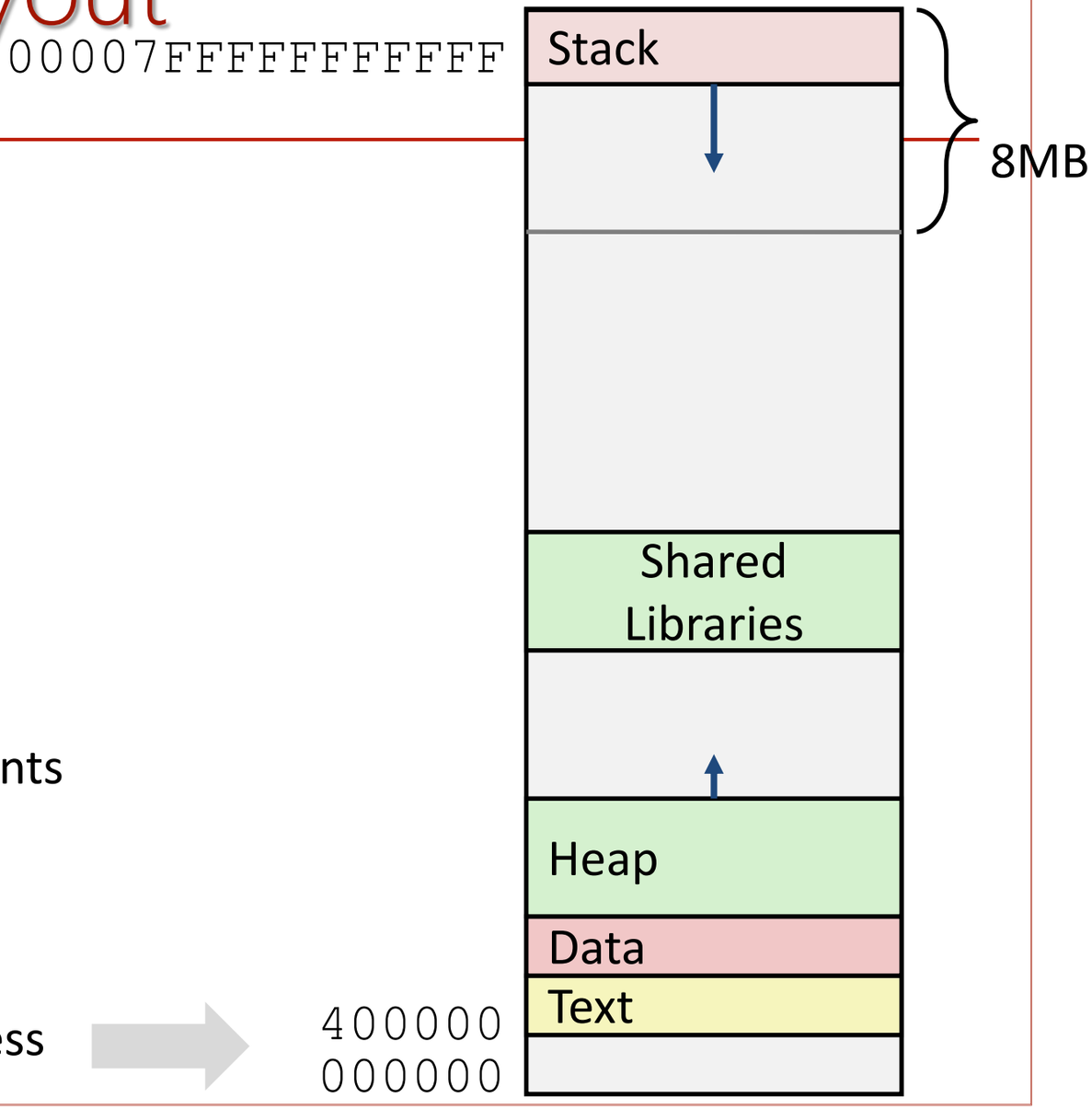
x86-64 Linux Memory Layout

- 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

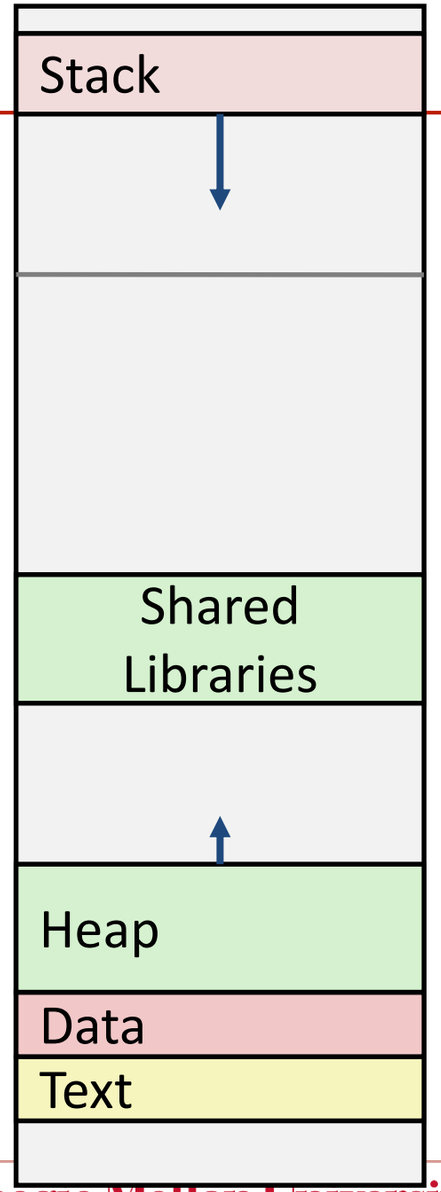
