

CS 241: Systems Programming

Lecture 22. Multidimensional Arrays

Spring 2020

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Two-dimensional arrays

```
int tab[4][5];
```

Rectangular 2D array,

- All memory allocated as a single, contiguous block

Indices are `tab[row][column]`;

Data is stored in **row-major** format

0,0	0,1	0,2	0,3	0,4
1,0	1,1	1,2	1,3	1,4
2,0	2,1	2,2	2,3	2,4
3,0	3,1	3,2	3,3	3,4

Row-major format

1	2	3	4	5
2	4	6	8	10
3	6	9	12	15
4	8	12	16	20

1 2 3 4 5 2 4 6 8 10 3 6 9 12 15 4 8 12 16 20

entry (r,c) is stored in position $r \cdot \text{cols} + c$ in memory

Where does C store the size of an array?

Column-major format (not C)

1	2	3	4	5
2	4	6	8	10
3	6	9	12	15
4	8	12	16	20

1 2 3 4 2 4 6 8 3 6 9 12 4 8 12 16 5 10 15 20

Given the 2D array, table, declared as follows,

```
size_t rows = 3;  
size_t cols = 4;  
double table[rows][cols];
```

how much memory does table occupy?

- A. $3 * 4$ bytes
- B. $3 * 4 * \text{sizeof}(\text{double})$ bytes
- C. $3 * \text{sizeof}(\text{size_t}) * 4$ bytes
- D. $3 * \text{sizeof}(\text{size_t}) * 4 * \text{sizeof}(\text{size_t})$ bytes
- E. $3 * \text{sizeof}(\text{size_t}) * 4 * \text{sizeof}(\text{size_t}) * \text{sizeof}(\text{double})$ bytes

Multidimensional arrays

```
float oneD[size];  
float twoD[rows][cols];  
float threeD[layers][rows][cols];  
...  
float general[size1][size2]...[sizeN];
```

Fixed-length arrays if all dimensions are integer constants

- `int const size = 10;` is not an integer constant!
- Can initialize using nested braces
- Can omit the size of the first dimension when using an initializer

Variable-length arrays if any dimensions are not integer constants

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float oneD[size];  
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1,0	1,1	1,2	1,3
2,0	2,1	2,2	2,3

0,0,0	0,0,1	0,0,2	0,0,3
0,1,0	0,1,1	0,1,2	0,1,3
0,2,0	0,2,1	0,2,2	0,2,3
1,0,0	1,0,1	1,0,2	1,0,3
1,1,0	1,1,1	1,1,2	1,1,3
1,2,0	1,2,1	1,2,2	1,2,3
2,0,0	2,0,1	2,0,2	2,0,3
2,1,0	2,1,1	2,1,2	2,1,3
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Three ways to declare the same function

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void foo(size_t len, int *arr);
```

```
void foo(size_t len, int arr[]);
```

```
void foo(size_t len, int arr[len]);
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For a multi-dimensional array, it's similar

```
void bar(size_t rows, size_t cols, int (*arr)[]);  
void bar(size_t rows, size_t cols, int (*arr)[cols]);  
void bar(size_t rows, size_t cols, int arr[][cols]);  
void bar(size_t rows, size_t cols, int arr[rows][cols]);
```

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Pointer to an
array

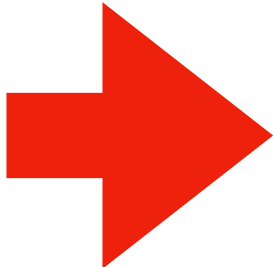
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```

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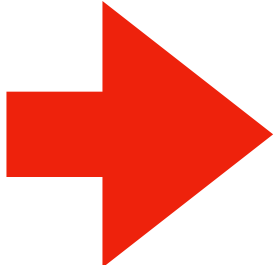
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void foo(size_t len, int *arr);  
void foo(size_t len, int arr[]);  
void foo(size_t len, int arr[len]);
```

Pointer to an
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For a multi-dimensional array, it's similar



