CSC 252: Computer Organization Spring 2026: Lecture 9

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Today: Data Structures and Buffer Overflow

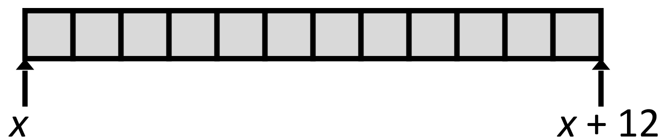
- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
- Structures
  - Allocation
  - Access
  - Alignment
- Buffer Overflow

Array Allocation: Basic Principle

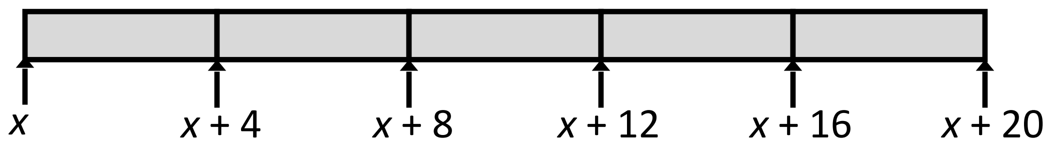
T **A[*L*];**

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

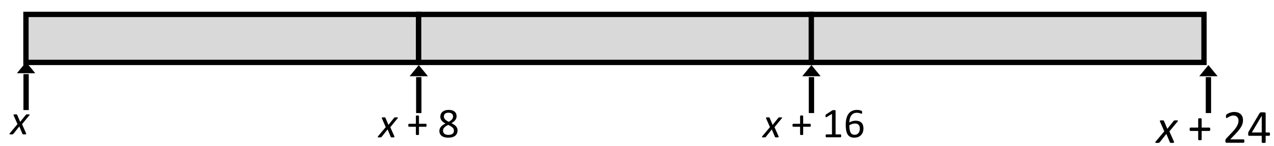
char string[12];



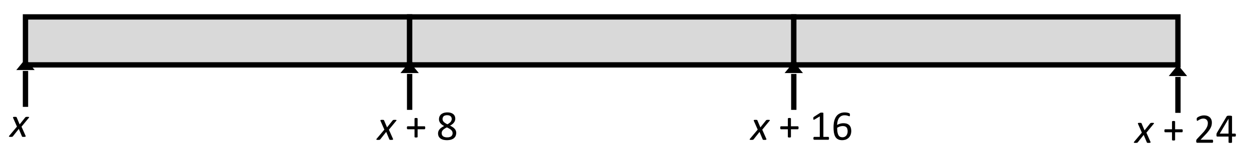
int val[5];



double a[3];



char* p[3];



Byte Ordering

- How are the bytes of a multi-byte variable ordered in memory?
- Example
  - Variable x has 4-byte value of 0x01234567
  - Address given by &x is 0x100
- 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)