```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

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 ... */
}
```

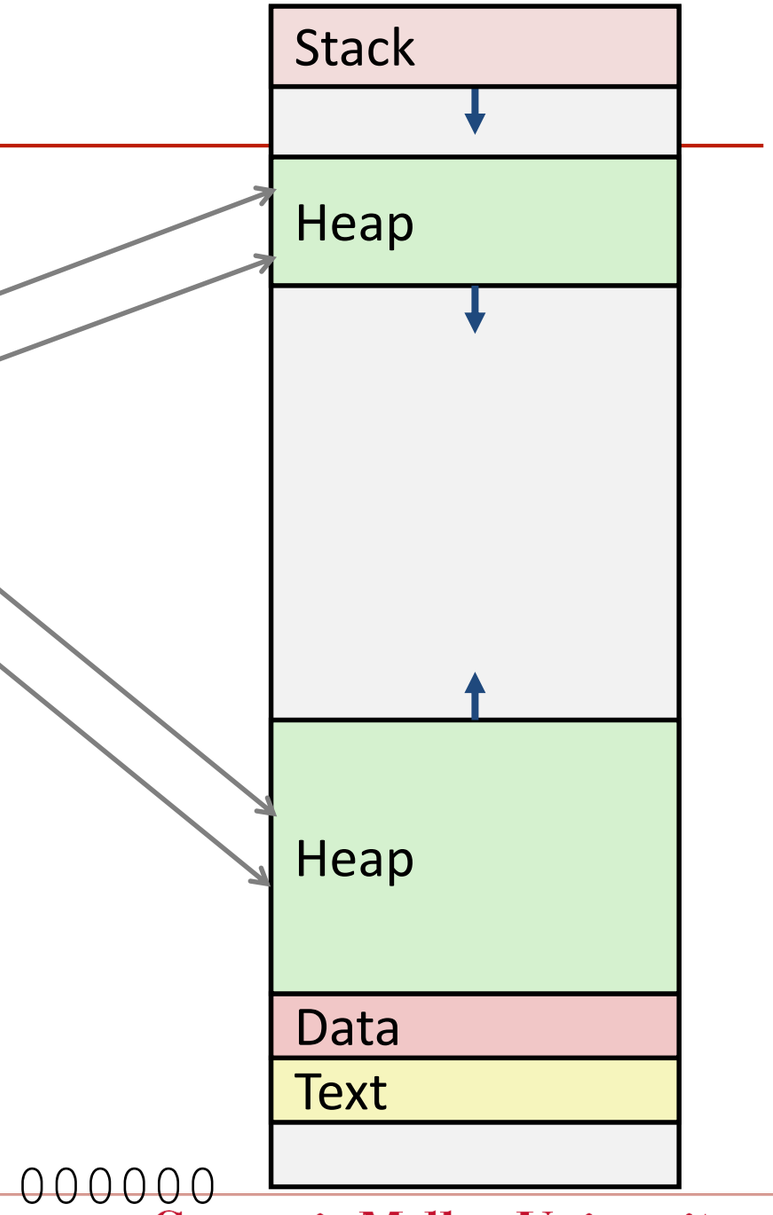
Where does everything go?