```
void bar(size_t rows, size_t cols, int (*arr)[]);  
void bar(size_t rows, size_t cols, int (*arr)[cols]);  
void bar(size_t rows, size_t cols, int arr[][cols]);  
void bar(size_t rows, size_t cols, int arr[rows][cols]);
```

Dynamically allocating multi-D arrays

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Allocate a 1D array and perform index calculations manually

Dynamically allocate an `int[rows][cols]`

```
int *arr = malloc(sizeof(*arr) * rows * cols);
```

We can't use `arr[r][c]` because the type is wrong, instead use
`arr[r*cols + c]`

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Pro: By far the most common method of dealing with multi-D arrays

Con: Indexing is error prone

Con: Can't pass `arr` and some other `int arr2[rows][cols]` to the same function because they have different types

We have a 1D array of floats representing a 3D array where we're keeping track of the indices manually.

```
size_t layers, rows, cols; // Assume these have values
float *arr = malloc(sizeof(float)*layers*rows*cols);
```

What is the expression for the 3rd column of the 4th row of the 5th layer?
(I.e., we want "arr[5][4][3]" but we can't actually use that because arr is 1D.)

- A. arr[5*4*3]
- B. arr[5+4+3]
- C. arr[5*layers + 4*rows + 3*cols]
- D. arr[5*rows*cols + 4*cols + 3]
- E. arr[5*layers*rows + 4*rows + 3]

0,0,0	0,0,1	0,0,2	0,0,3
0,1,0	0,1,1	0,1,2	0,1,3
0,2,0	0,2,1	0,2,2	0,2,3
1,0,0	1,0,1	1,0,2	1,0,3
1,1,0	1,1,1	1,1,2	1,1,3
1,2,0	1,2,1	1,2,2	1,2,3
2,0,0	2,0,1	2,0,2	2,0,3
2,1,0	2,1,1	2,1,2	2,1,3
2,2,0	2,2,1	2,2,2	2,2,3

Dynamically allocating multi-D arrays

Allocate the multi-dimensional array and let the compiler deal with indexes

Dynamically allocate an `int[rows][cols]`

```
int (*arr)[cols] = malloc(sizeof(int[rows][cols]));
```

Now we can just use `arr[r][c]` to access an element!

Pro: Convenient array indexing

Pro: Can use the same function for local and dynamic multi-D arrays

Con: Hideous syntax!

Con: Returning them from functions requires *very* unusual syntax and really only works with fixed-length arrays or 2D variable-length arrays

Returning dynamic arrays

For the 1-D case (as well as faking multi-D with 1-D), just return a pointer