Big Endian

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

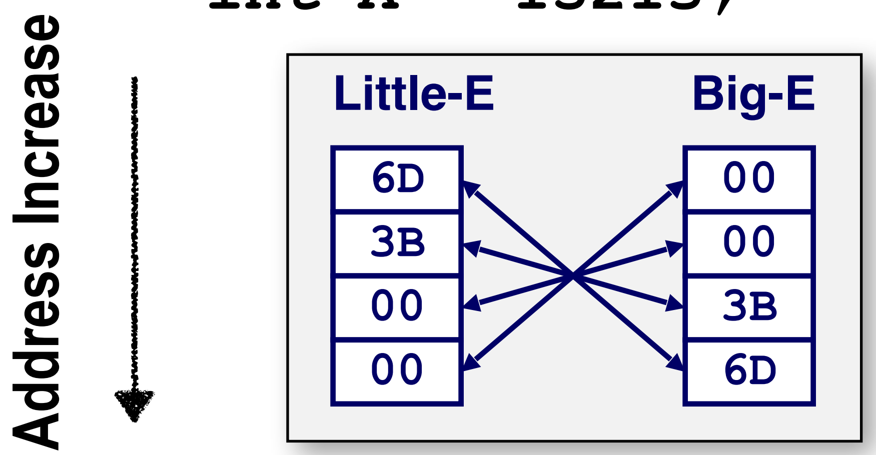
Little Endian

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

Representing Integers

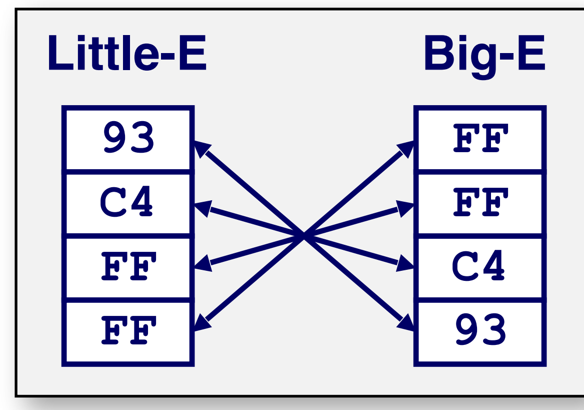
Hex: `00003B6D`

```
int A = 15213;
```



Hex: `FFFFC493`

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

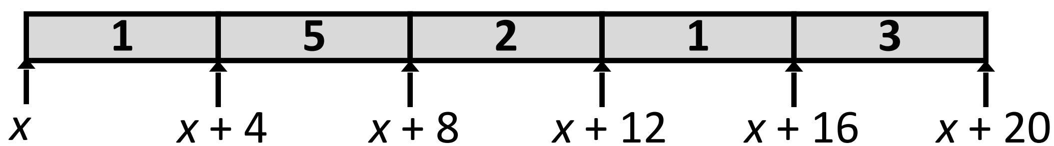


Array Access: Basic Principle

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 + `*i*	`int *`	$x + 4i$
`&val[2]`	`int *`	$x + 8$
`val[5]`	`int`	??
`*(val+1)`	`int`	5

Multidimensional (Nested) Arrays

- Declaration

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

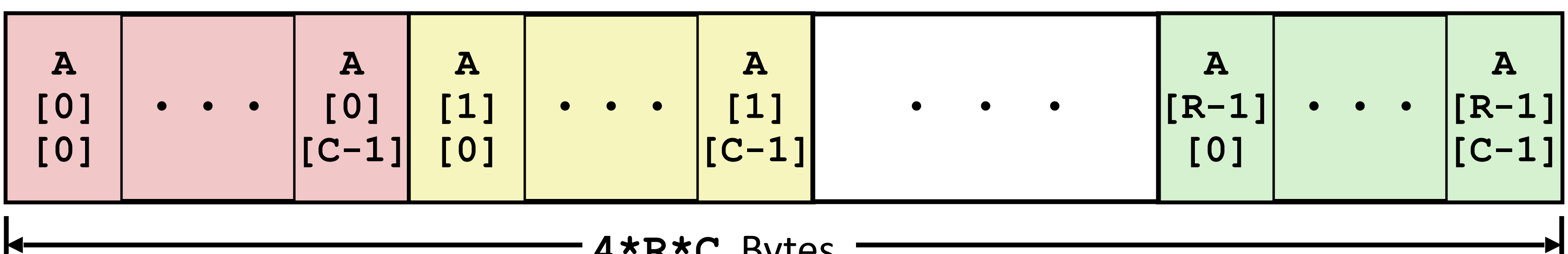
  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes

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

- Array Size
  - *R* * *C* * *K* bytes

- Arrangement
  - Row-Major Ordering in most languages, including C

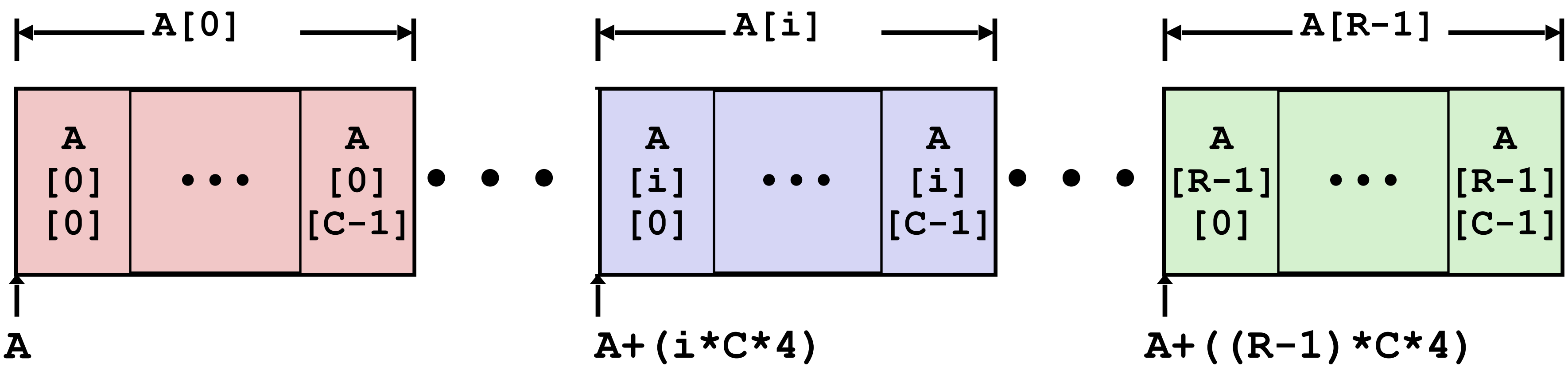
`int A[R][C];`



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)

