Arrays

CSE 351 Winter 2021

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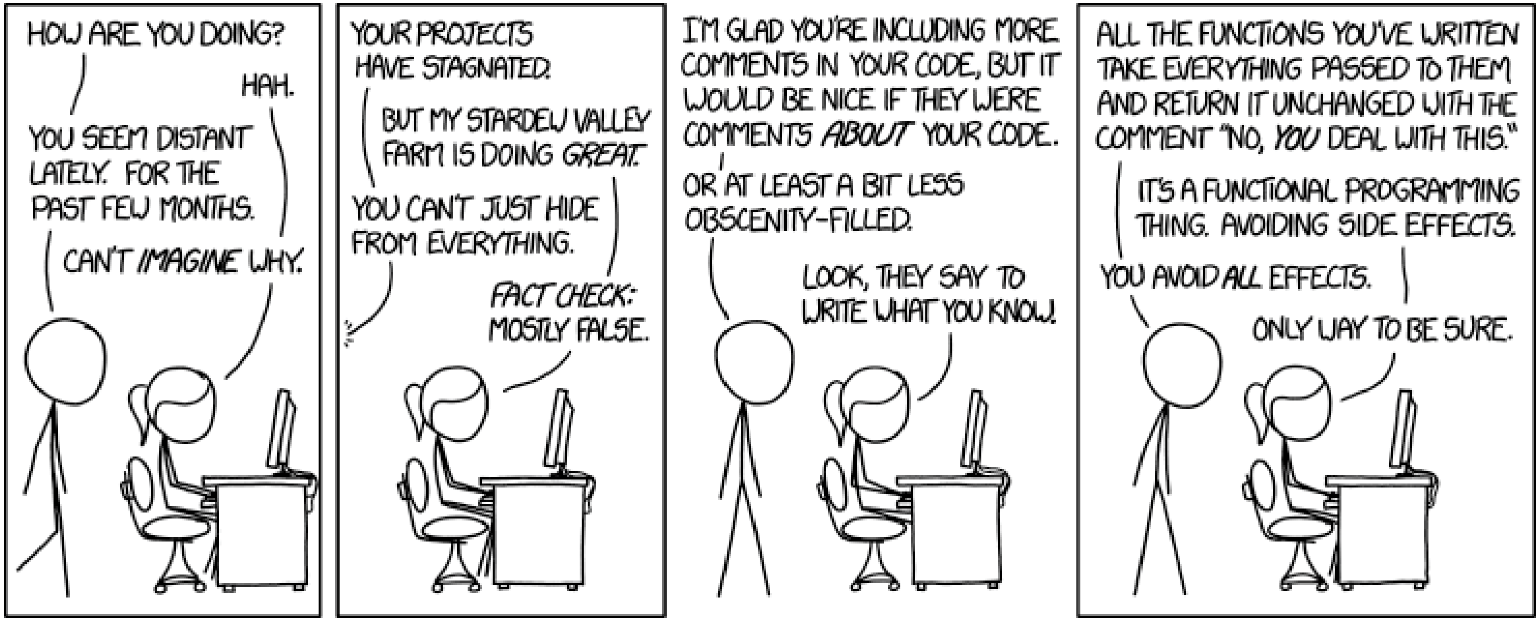


http://xkcd.com/1790/

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

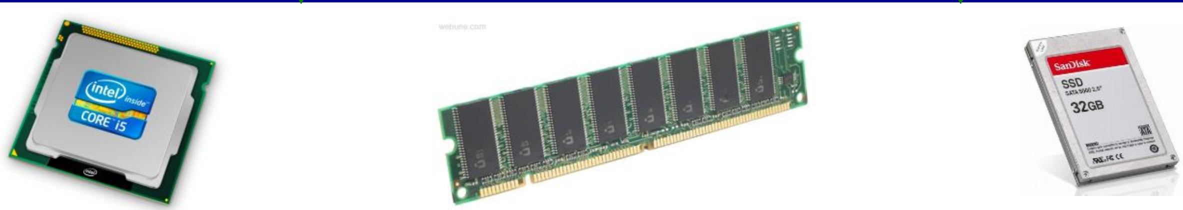
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10

OS X Yosemite

Computer system:



- Memory & data
- Integers & floats
- x86 assembly
- Procedures & stacks
- Executables
- **Arrays & structs**
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

Data Structures in Assembly

- **Arrays**
  - **One-dimensional**
  - Multidimensional (nested)
  - Multilevel
- Structs – on Friday w/ Cosmo!
  - Alignment
- ~~Unions~~

