CSC 252: Computer Organization
Spring 2020: Lecture 9

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Announcement

- Programming assignment 2 is DUE SOON
  - Details: https://www.cs.rochester.edu/courses/252/spring2020/labs/assignment2.html
  - Due on **Feb. 14**, 11:59 PM
  - You (may still) have 3 slip days

2	3	4	5	6	7	8
9	10	11	12	13 **Today**	14 **Due**	15

Announcement

- A problem set for arithmetics: http://www.cs.rochester.edu/courses/252/spring2020/handouts.html
- Not to be turned in
- Form study groups

Announcement

- Programming assignment 2 is in x86 assembly language. Seek help from TAs.
- TAs are best positioned to answer your questions about programming assignments!!!
- Programming assignments do NOT repeat the lecture materials. They ask you to synthesize what you have learned from the lectures and work out something new.

Managing Function Local Variables

- Two ways: registers and memory (stack)
- Registers are faster, but limited. Memory is slower, but large. Smart compilers will optimize the usage.

```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

Register Saving Conventions

Register Saving Conventions

- Any issue with using registers for temporary storage?

Caller

```
yoo:
    …
    movq $15213, %rdx
    call who
    addq %rdx, %rax
    …
    ret
```

Callee

```
who:
    …
    subq $18213, %rdx
    …
    ret
```

Register Saving Conventions

- Any issue with using registers for temporary storage?
  - Contents of register **`%rdx`** overwritten by **`who()`**

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yoo:
    …
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Callee

```
who:
    …
    subq $18213, %rdx
    …
    ret
```

Register Saving Conventions

- Any issue with using registers for temporary storage?
  - Contents of register **`%rdx`** overwritten by **`who()`**
  - This could be trouble ➙ Need some coordination

Caller

```
yoo:
   …
   movq $15213, %rdx
   call who
   addq %rdx, %rax
   …
   ret
```

Callee

```
who:
   …
   subq $18213, %rdx
   …
   ret
```

Register Saving Conventions

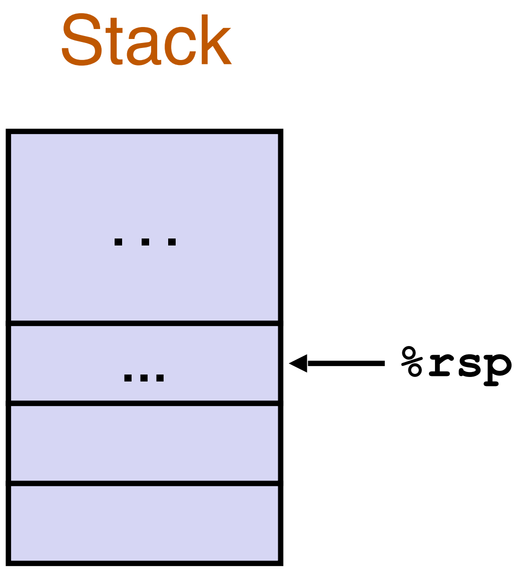
- Common conventions
  - "*Caller Saved*"
    - Caller saves temporary values in its frame (on the stack) before the call
    - Callee is then free to modify their values
  - "*Callee Saved*"
    - Callee saves temporary values in its frame before using
    - Callee restores them before returning to caller
    - Caller can safely assume that register values won't change after the function call

Register Saving Conventions

- Conventions used in x86-64 (*Part of the Calling Conventions*)
  - Some registers are saved by caller, some are by callee.
  - Caller saved: `%rdi,%rsi,%rdx,%rcx,%r8,%r9,%r10,%r11`
  - Callee saved: `%rbx,%rbp,%r12,%r13,%14,%r15`
  - `%rax` holds return value, so implicitly caller saved
  - `%rsp` is the stack pointer, so implicitly callee saved

Example