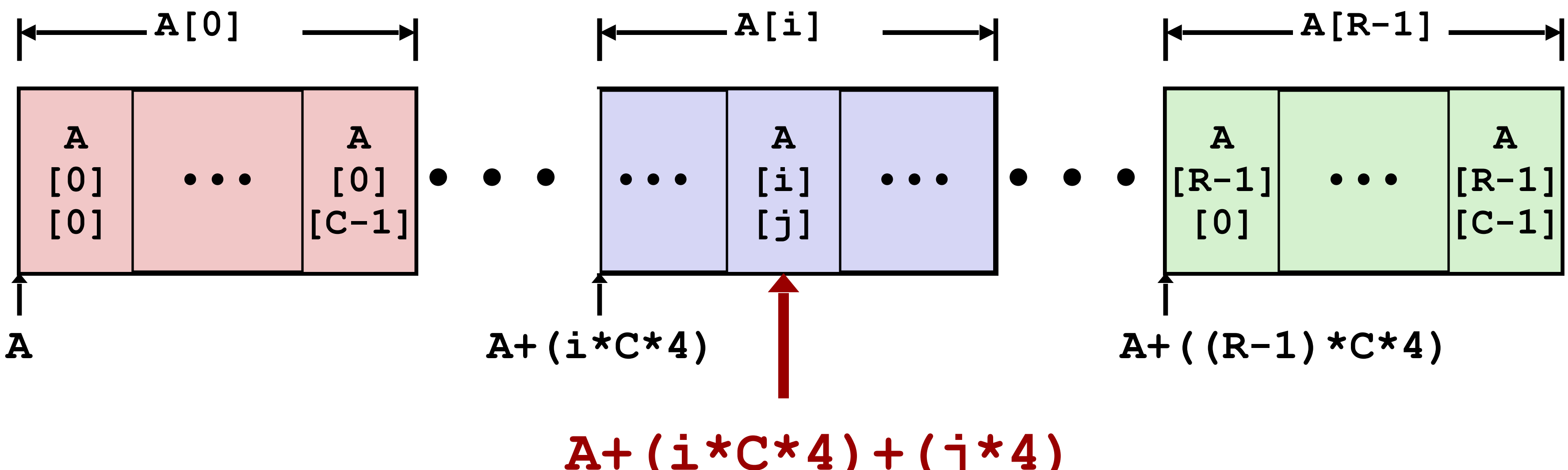
```
int A[R][C];
```



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];
```

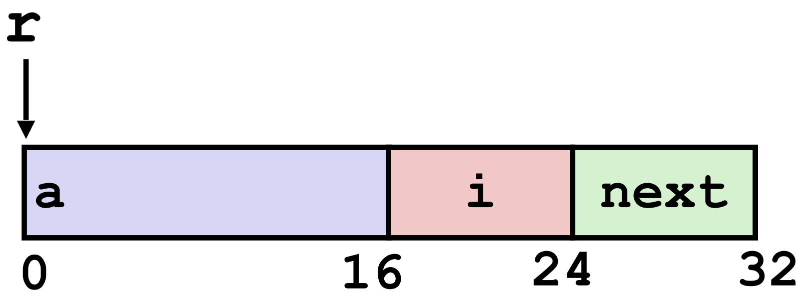


Today: Data Structures and Buffer Overflow

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

Structures

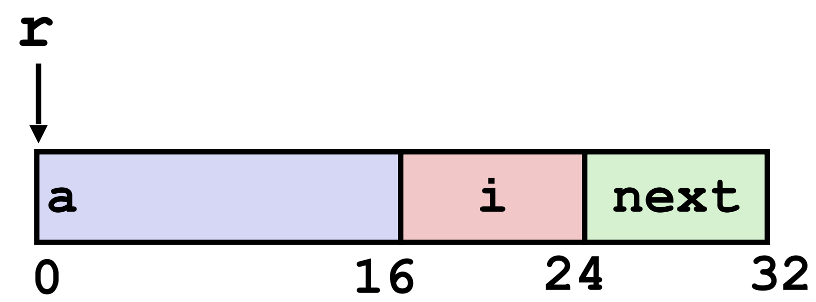
```
struct rec {
    int a[4];
    double i;
    struct rec *next;
};
```



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

Access Struct Members

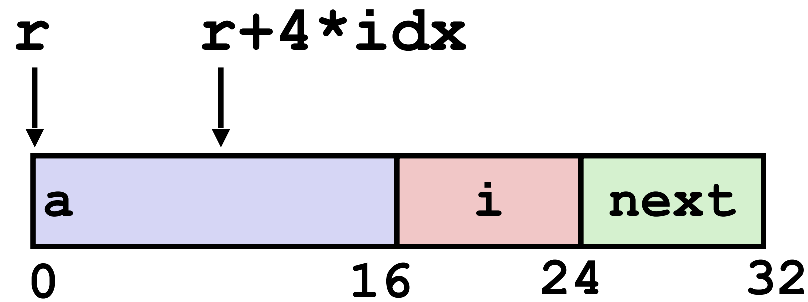
```
struct rec {
    int a[4];
    double i;
    struct rec *next;
};
```



- Given a struct, we can use the . operator:
  - `struct rec r1; r1.i = val;`
- Suppose we have a pointer `r` pointing to `struct res`. How to access `res`'s member using `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;
};
```



