CS 241: Systems Programming
Lecture 22. Multidimensional Arrays

Fall 2019
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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*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*sizeof(double)` bytes

C. `3*sizeof(size_t)*4` bytes

D. `3*sizeof(size_t)*4*sizeof(size_t)` bytes

E. `3*sizeof(size_t)*4*sizeof(size_t)*sizeof(double)` bytes

Multidimensional arrays

```
float oneD[size];
float twoD[rows][cols];
float threeD[layers][rows][cols];
...
float general[size1][size2]...[sizeN];
```
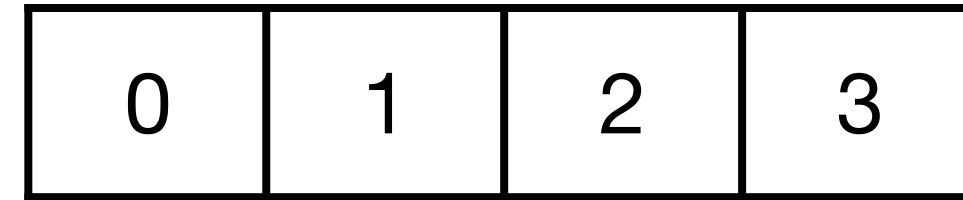
Fixed-length arrays if all dimensions are integer constants
- ‣ `int const` size = 10; is not an integer constant!
- ‣ Can initialize using nested braces
- ‣ Can omit the size of the first dimension when using an initializer

Variable-length arrays if any dimensions are not integer constants

Multidimensional arrays

0	1	2	3

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```
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```

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

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

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

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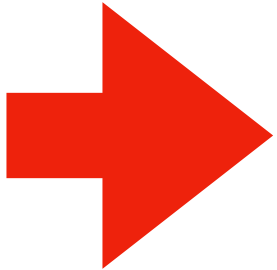
For a multi-dimensional array, it's similar
```
void bar(size_t rows, size_t cols, int (*arr)[]);
void bar(size_t rows, size_t cols, int (*arr)[cols]);
void bar(size_t rows, size_t cols, int arr[][cols]);
void bar(size_t rows, size_t cols, int arr[rows][cols]);
```