```
int *bar(void);
```

For the 2-D case, we have some more horrible syntax

```
int (*new_array(size_t rows, size_t cols))[] {  
    int (*arr)[cols] = malloc(sizeof(int[rows][cols]));  
    for (size_t r = 0; r < rows; ++r) {  
        for (size_t c = 0; c < cols; ++c)  
            arr[r][c] = r + c;  
    }  
    return arr;  
}
```

More than 2-D is worse

Aside about alignment

Types have a size and an **alignment**

Alignment constrains where in memory a variable can reside

- Alignment is a property of the underlying architecture
- An alignment of n means that the address of the variable must be a multiple of n

There's an **alignof** operator that works like **sizeof** except it returns the alignment of a variable or type

- This is almost never needed in real code

If an **int** has an alignment of 4 (which is common), which of the following address is **not** valid for a variable of type **int**?

A. 0x1234

B. 0x248A

C. 0x333C

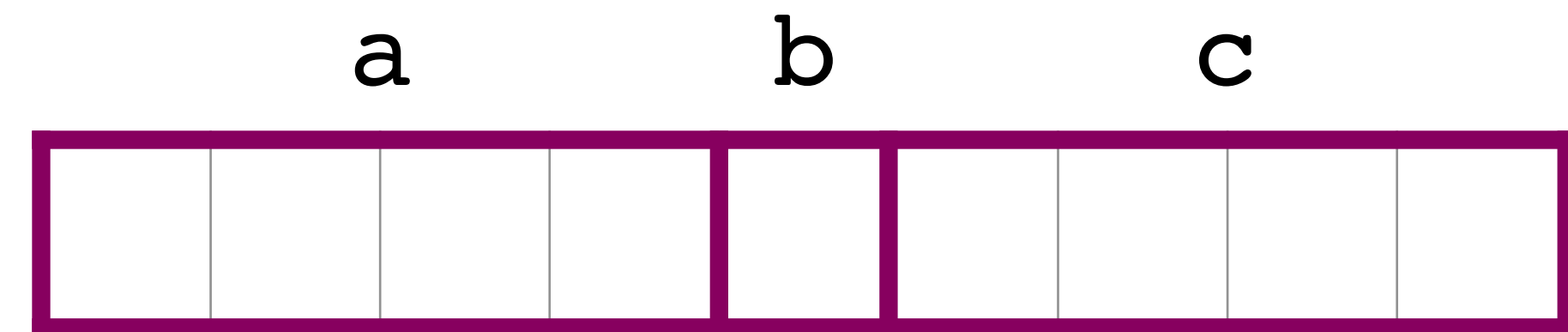
D. 0x4440

E. 0xA2D8

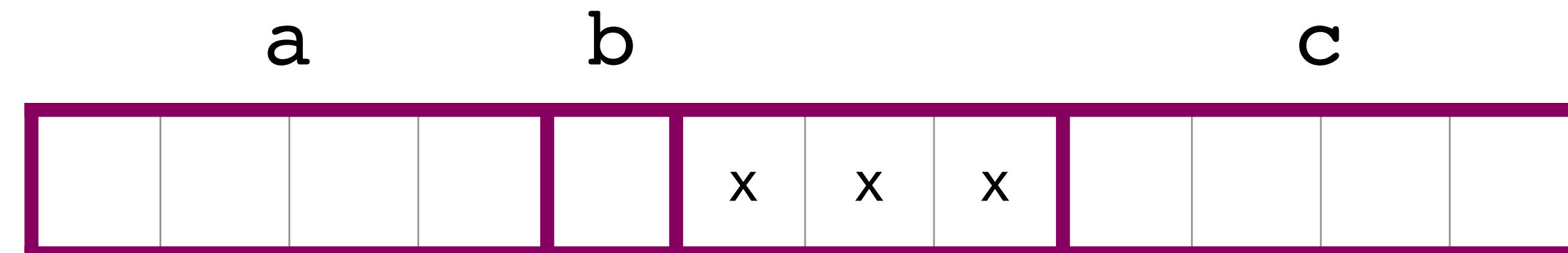
Padding in structs