```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```



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call_incr2:
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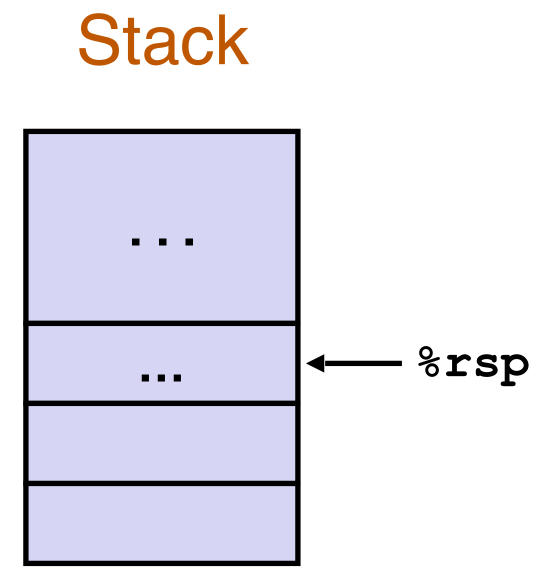
  movq     %rdi, %rbx
  movl     $3000, %esi
  leaq     (%rsp), %rdi
  call     incr
  addq     %rbx, %rax
  addq     $8, %rsp
  popq     %rbx
  ret
```



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```
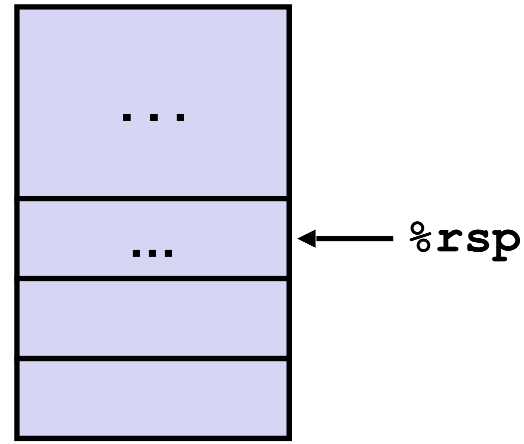

Stack



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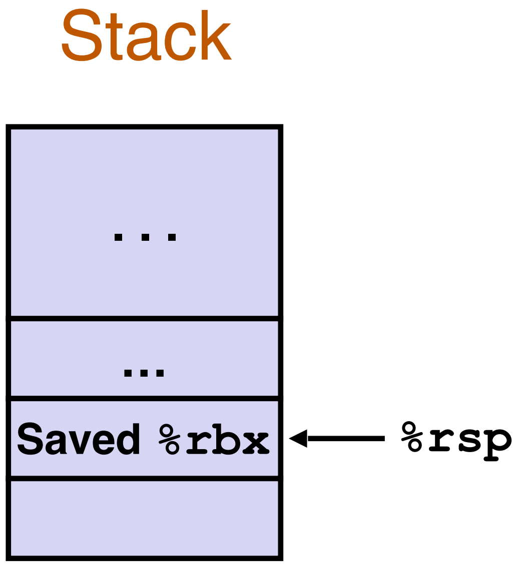

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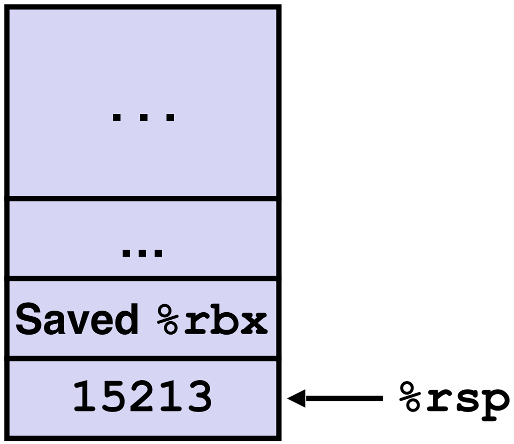

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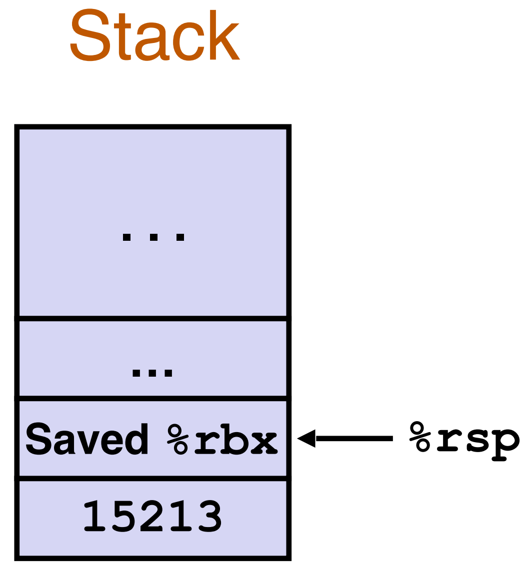

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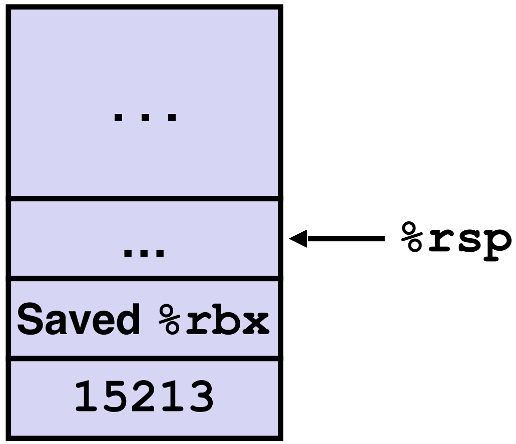

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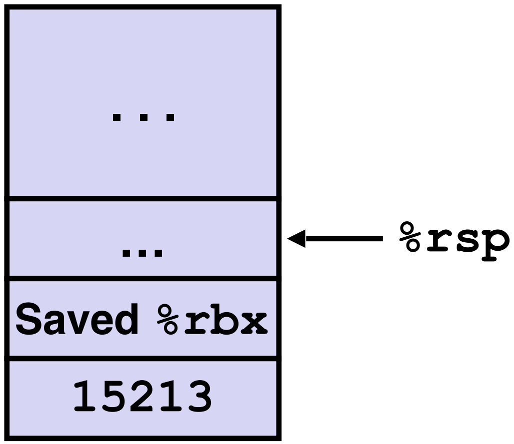
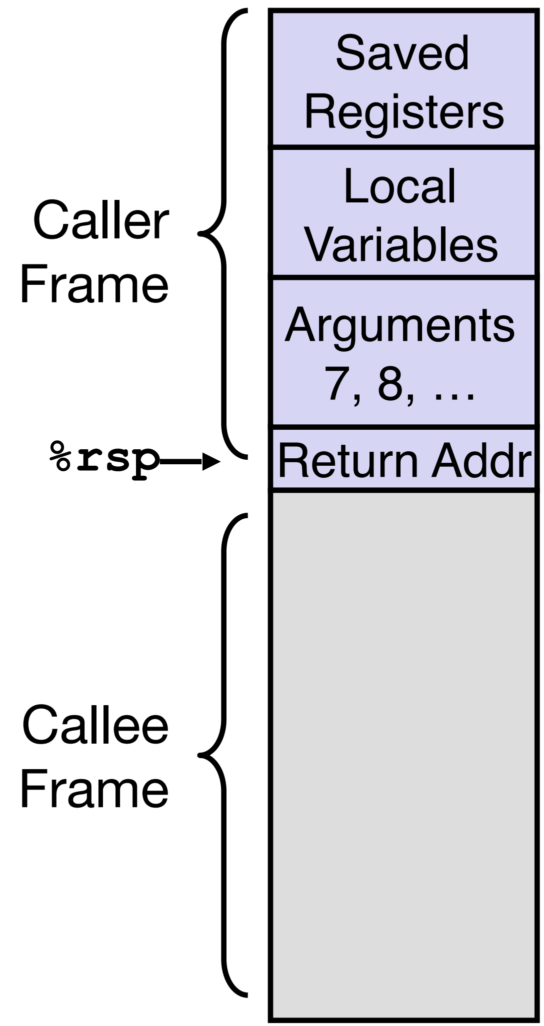


- `call_incr2` needs to save `%rbx` (callee-saved) because it will modify its value
- It can safely use `%rbx` after `call incr` because `incr` will have to save `%rbx` if it needs to use it (again, `%rbx` is callee saved)

Stack Frame: Putting It Together



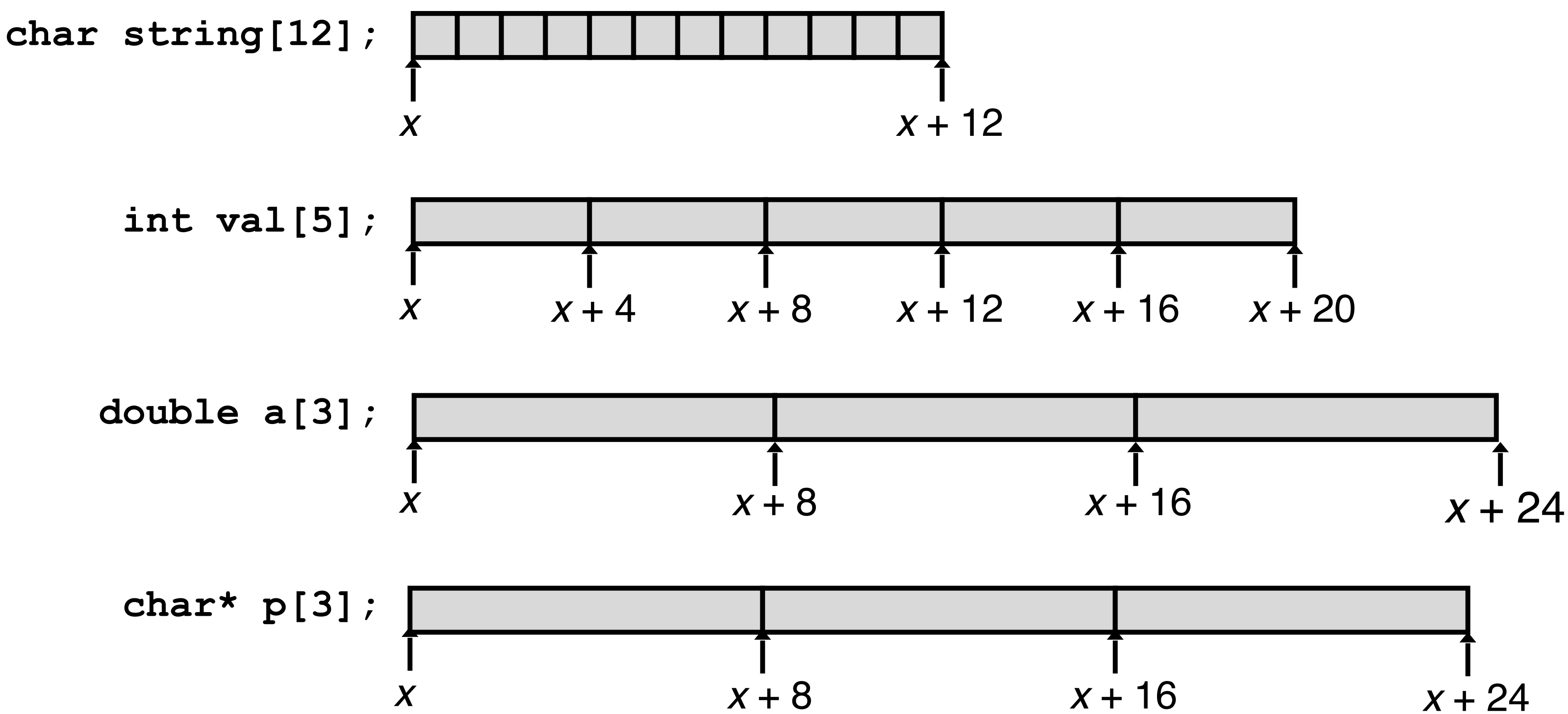
Today: Data Structures and Buffer Overflow

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

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



Byte Ordering

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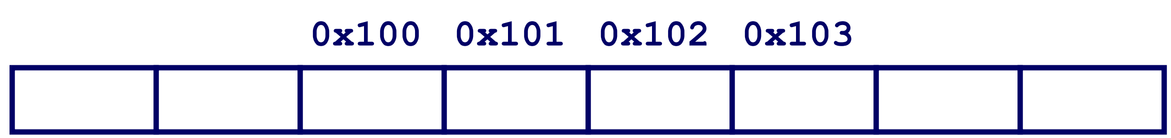
  - Variable x has 4-byte value of 0x01234567
  - Address given by &x is 0x100



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  - Variable x has 4-byte value of 0x01234567
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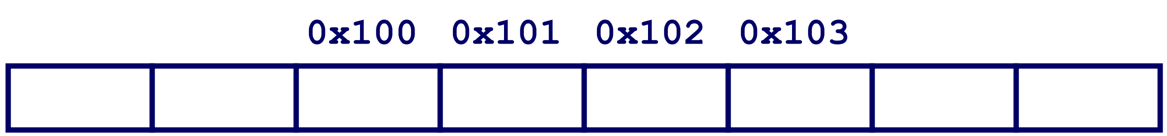
- Conventions
  - **Big Endian**: Sun, PPC Mac, IBM z, Internet
    - Most significant byte has lowest address (MSB first)
  - **Little Endian**: x86, ARM
    - Least significant byte has lowest address (LSB first)



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Big Endian

		0x100	0x101	0x102	0x103		
		01	23	45	67		

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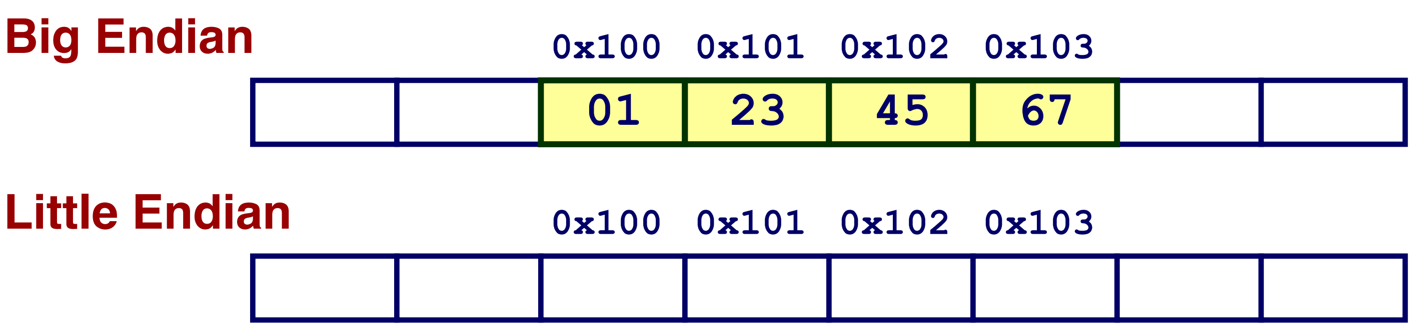

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		0x100	0x101	0x102	0x103		
		01	23	45	67		

Little Endian

		0x100	0x101	0x102	0x103		
		67	45	23	01		

Representing Integers

Hex: `00003B6D`