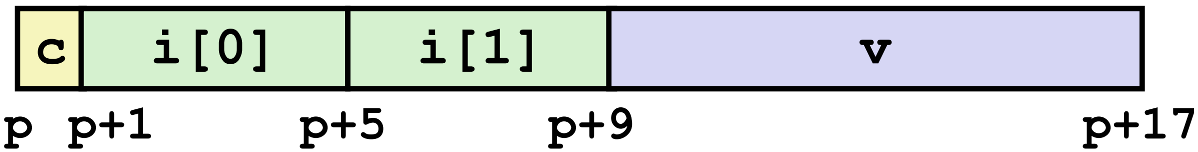

```
int *get_ap
 (struct rec *r, size_t idx)
{
  return &(r->a[idx]);
}
```

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

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

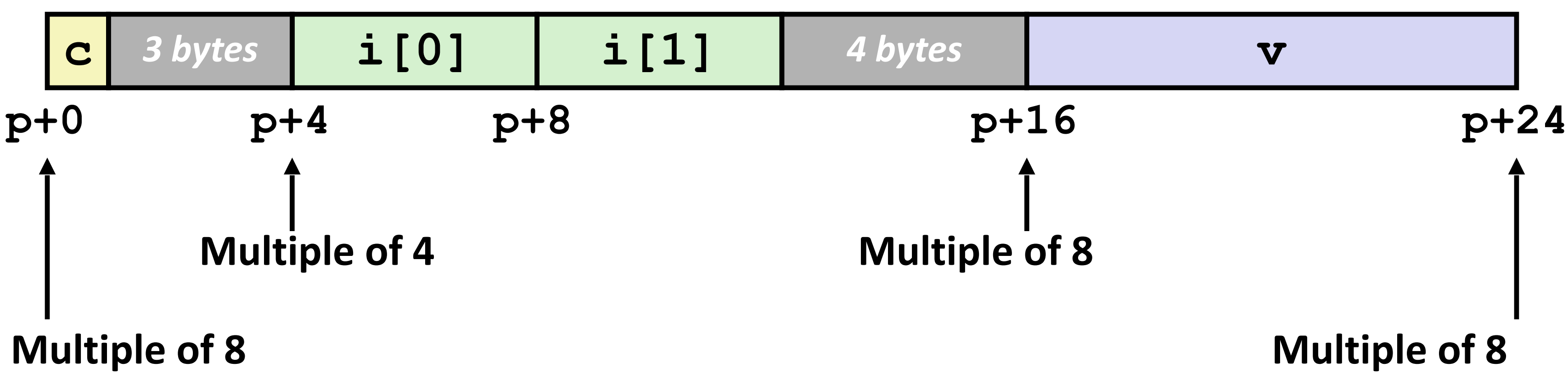
Alignment

- Unaligned Data




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

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



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 even 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)