x86-64 Example Addresses

address range ~2^{47}

local	0x00007ffe4d3be87c
p1	0x00007f7262a1e010
p3	0x00007f7162a1d010
p4	0x0000000008359d120
p2	0x0000000008359d010
big_array	0x0000000080601060
huge_array	0x0000000000601060
main()	0x000000000040060c
useless()	0x0000000000400590



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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
```

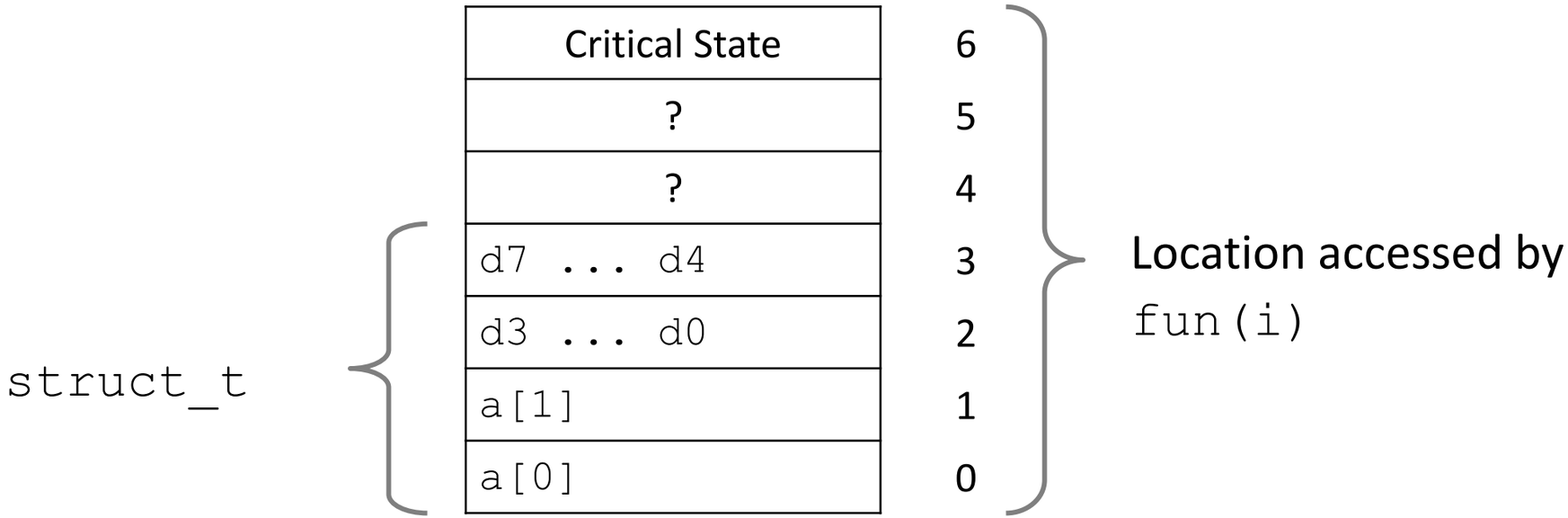
- Result is system specific

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);
}
```