```
struct foo {  
    int a;  
    char b;  
    int c;  
};
```

This can't be laid out in memory like this
because of the alignment of a and c



It needs **padding** bytes

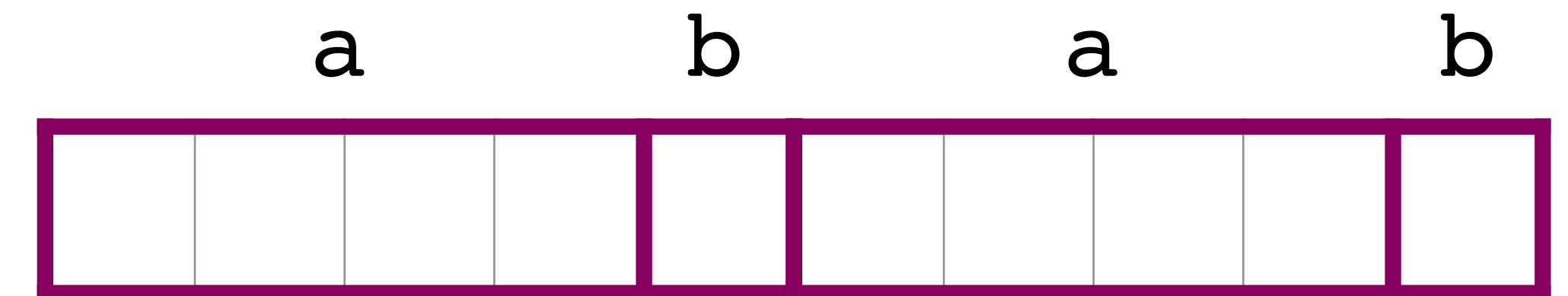
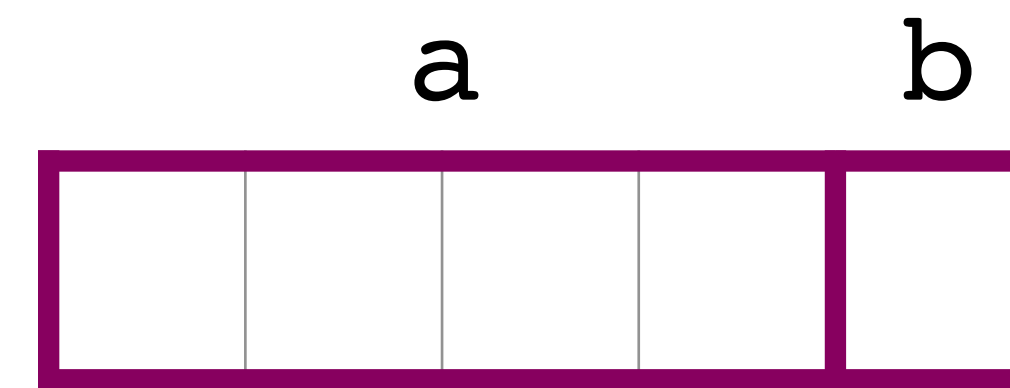


The alignment of a struct is the
maximum of the alignments of its
members

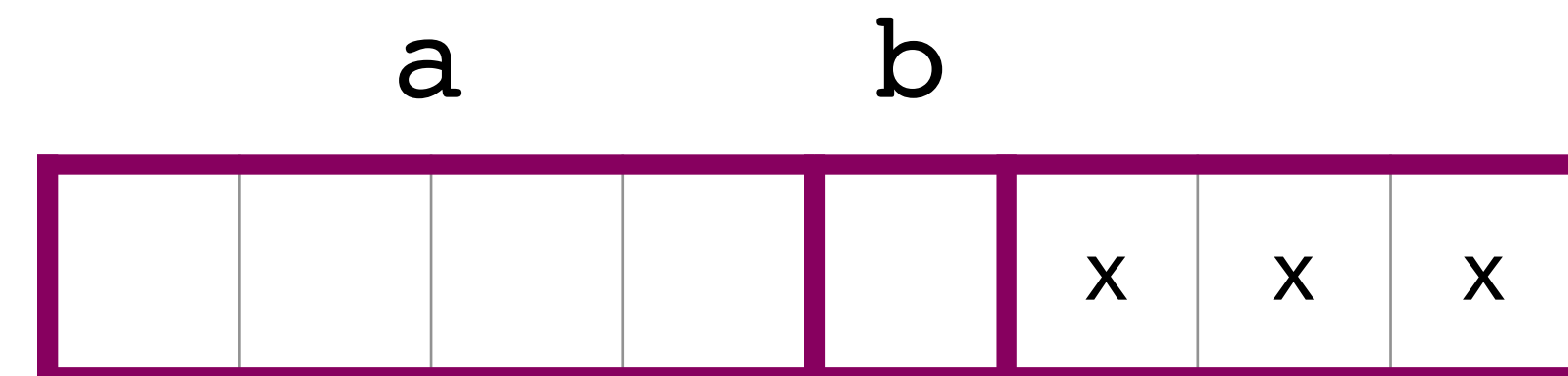
Array of structs

```
struct bar {  
    int a;  
    char b;  
};
```

This can't be laid out in memory like this
because of the alignment of a in
subsequent elements of the array



It needs **padding** bytes at the end



What can we say about the sizes of these two structures (assuming `alignof(int) > alignof(char)`)?

```
struct s1 {  
    char ch1;  
    int x;  
    char ch2;  
};
```

```
struct s2 {  
    char ch1;  
    char ch2;  
    int x;  
};
```

- A. `struct s1` is larger than `struct s2`
- B. `struct s2` is larger than `struct s1`
- C. Both are the same size
- D. Sizes are implementation defined so there's no way to know
- E. It's impossible for `alignof(int)` to be greater than `alignof(char)`

In-class exercise

<https://checkoway.net/teaching/cs241/2020-spring/exercises/Lecture-22.html>

Grab a laptop and a partner and try to get as much of that done as you can!