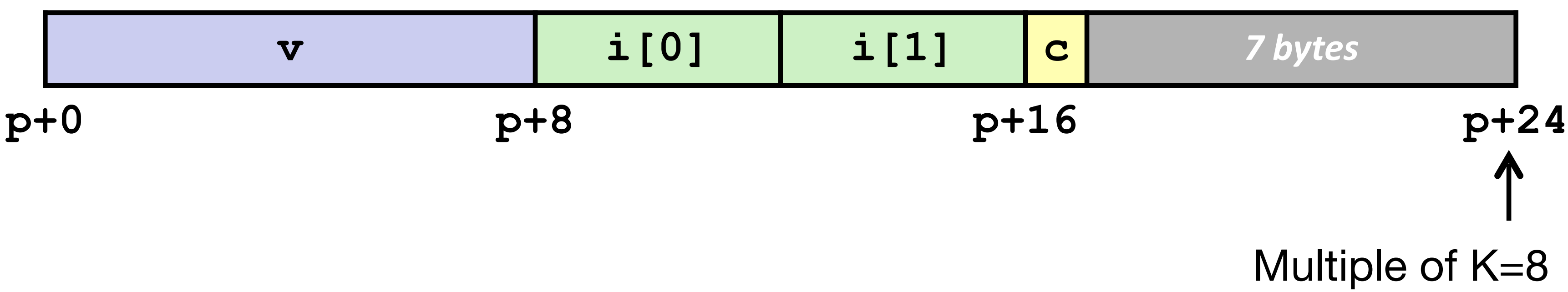
Specific Cases of Alignment (x86-64)

- 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

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

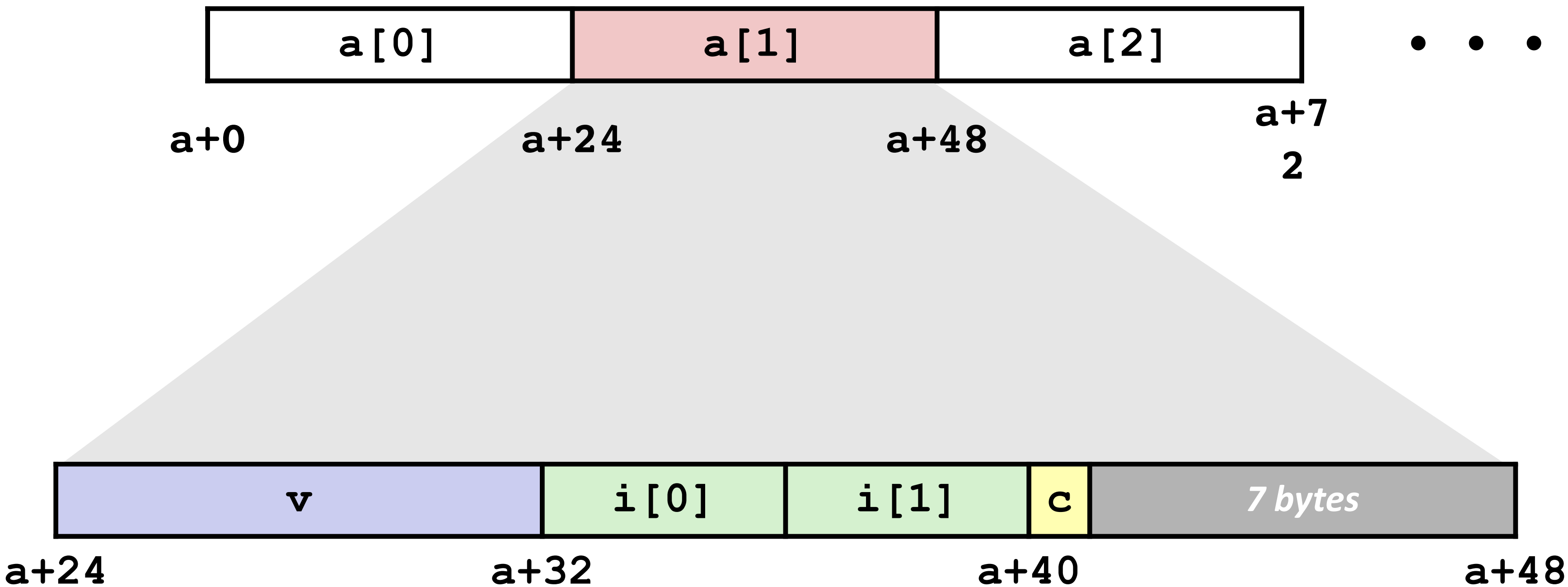
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

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

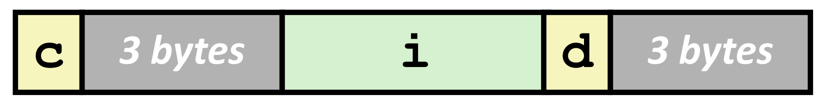
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