```
int A = 15213;
```

Address Increase

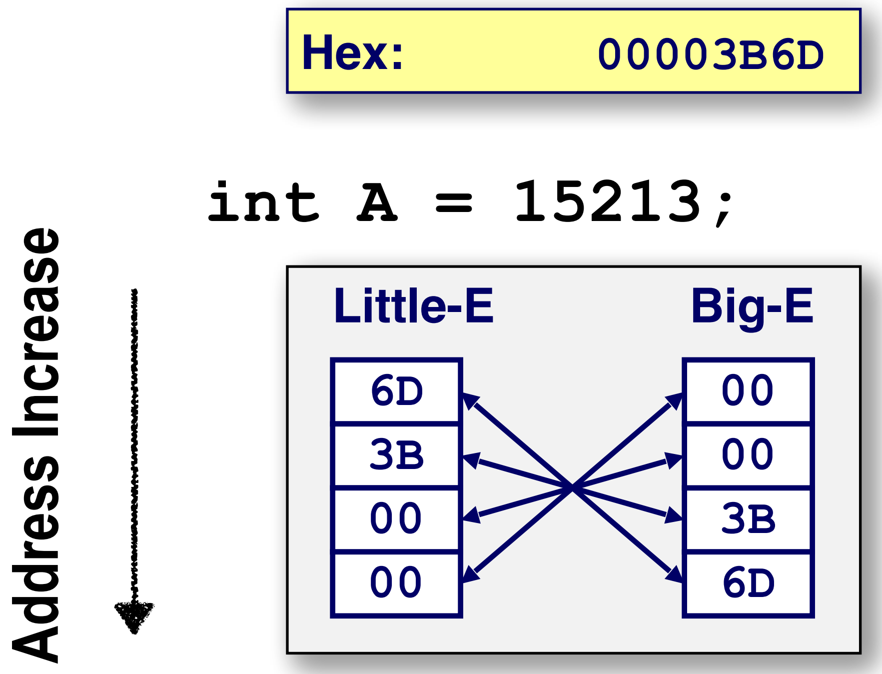
Little-E	Big-E
6D	00
3B	00
00	3B
00	6D

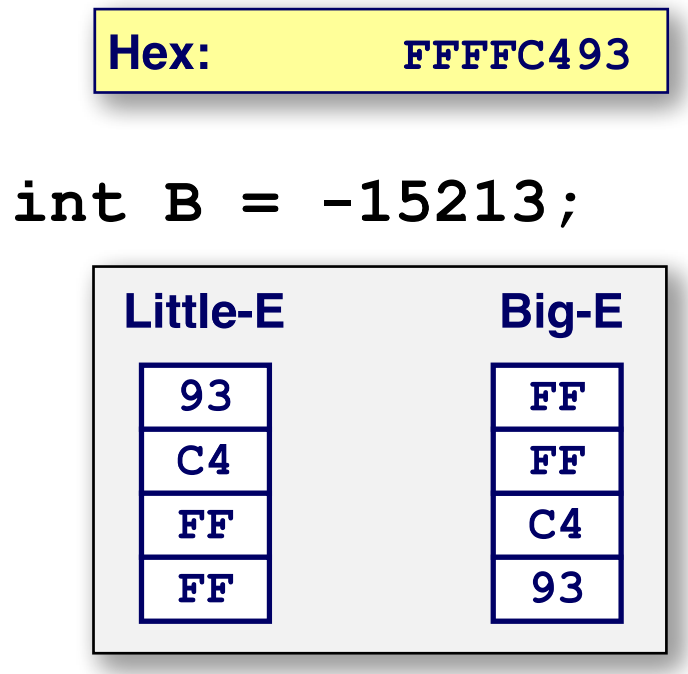
Hex: `FFFFC493`