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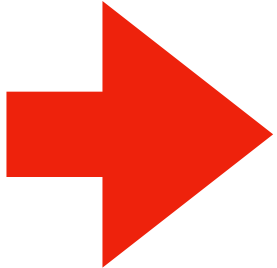
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void bar(size_t rows, size_t cols, int arr[rows][cols]);
```

Pointer to an array

Passing arrays to functions

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

Pointer to an array

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]`

Dynamically allocating multi-D arrays

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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]

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`?
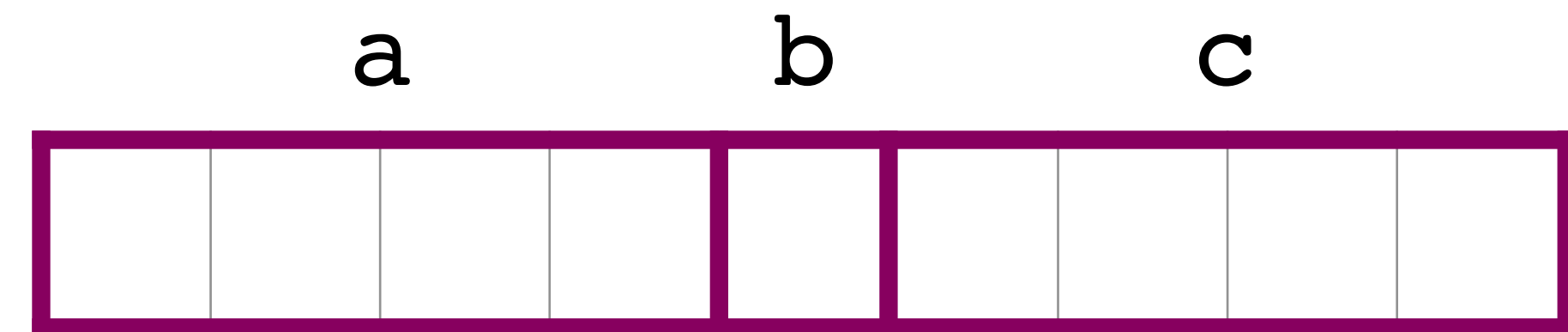
A. 0x1234

B. 0x248A

C. 0x333C

D. 0x4440
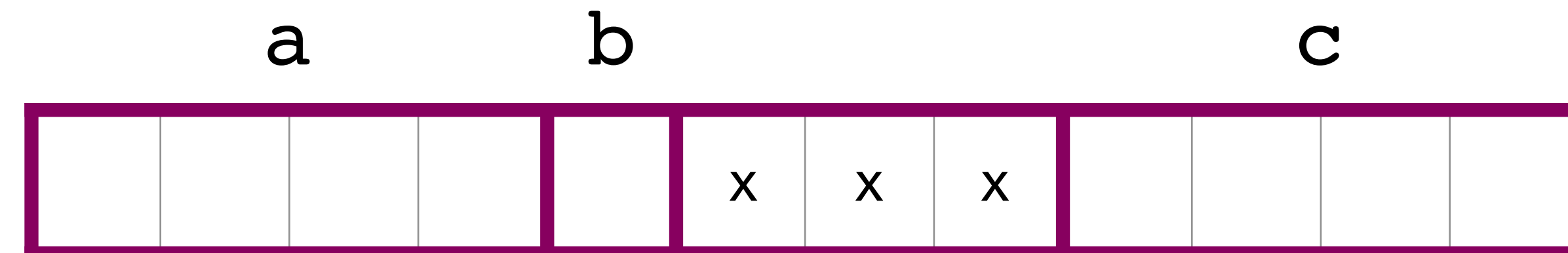
E. 0xA2D8

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
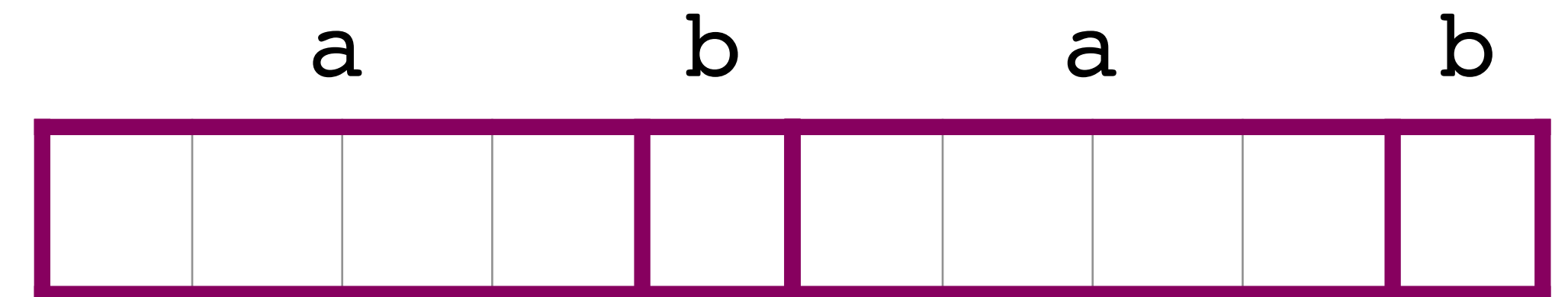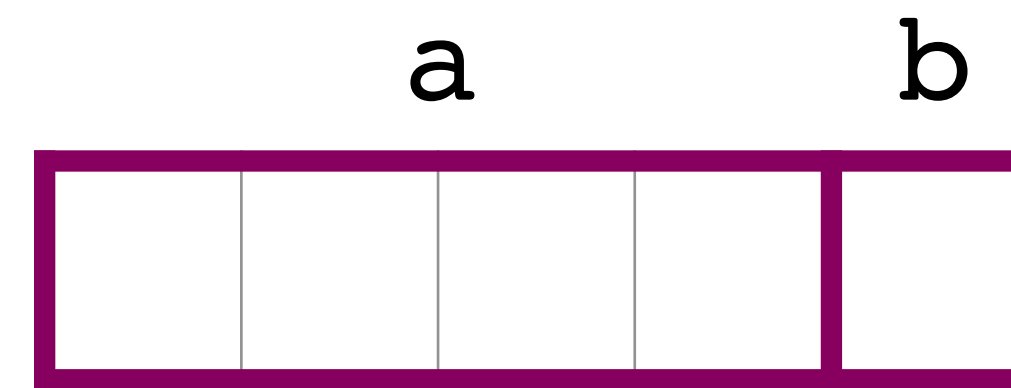
It needs **padding** bytes

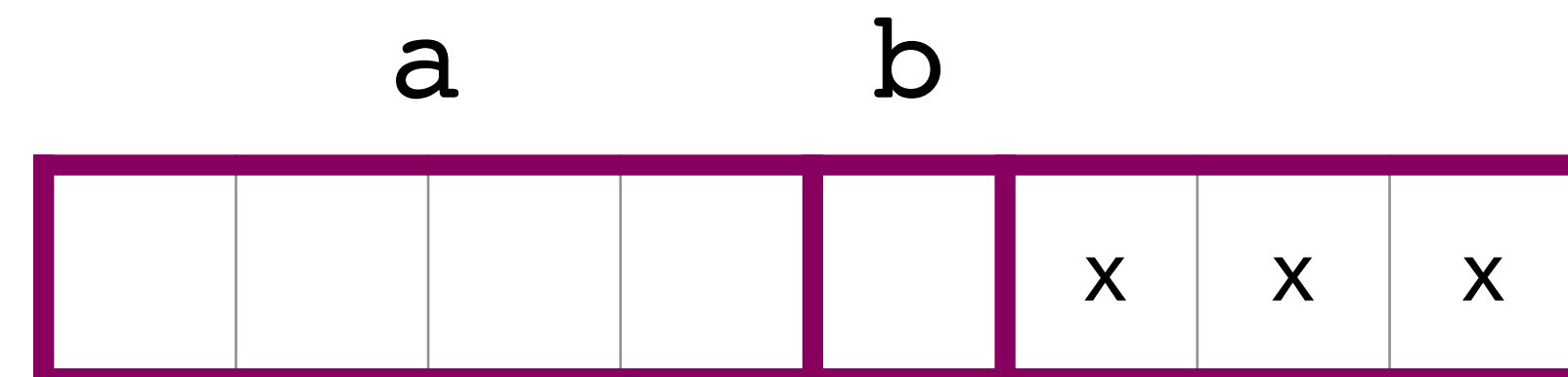The alignment of a struct is the maximum of the alignments of its members

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 {                              struct s2 {
  char ch1;                                char ch1;
  int x;                                   char ch2;
  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/cs241/2019-fall/exercises/Lecture-22.html

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