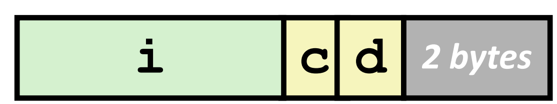
Saving Space

- 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;
```



Return Struct Values

```
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",
test.a, test.b);
  // you will get "3, 4" from
the terminal
}
```

- This is perfectly fine.
- A struct could contain many members, how would this work if the return value has to be in **`%rax`**??
- We don't have to follow that convention…
- 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

```
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”,
test.a, test.b);
  // you will get “3, 4” from
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`**

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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);
}
```

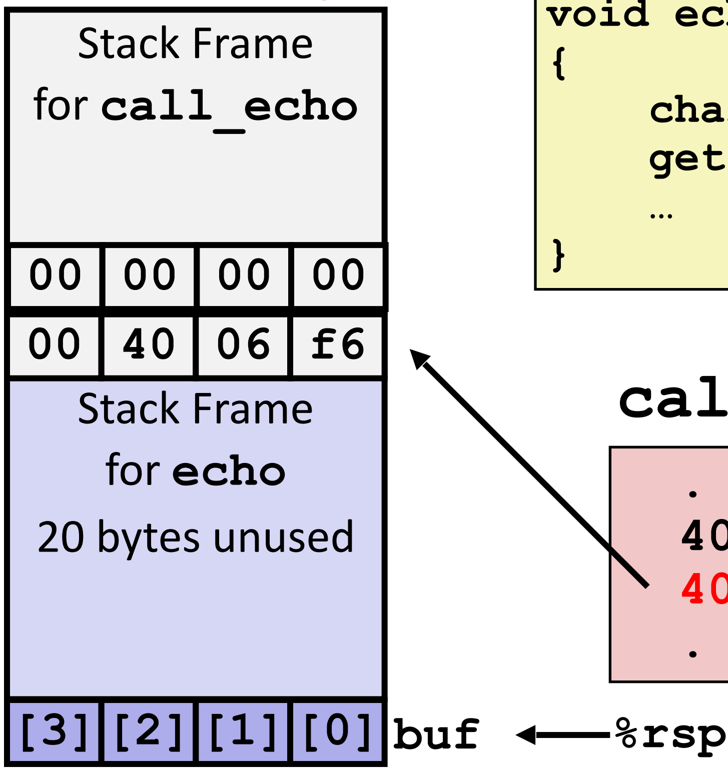
```
void call_echo() {
    echo();
}
```

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

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

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

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-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:

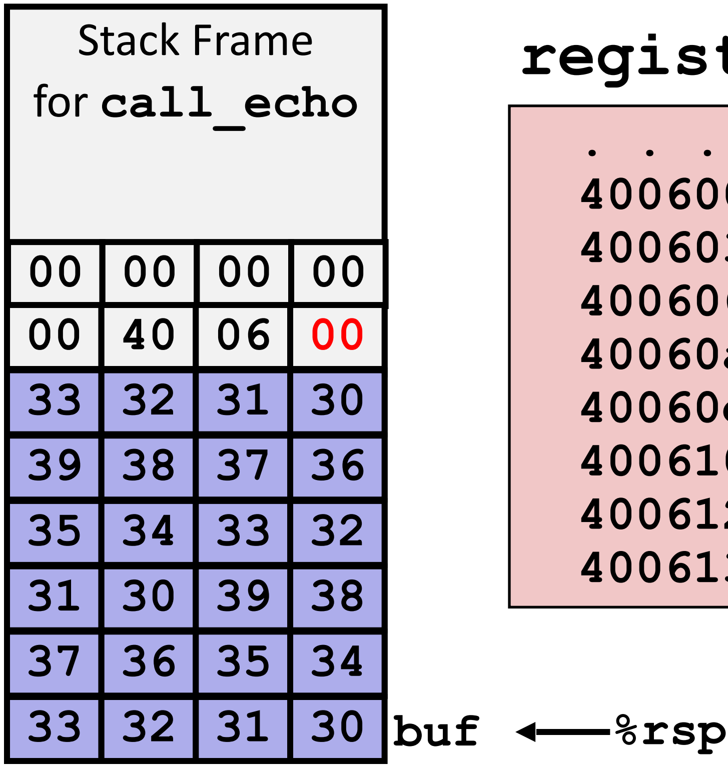
```
  . . .
  4006f1:  callq   4006cf <echo>
  4006f6:  add     $0x8,%rsp
  . . .
```

```
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



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!