```
int B = -15213;
```

Little-E	Big-E
93	FF
C4	FF
FF	C4
FF	93

Representing Integers





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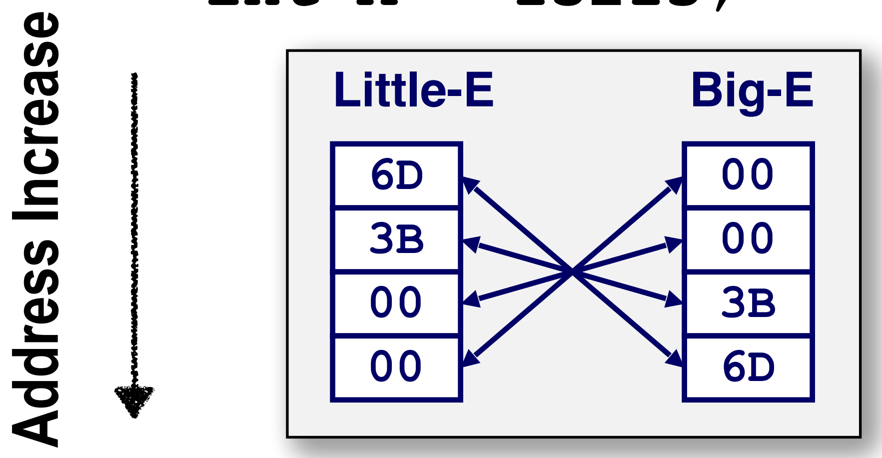

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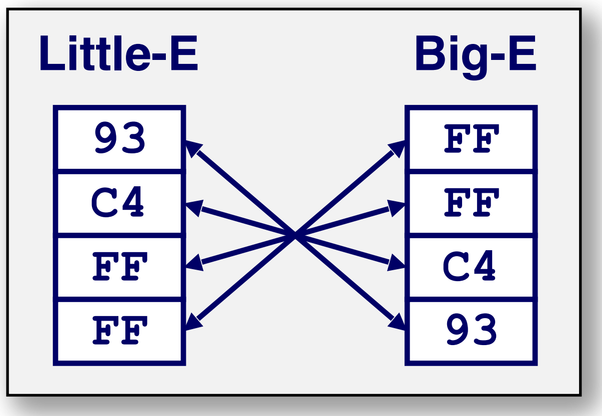


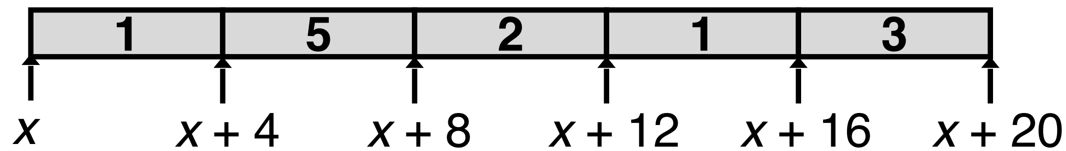
Array Access: Basic Principle

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];`

address



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

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- Declaration

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

  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes

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

Multidimensional (Nested) Arrays

- Declaration

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

  - 2D array of data type *T*
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- Array Size
  - *R* * *C* * *K* bytes

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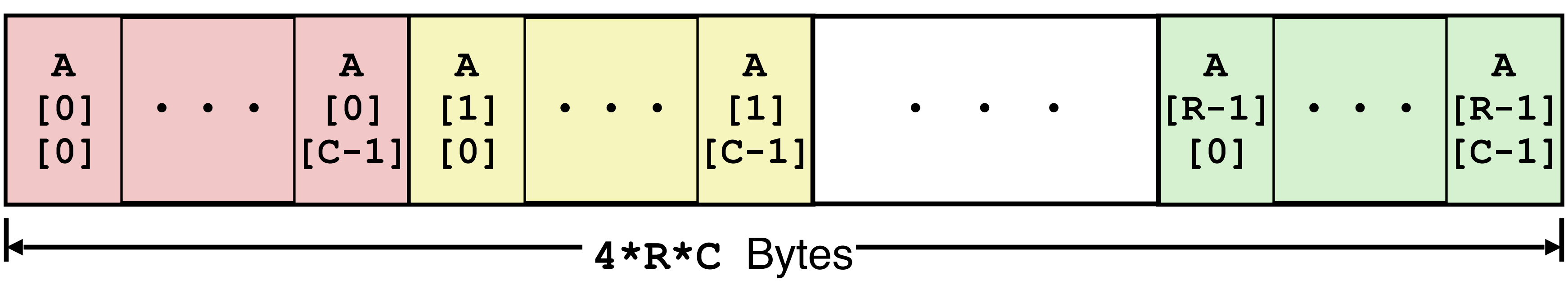
- Array Size
  - *R* * *C* * *K* bytes
- Arrangement
  - Row-Major Ordering in most languages, including C

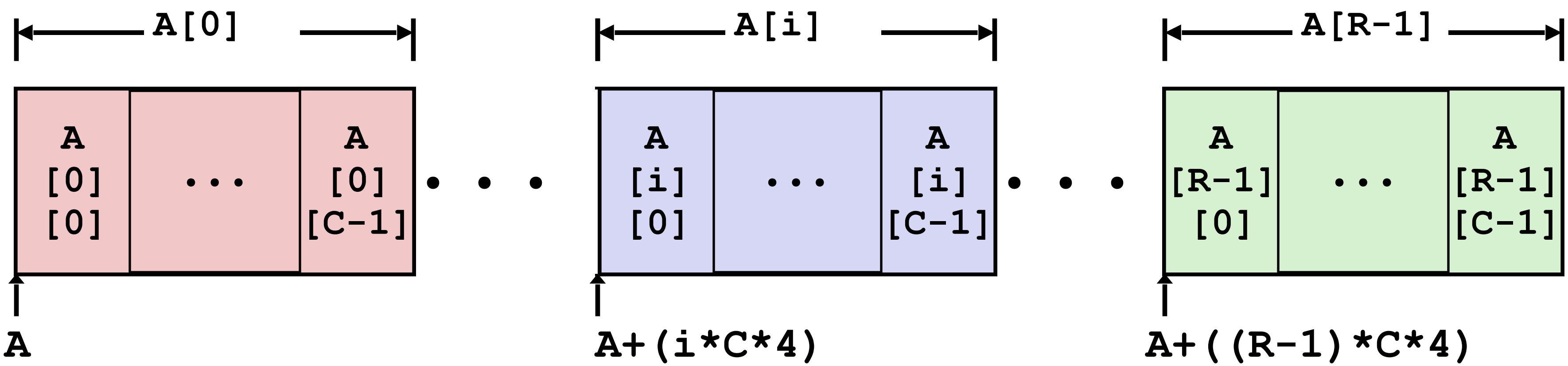
```
int A[R][C];
```



Nested Array Row Access

- T **`A`**[R][C]**`;`**
  - **`A[i]`** is array of *C* elements
  - Each element of type T requires K bytes
  - Starting address A + i * (C * K)

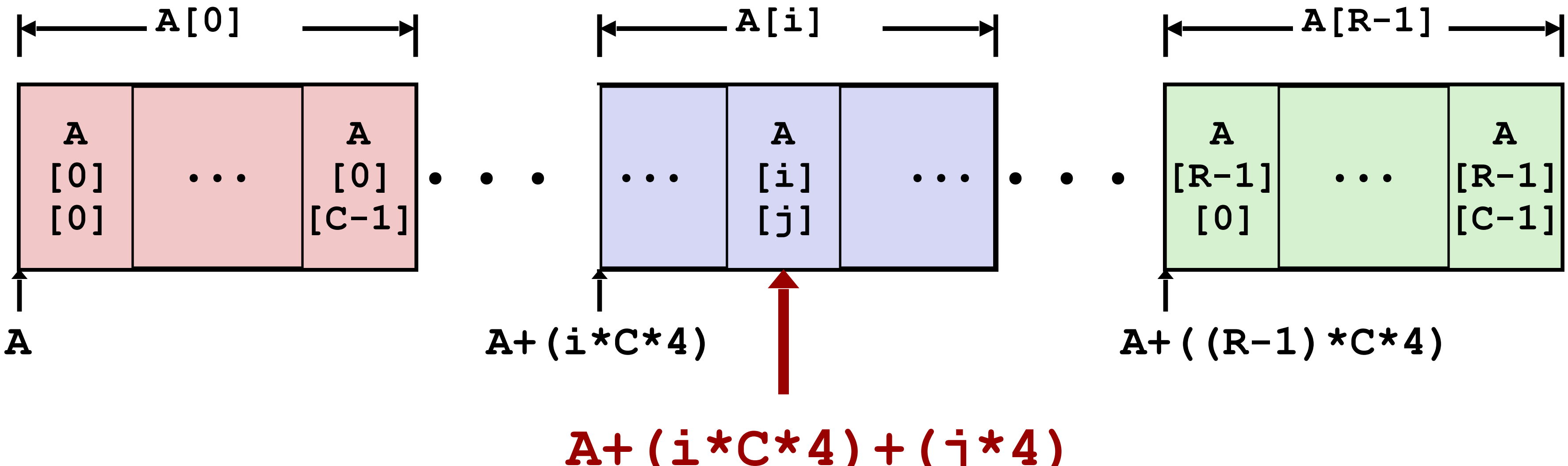
`int A[R][C];`



Nested Array Element Access

- 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];`

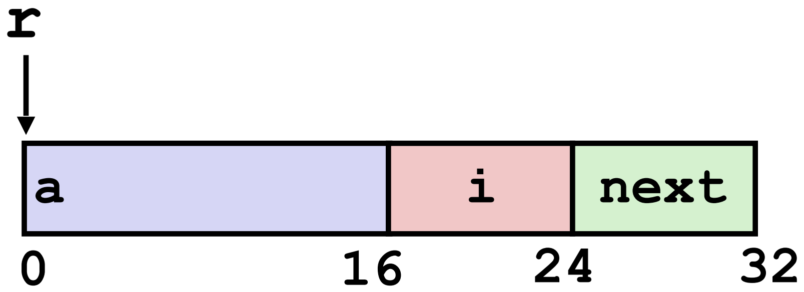


Today: Data Structures and Buffer Overflow

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

Structures

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



- Characteristics
  - Contiguously-allocated region of memory
  - Refer to members within struct by names
  - Members may be of different types

Structures

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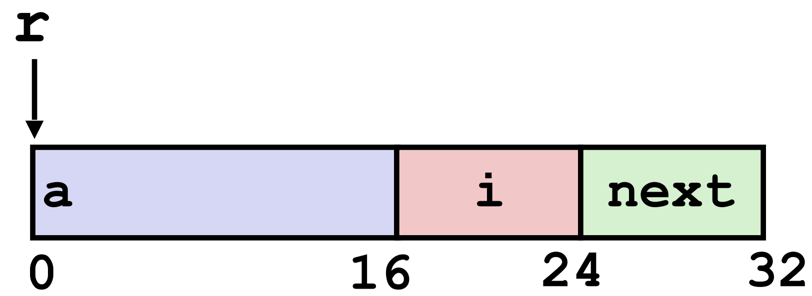
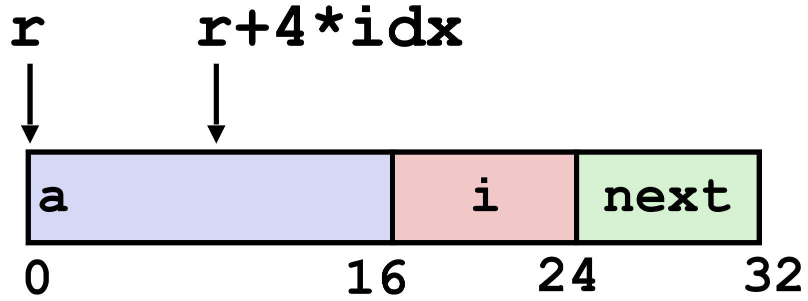


- Accessing struct member
  - Given a struct, we can use the `.` operator:
    - `struct rec r1; r1.i = val;`
  - Suppose we have a struct `r1`, and we have a pointer `r` pointing to it. How to access `r1`'s member with `r`?
    - Using `*` and `.` operators: `(*r).i = val;`
    - Or simply, the -> operator for short: `r->i = val;`

Generating Pointer to Structure Member

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



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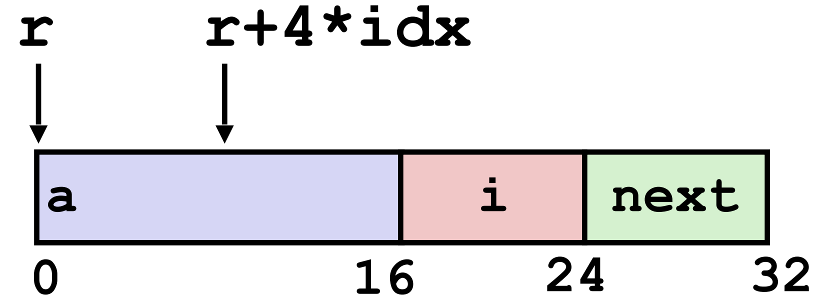