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

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

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012345
Segmentation Fault
```

Buffer Overflow Disassembly

echo:

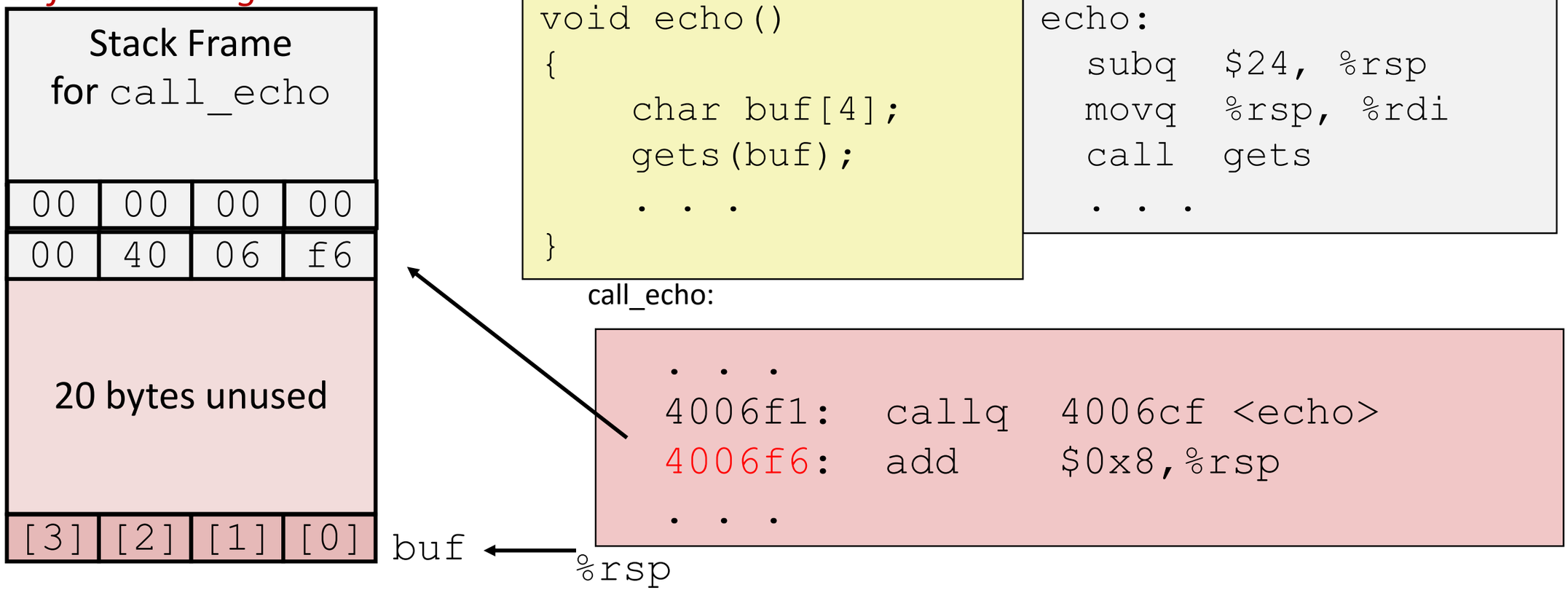
```
00000000004006cf <echo>:
 4006cf:  48 83 ec 18           sub    $0x18,%rsp
 4006d3:  48 89 e7              mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff        callq  400680 <gets>
 4006db:  48 89 e7              mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff        callq  400520 <puts@plt>
 4006e3:  48 83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

Before call to gets



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
   . . .
```

Overflowed buffer, but did not corrupt state

```
unix>./bufdemo-nsp
Type a string:0123456789012345678901 2
0123456789012345678901 2
```

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
   . . .
```

Overflowed buffer and corrupted return pointer

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

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 ←

```
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
   . . .
```

%rsp

```
unix>./bufdemo-nsp
Type a string:0123456789012345678901 23
0123456789012345678901 23
```