Review: Array Allocation

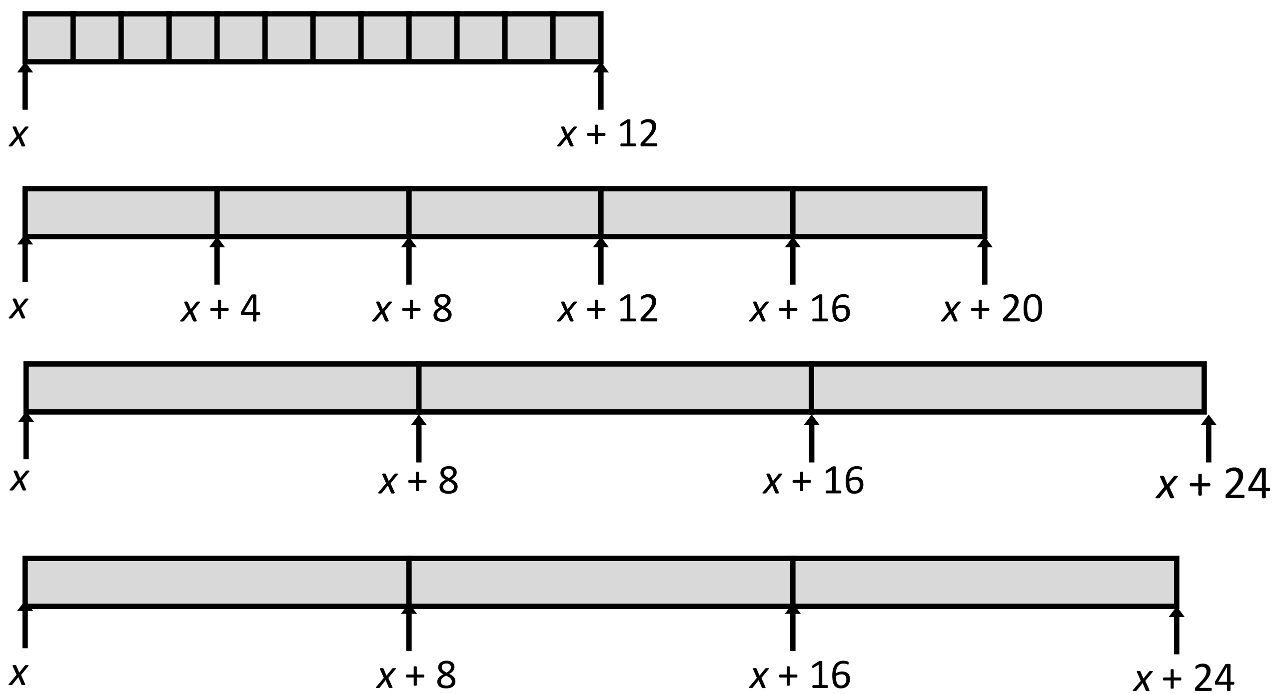
- Basic Principle
  - **`T`** `A[N];` → array of data type **`T`** and length `N`
  - *Contiguously* allocated region of `N*sizeof(`**`T`**`)` bytes
  - Identifier `A` returns address of array (type **`T*`**)

`char` `msg[12];`

`int` `val[5];`

`double` `a[3];`

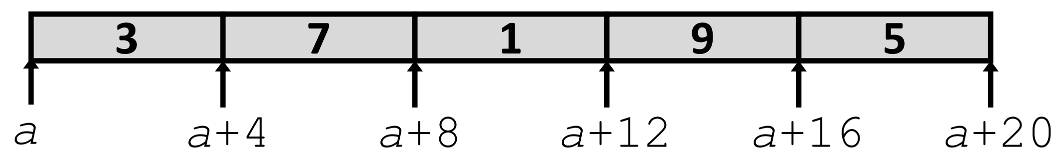
`char*` `p[3];`
(or **`char`** **`*`**`p[3];`)



Review: Array Access

- Basic Principle
  - `T A[N];` → array of data type `T` and length `N`
  - Identifier `A` returns address of array (type `T*`)

`int x[5];`



- Reference / Type / Value

Reference	Type	Value
`x[4]`	`int`	`5`
`x`	`int*`	`a`
`x+1`	`int*`	`a + 4`
`&x[2]`	`int*`	`a + 8`
`x[5]`	`int`	`??` (whatever's in memory at addr `x+20`)
`*(x+1)`	`int`	`7`
`x+i`	`int*`	`a + 4*i`