```
int *get_ap
 (struct rec *r, size_t idx)
{
  return &(r->a[idx]);
}
```

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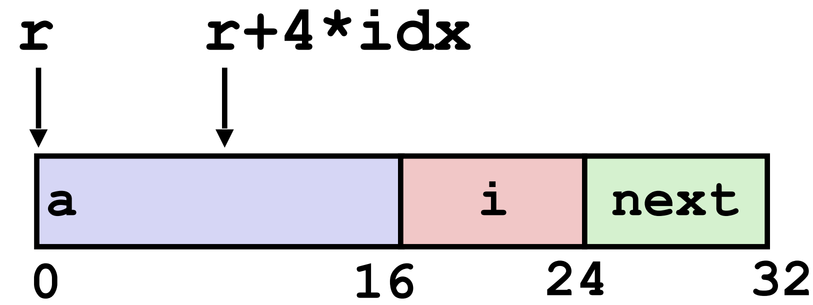


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int *get_ap
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```
&((*r).a[idx])
```

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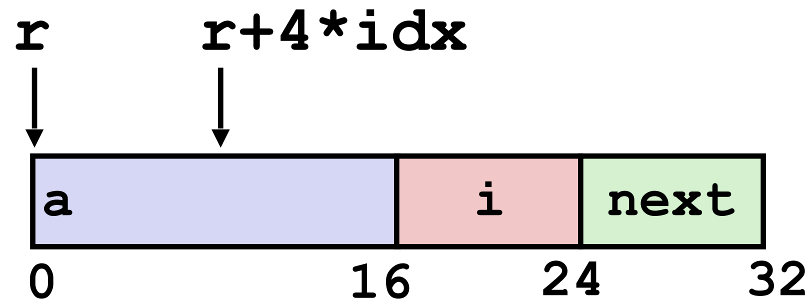



```
int *get_ap
 (struct rec *r, size_t idx)
{
  return &(r->a[idx]);
}
```

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

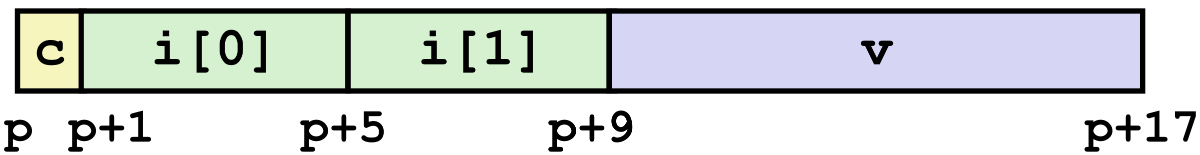
```
&((*r).a[idx])
```

Alignment

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

Alignment

- Unaligned Data

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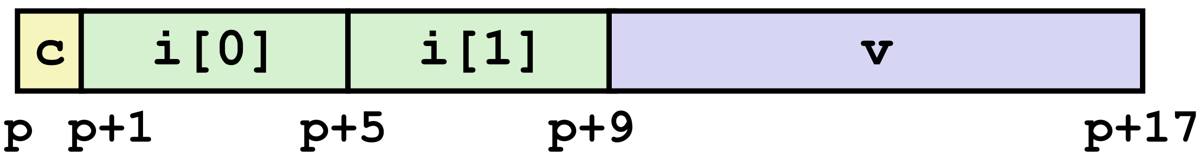


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- Aligned Data
  - If the data type requires ***K*** bytes, address must be multiple of ***K***

Alignment

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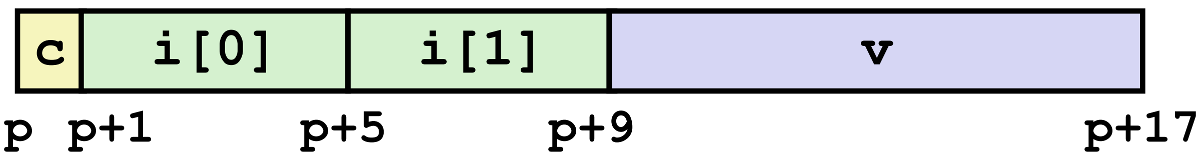
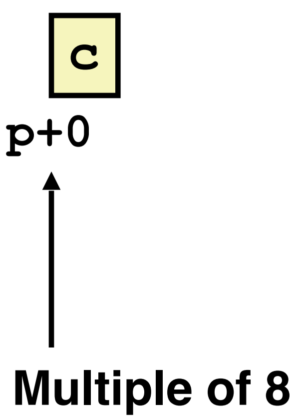
```

- Unaligned Data

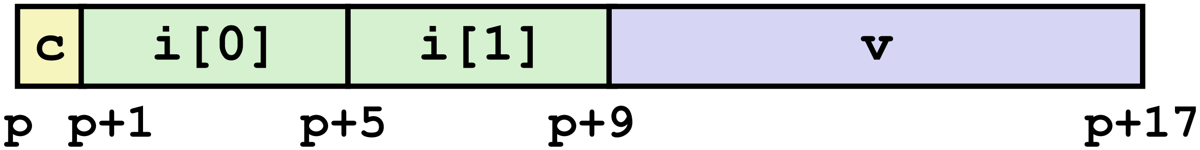


- Aligned Data
  - If the data type requires ***K*** bytes, address must be multiple of ***K***



Alignment

- Unaligned Data