What to do about buffer overflow attacks

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

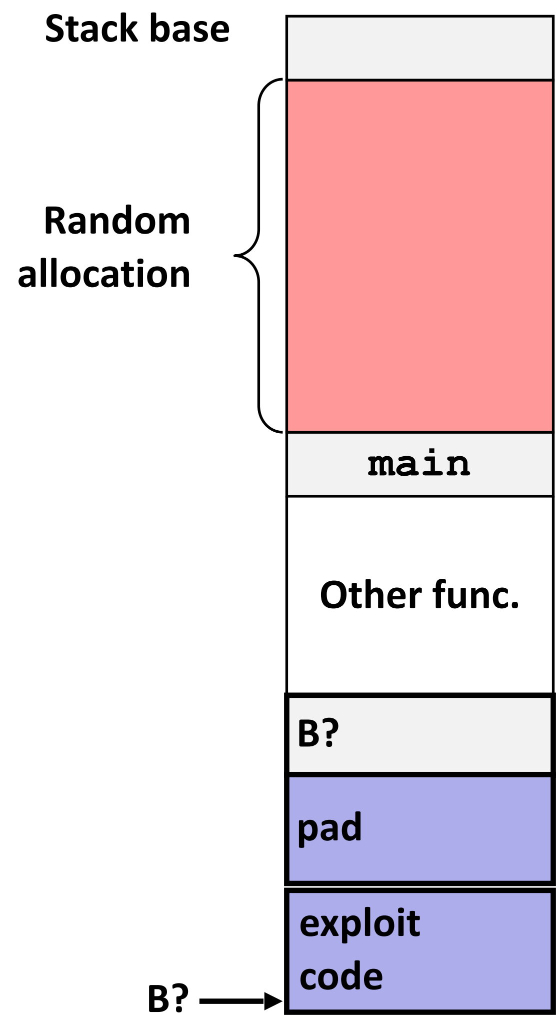
1. Avoid Overflow Vulnerabilities in Code (!)

```
/* 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

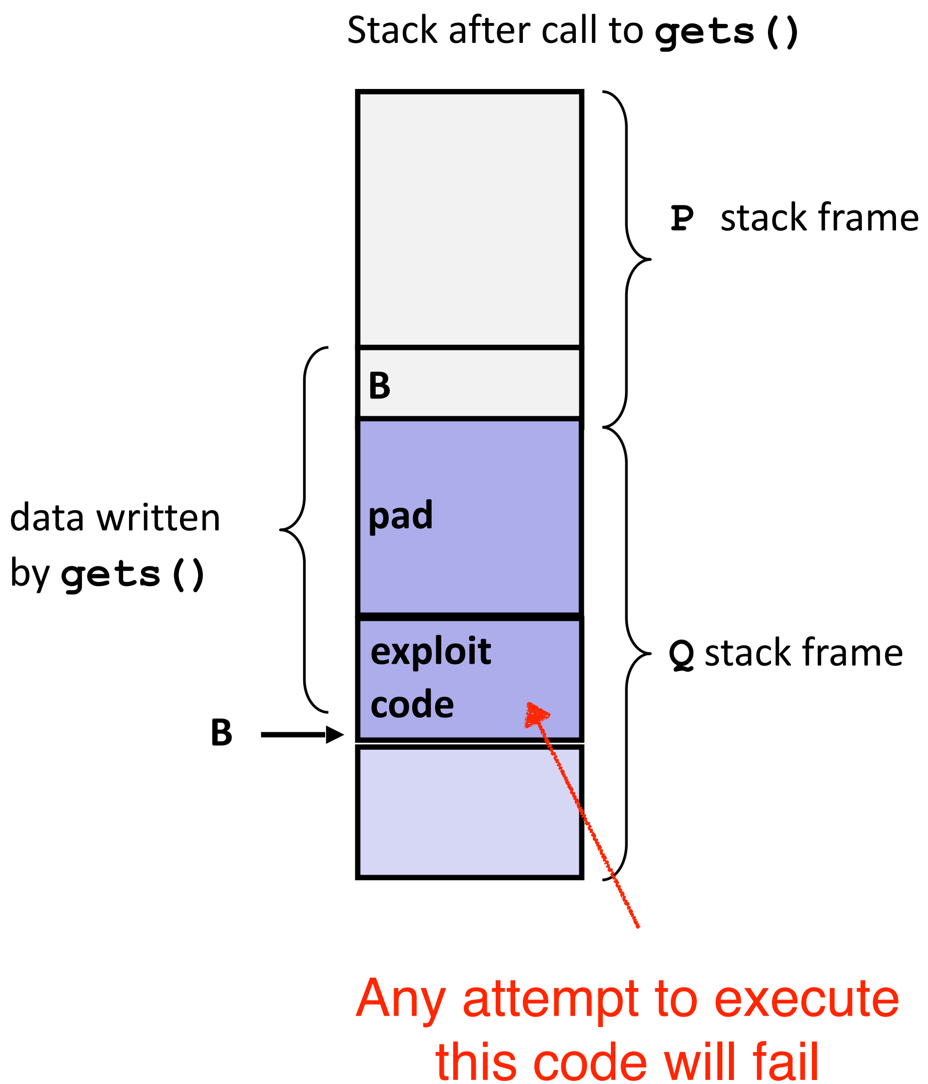
2. System-Level Protections can help

- 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

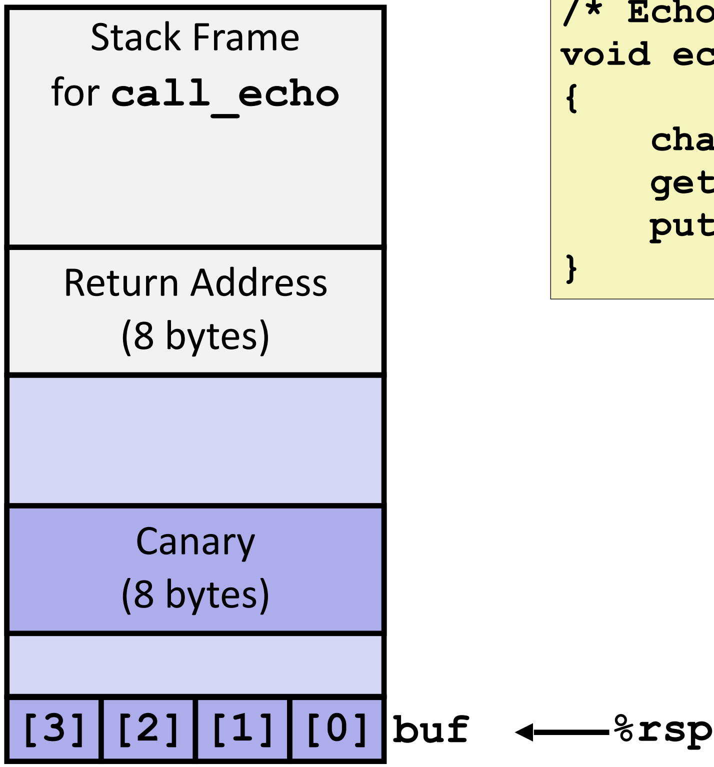
- Idea
  - Place special value (“canary”) on stack just beyond buffer
  - Check for corruption before exiting function
- GCC Implementation
  - `-fstack-protector`
  - Now the default (disabled earlier)