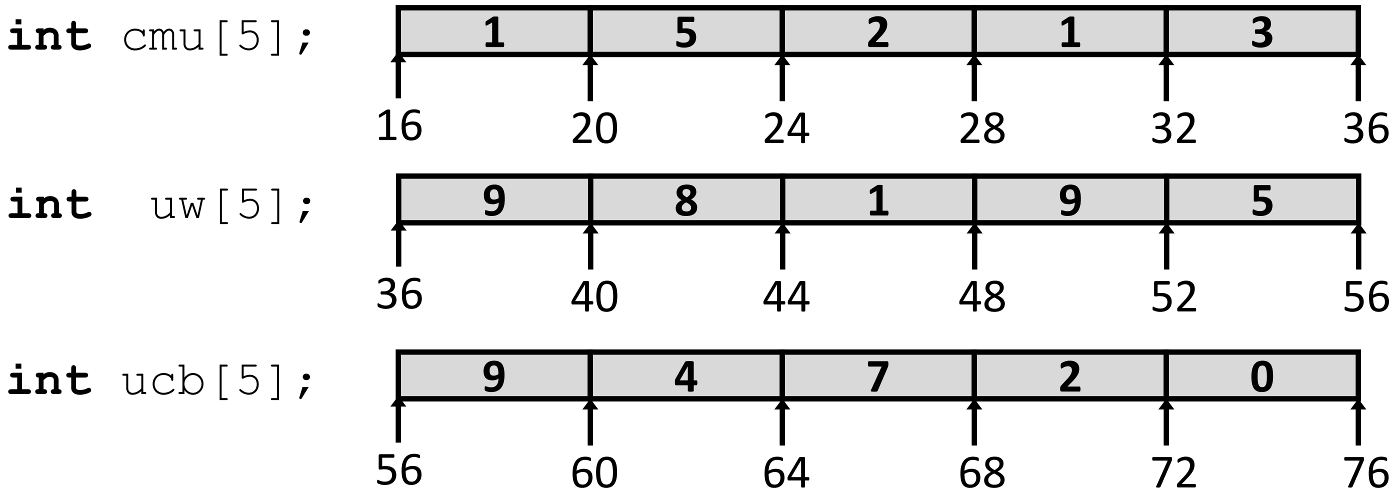
Array Example

```
// arrays of ZIP code digits
int cmu[5] = { 1, 5, 2, 1, 3 };
int  uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

brace-enclosed list initialization

Array Example

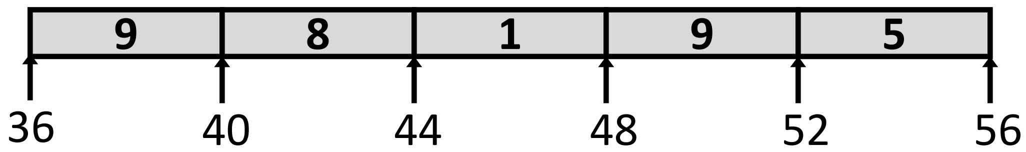
```
// arrays of ZIP code digits
int cmu[5] = { 1, 5, 2, 1, 3 };
int  uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```



- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

Array Accessing Example

```
int  uw[5];
```



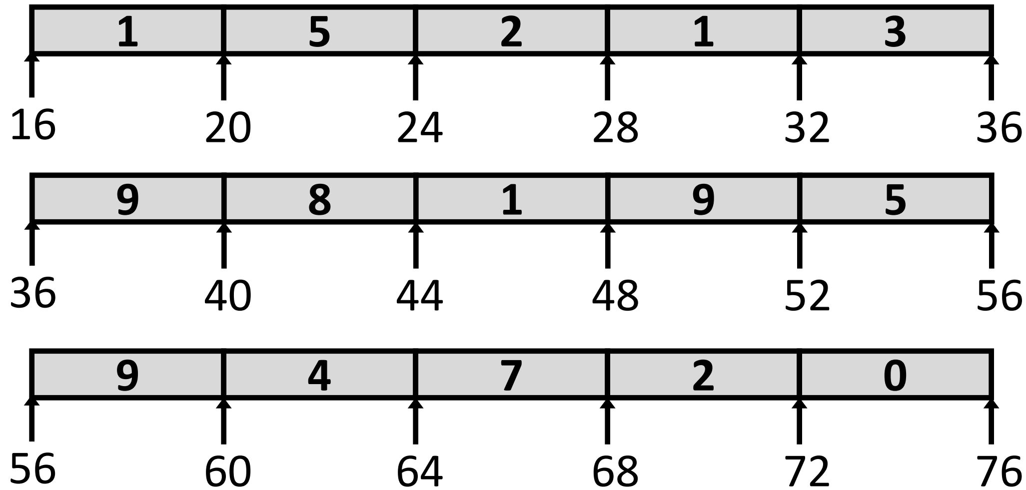

```
// return specified digit of ZIP code
int get_digit(int z[5], int digit) {
  return z[digit];
}
```

```
get_digit:
  movl  (%rdi,%rsi,4), %eax   # z[digit]
```