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

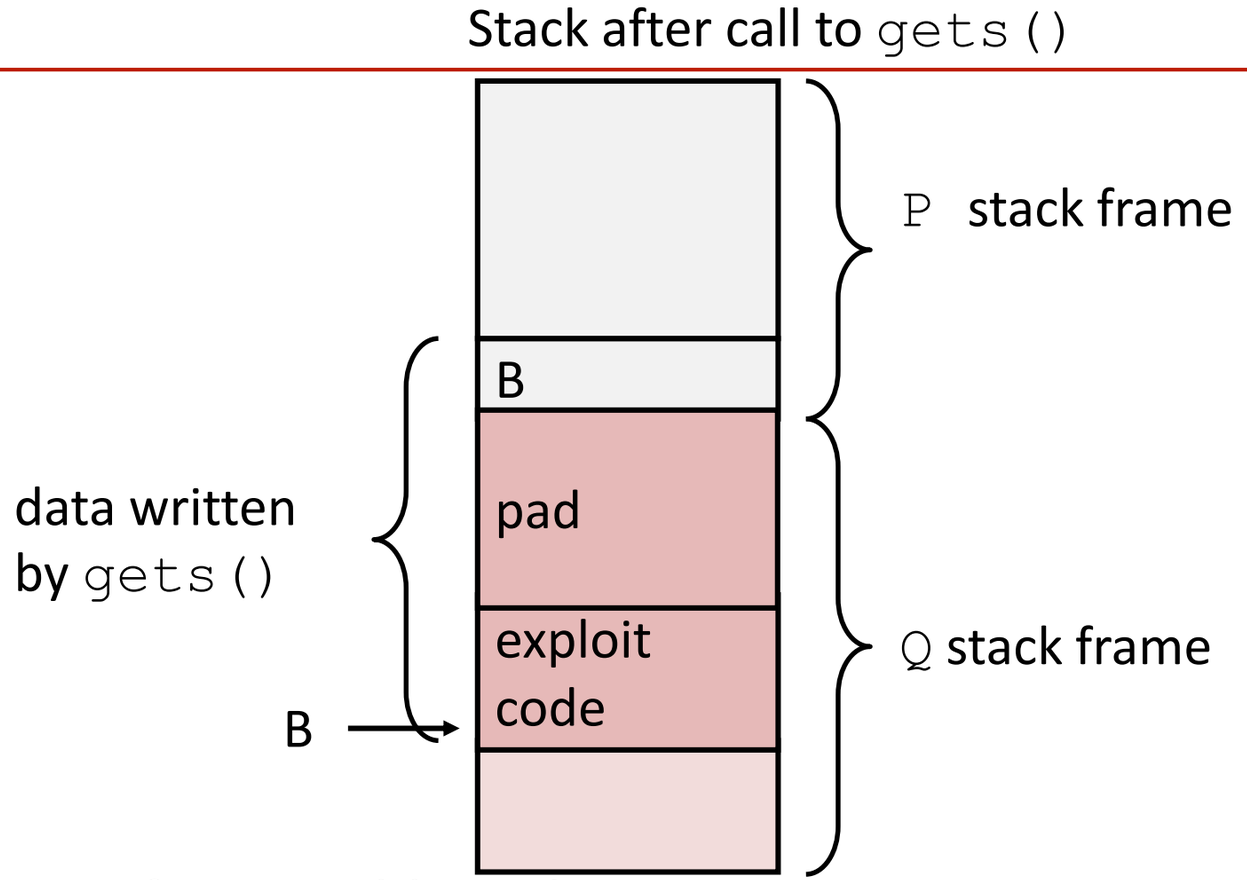
But "Returns" to unrelated code

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

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 (!)