```
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

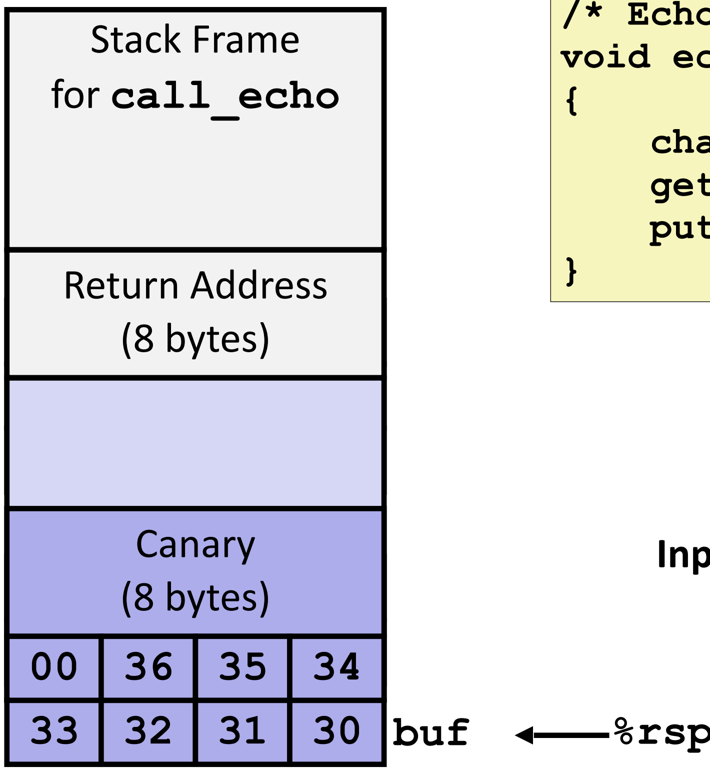



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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