```
struct S1 {
  char c;
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  double v;
} *p;
```

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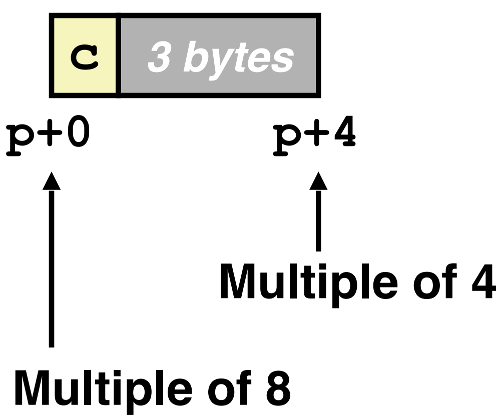

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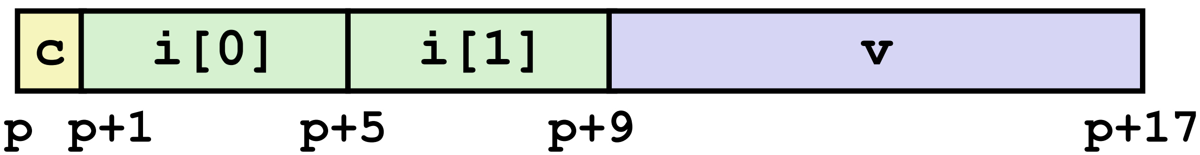


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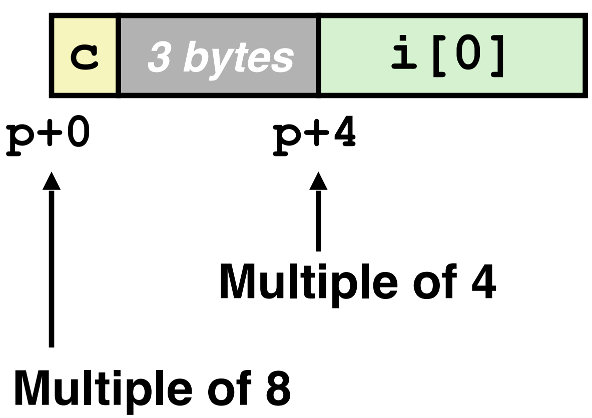

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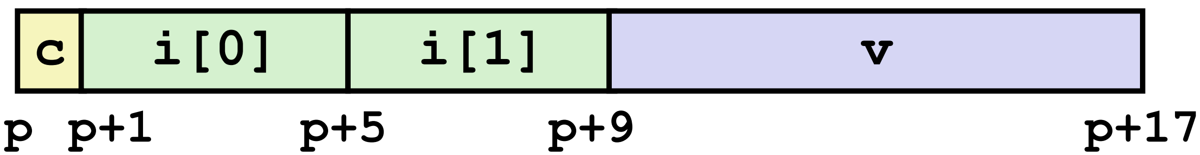


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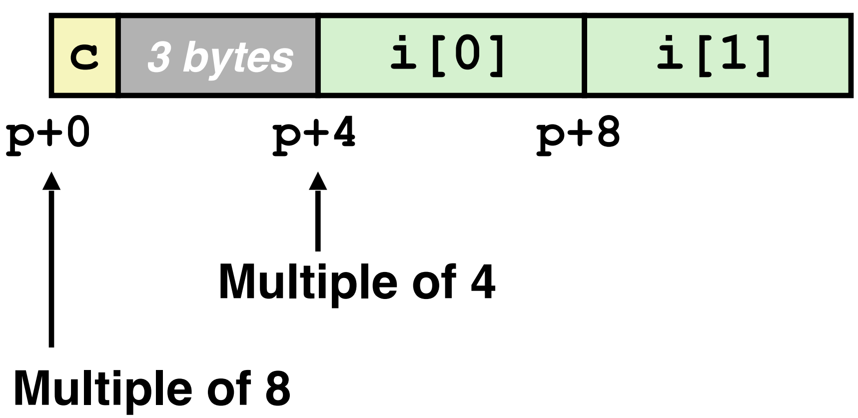

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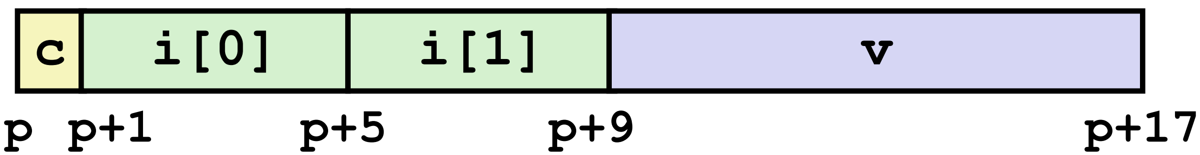

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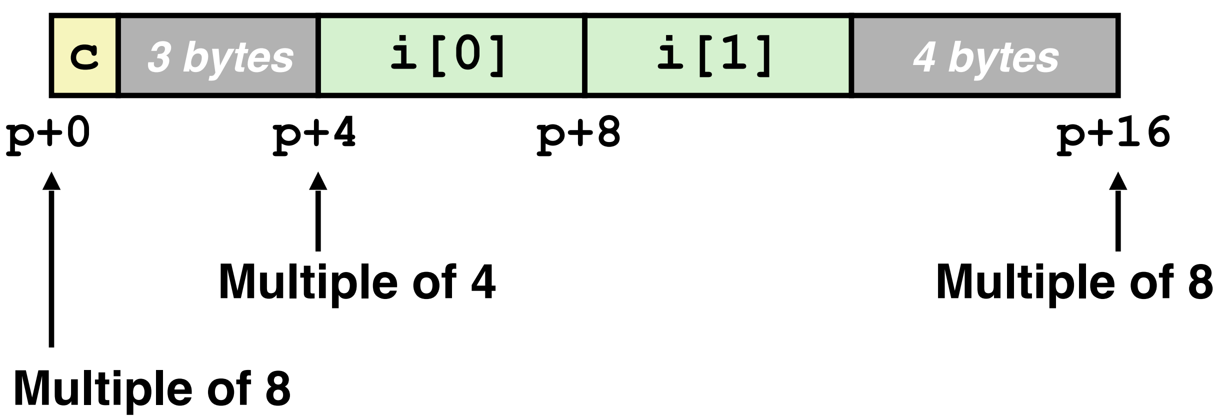

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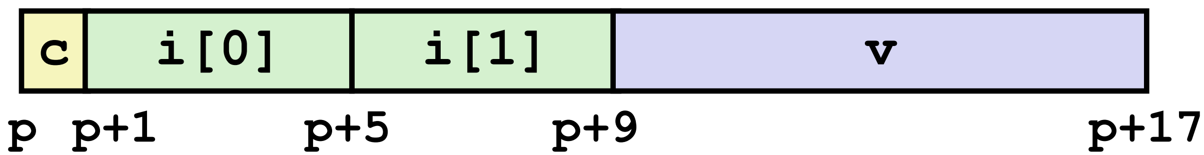


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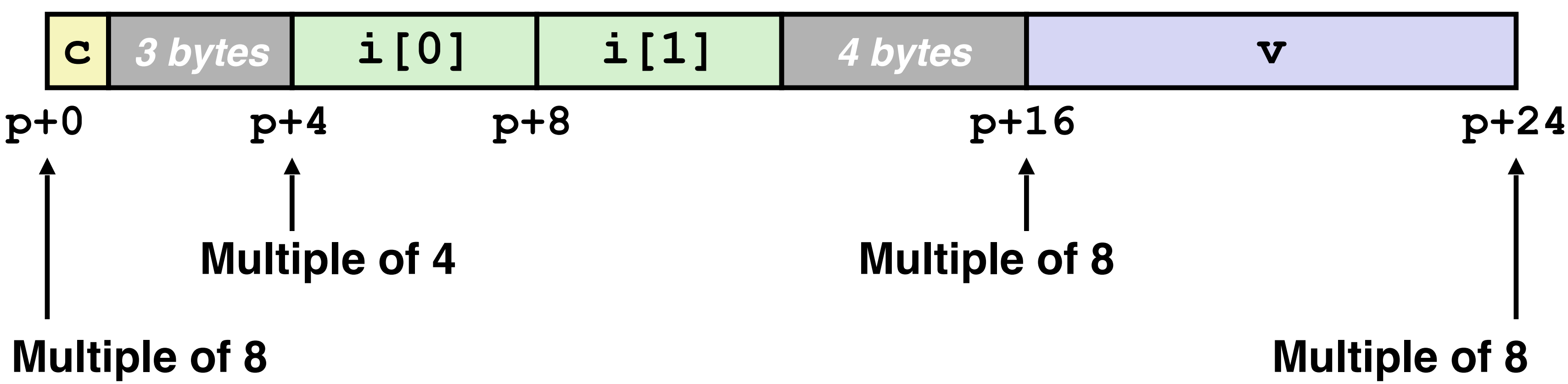

Alignment Principles

- Aligned Data
  - If the data type requires K bytes, address must be multiple of K
- Required on some machines; advised on x86-64
- Motivation for Aligning Data: Performance
  - Inefficient to load or store data that is unaligned
  - Some machines don't event support unaligned memory access
- Compiler
  - Inserts gaps in structure to ensure correct alignment of fields
  - `sizeof()` returns the actual size of structs (i.e., including padding)

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

Satisfying Alignment with Structures

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- Within structure:
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  - Structure length must be multiples of **K**, where:
    - **K** = Largest alignment of any element
  - **WHY?!**

Satisfying Alignment with Structures

- Within structure:
  - Must satisfy each element's alignment requirement
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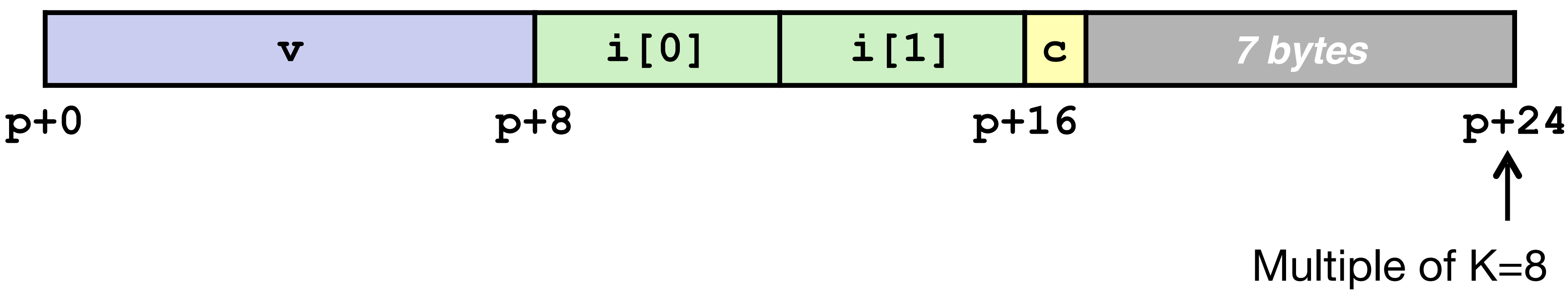
  - Structure length must be multiples of **K**, where:
    - **K** = Largest alignment of any element
  - **WHY?!**

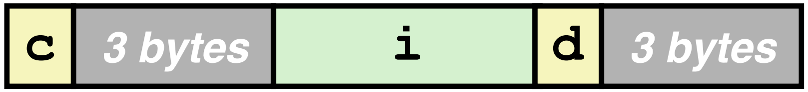
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



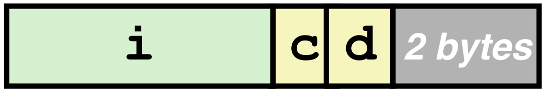
Saving Space

- Put large data types first in a Struct
- This is not something that a C compiler would always do
    - But knowing low-level details empower a C programmer to write more efficient code

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



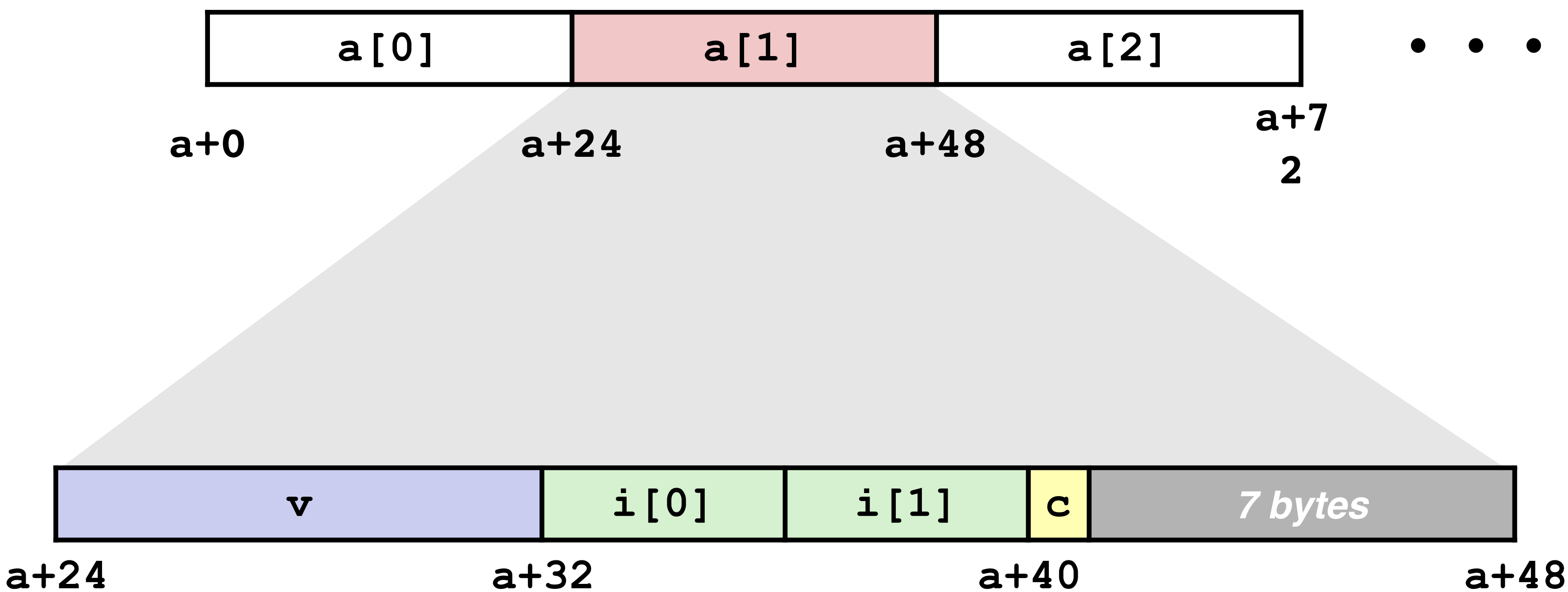