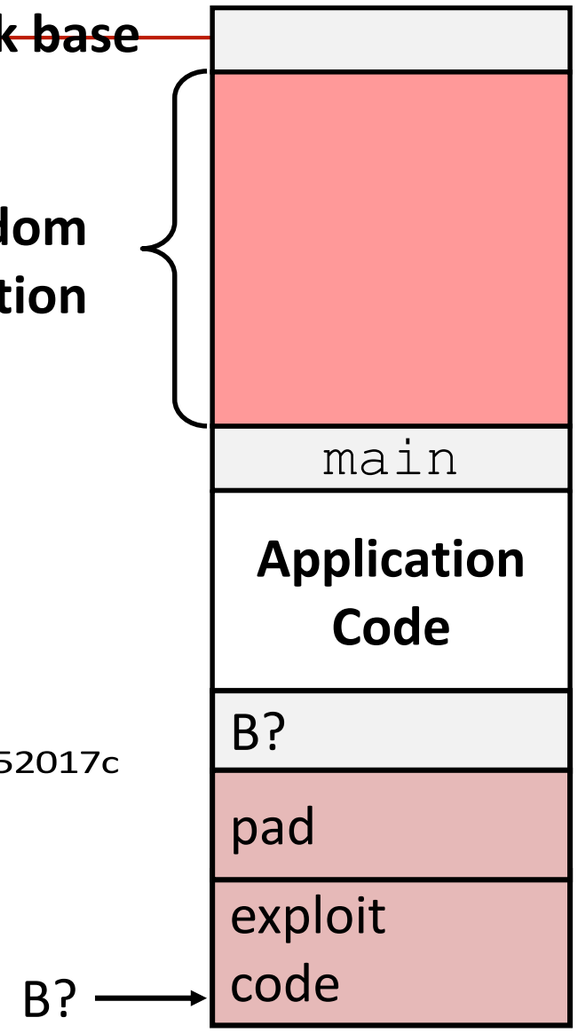
```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

- 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

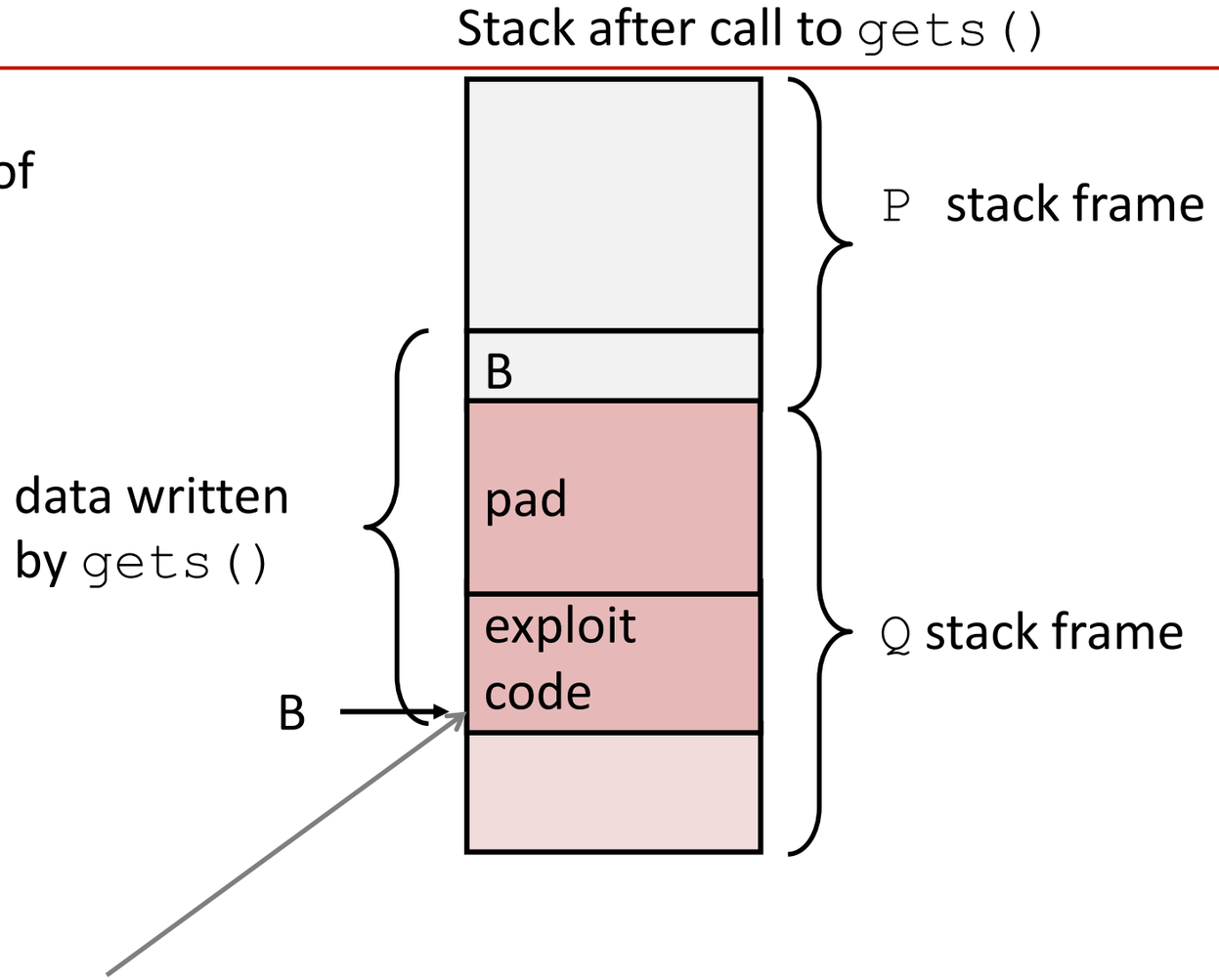
- Randomized stack offsets
  - At start of program, allocate random amount of space on stack
  - Shifts stack addresses for entire program
  - Makes it difficult for hacker to predict beginning of inserted code
  - E.g.: 5 executions of memory allocation code
    - Stack repositioned each time program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

local	0x7ffe4d3be87c	0x7fff75a4f9fc	0x7ffeadb7c80c	0x7ffeaea2fdac	0x7ffcd452017c



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

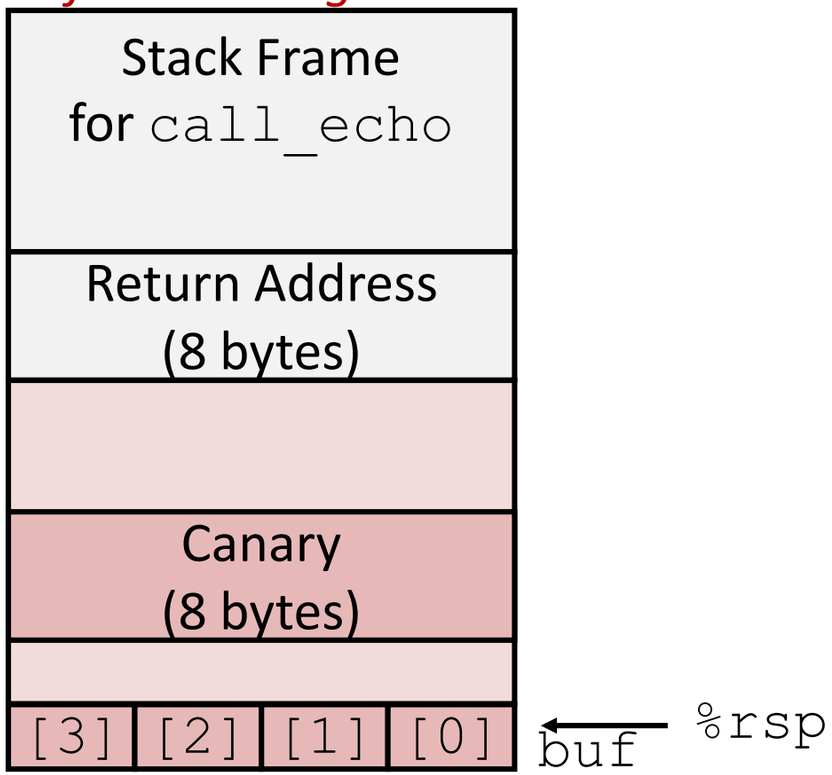
- Idea
  - Place special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function
- GCC Implementation
  - **`-fstack-protector`**
  - Now the default (disabled earlier)

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

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

Setting Up Canary

Before call to gets

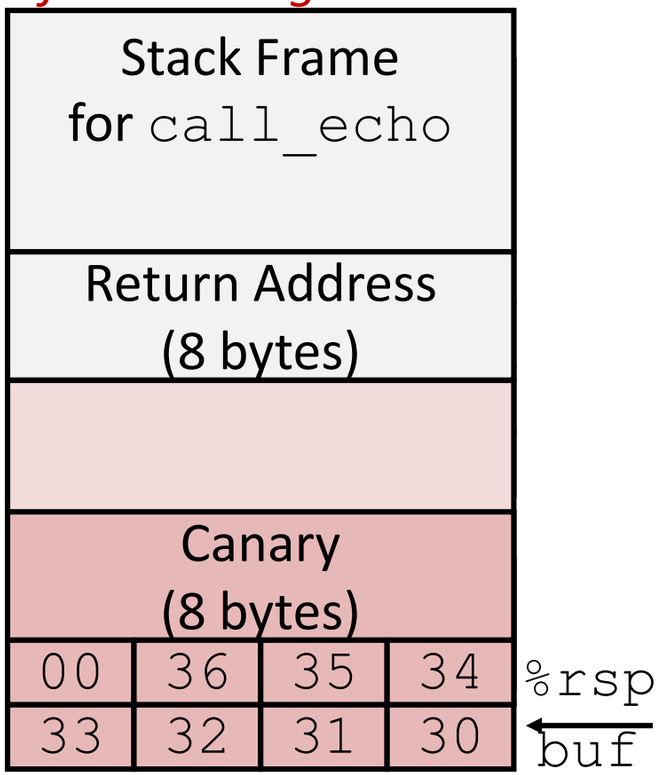



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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:        . . .
```