```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```



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];
```



Return Struct Values

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```
struct S{
  int a,b;
};

struct S foo(int c, int d){
    struct S retval;
    retval.a = c;
    retval.b = d;
    return retval;
}

void bar() {
  struct S test = foo(3, 4);
  fprintf(stdout, "%d, %d\n",
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  // you will get "3, 4" from
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- If there are only a few members in a struct, we could return through a few registers.
- If there are lots of members, we could return through memory, i.e., requires memory copy.
- But either way, there needs to be some sort convention for returning struct.

Return Struct Values

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  int a,b;
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}

void bar() {
  struct S test = foo(3, 4);
  fprintf(stdout, “%d, %d\n”,
test.a, test.b);
  // you will get 3, and 4 from
the terminal
}
```

Return Struct Values

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struct S{
  int a,b;
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  struct S test = foo(3, 4);
  fprintf(stdout, "%d, %d\n",
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the terminal
}
```

- The entire calling convention is part of what's called Application Binary Interface (ABI), which specifies how **two binaries** should interact.
- ABI includes: ISA, data type size, calling convention, etc.
- API defines the interface as the **source code** (e.g., C) level.
- The OS and compiler have to agree on the ABI.
- Linux x86-64 ABI specifies that returning a struct with two scalar (e.g. pointers, or long) values is done via **`%rax`** & **`%rdx`**

Today: Data Structures and Buffer Overflow

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

String Library Code

```
/* 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;
}
```

String Library Code

- Implementation of Unix function `gets()`
  - No way to specify limit on number of characters to read

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    }
    *p = '\0';
    return dest;
}
```

String Library Code

- Implementation of Unix function `gets()`
  - 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

```
/* 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;
}
```

Vulnerable Buffer Code

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

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

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void call_echo() {
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}
```

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

Vulnerable Buffer Code

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

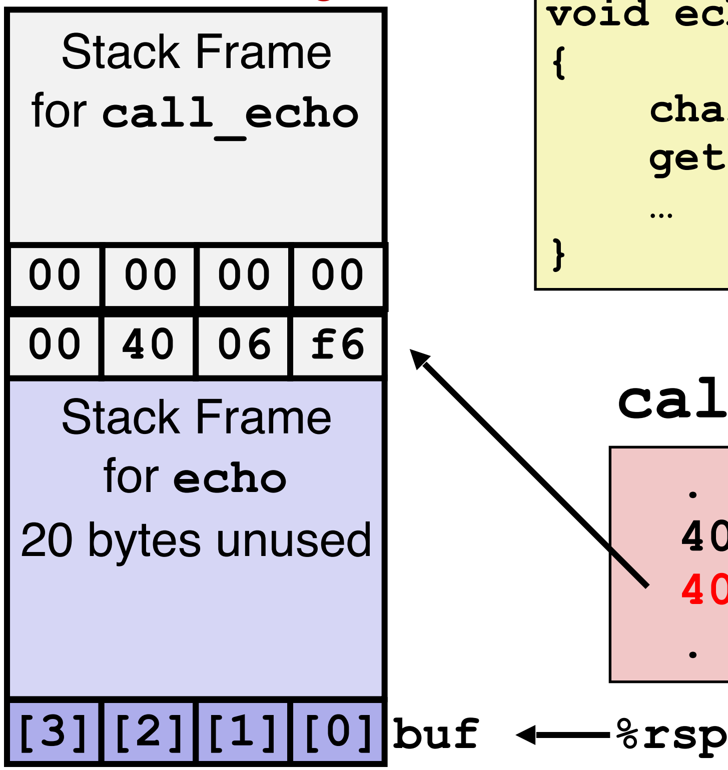
```
void call_echo() {
    echo();
}
```

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012
01234567890123456789012
```

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

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
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  …
```

call_echo:

```
 . . .
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 . . .
```

```
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()
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    char buf[4];
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    …
}
```

```
echo:
  subq   $24, %rsp
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  …
```

call_echo:

```
  . . .
  4006f1:  callq   4006cf <echo>
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  . . .
```

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012345678901234
Segmentation Fault
```

Overflowed buffer, and corrupt return address

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, corrupt return address, but program appears to still work!

Buffer Overflow Stack Example #4

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
Could be code controlled by attackers!

Such problems are a BIG deal

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- Generally called a “buffer overflow”
  - when exceeding the memory size allocated for an array
  - It’s the #1 technical cause of security vulnerabilities

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- Generally called a “buffer overflow”
  - when exceeding the memory size allocated for an array
  - It’s the #1 technical cause of security vulnerabilities
- The original Internet worm (1988) exploits buffer overflow
  - Invaded 10% of the Internet
  - Robert Morris, the authors of the worm, was a graduate student at Cornell and was later prosecuted

Such problems are a BIG deal

Robert Tappan Morris

From Wikipedia, the free encyclopedia

For other people named Robert Morris, see Robert Morris (disambiguation).

Robert Tappan Morris (born November 8, 1965) is an American computer scientist and entrepreneur. He is best known[3] for creating the Morris Worm in 1988, considered the first computer worm on the Internet.[4]

Morris was prosecuted for releasing the worm, and became the first person convicted under the then-new Computer Fraud and Abuse Act.[2][5] He went on to co-found the online store Viaweb, one of the first web-based applications[6], and later the funding firm Y Combinator—both with Paul Graham.

He later joined the faculty in the department of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology, where he received tenure in 2006.[7]

Robert Tappan Morris

Robert Morris in 2008

What to do about buffer overflow attacks

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

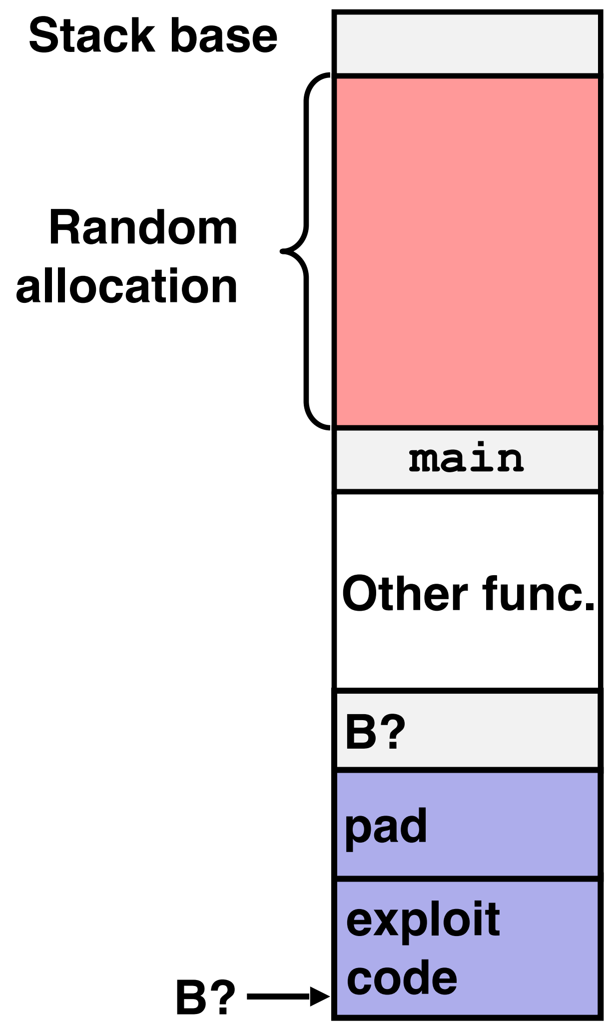
1. Avoid Overflow Vulnerabilities in Code (!)

```
/* 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

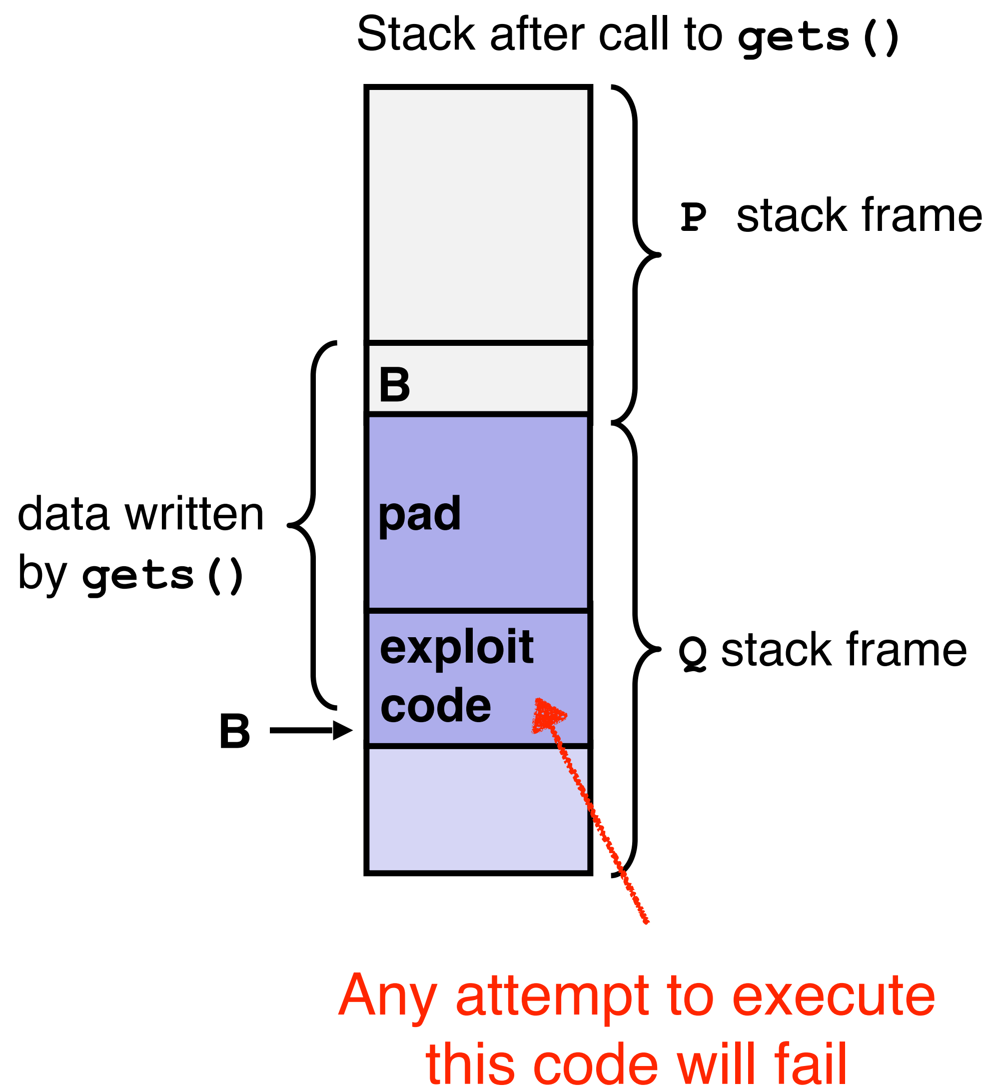
2. System-Level Protections can help

- 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



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)

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- Idea
  - Place special value (“canary”) on stack just beyond buffer
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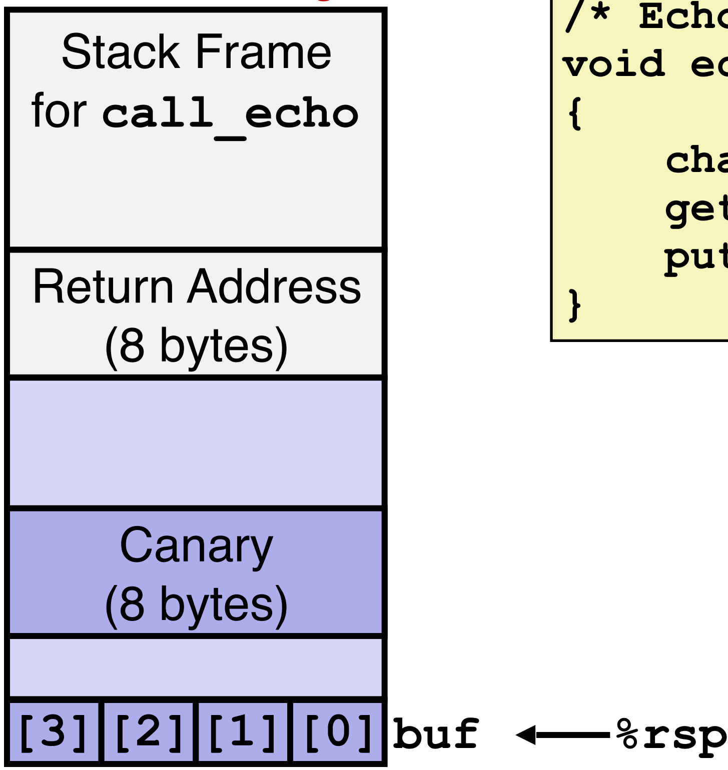
  - `-fstack-protector`
  - Now the default (disabled earlier)

```
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

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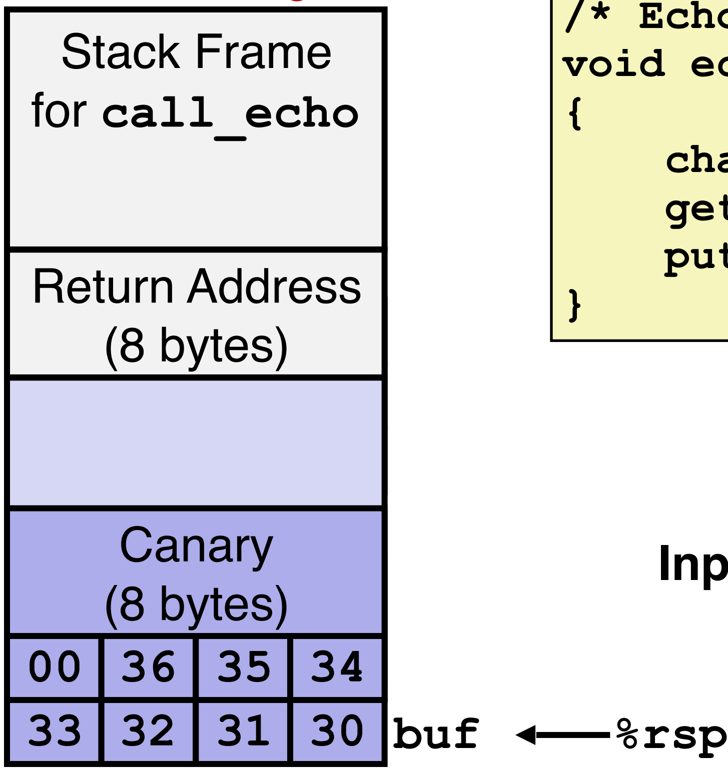

```
echo:
    . . .
    movq    %fs:40, %rax   # Get canary
    movq    %rax, 8(%rsp) # Place on stack
    xorl    %rax, %rax     # Erase canary
    . . .
```

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:        . . .
```

Why Does This Happen?

```
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; /* a huge value */
  return s.d;
}
```

Why Does This Happen?

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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; /* a huge value */
  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

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fun(6)  →   Segmentation fault
```