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
```

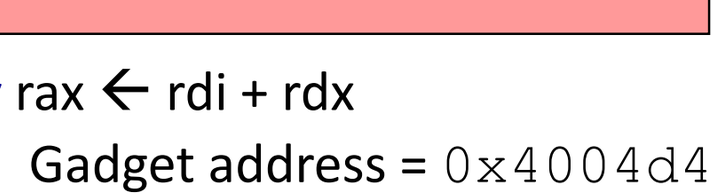
Return-Oriented Programming Attacks

- 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
```



- Use tail end of existing functions

Gadget Example #2

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

Encodes `movq %rax, %rdi`

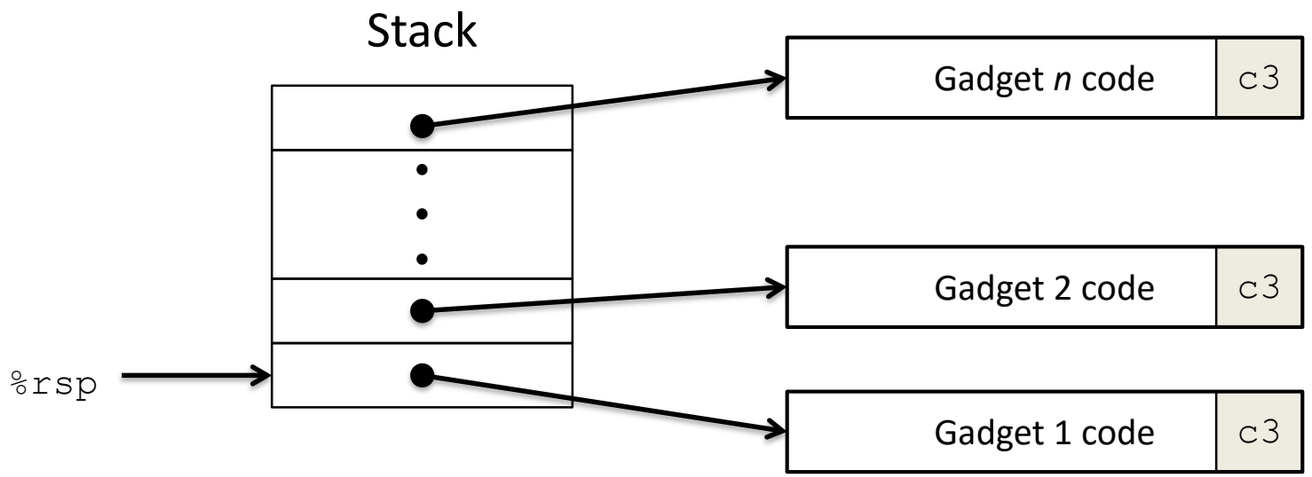
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7   movl   $0xc78948d4,(%rdi)
  4004df:  c3                  retq
```

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

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
- Unions
  - Overlay declarations
  - Way to circumvent type system
- Floating Point
  - Data held and operated on in XMM registers
- "Buffer overflow" exceeds the memory size allocated for an array

18-600 Foundations of Computer Systems

Lecture 8: "Processor Architecture and Design"

John P. Shen & Zhiyi Yu

September 26, 2016

Next Time ...

- Required Reading Assignment:
  - **Chapter 4 of CS:APP (3rd edition) by Randy Bryant & Dave O'Hallaron.**
- Recommended Reference:
  - **Chapters 1 and 2 of Shen and Lipasti (SnL).**

Electrical & Computer ENGINEERING