- Register `%rdi` contains starting address of array
- Register `%rsi` contains array index
- Desired digit at `%rdi+4*%rsi`, so use memory reference `(%rdi,%rsi,4)`

Referencing Examples

```
int cmu[5];
int  uw[5];
int ucb[5];
```



Reference	Address	Value	Guaranteed?
`uw[3]`			
`uw[6]`			
`uw[-1]`			
`cmu[15]`			

- No bounds checking
- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

C Details: Arrays and Pointers

- Arrays are (almost) identical to pointers
  - `char* string` and `char string[]` are nearly identical declarations
  - Differ in subtle ways: initialization, `sizeof()`, etc.

- An array name is an expression (not a variable) that returns the address of the array
  - It *looks* like a pointer to the first (0^{th}) element
    - `*ar` same as `ar[0]`, `*(ar+2)` same as `ar[2]`
  - An array name is read-only (no assignment) because it is a *label*
    - Cannot use "`ar = <anything>`"

C Details: Arrays and Functions

- Declared arrays only allocated while the scope is valid:

```
char* foo() {
    char string[32]; ...;
    return string;
}
```

BAD!

- An array is passed to a function as a pointer:
  - Array size gets lost!

Really `int *ar`

```
int foo(int ar[], unsigned int size) {
    ... ar[size-1] ...
}
```

Must explicitly pass the size!

Data Structures in Assembly

- **Arrays**
  - One-dimensional
  - **Multidimensional (nested)**
  - Multilevel
- Structs
  - Alignment
- ~~Unions~~

Nested Array Example

```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

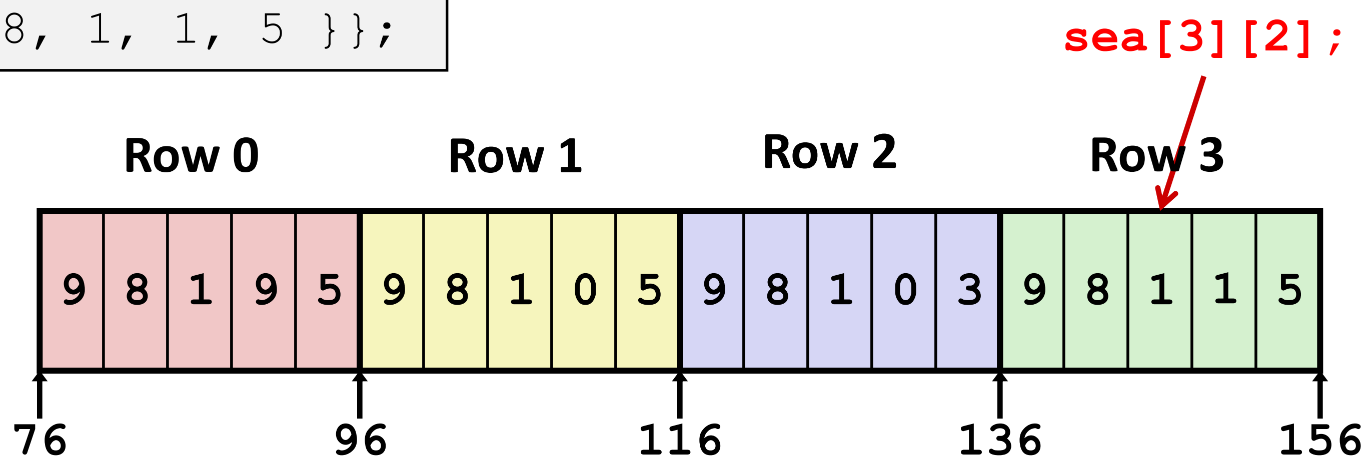
Remember, **`T`** `A[N]` is an array with elements of type **`T`**, with length `N`

- What is the layout in memory?

Nested Array Example

```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

Remember, **`T`** `A[N]` is an array with elements of type **`T`**, with length `N`



- "Row-major" ordering of all elements
- Elements in the same row are contiguous
- Guaranteed (in C)

Two-Dimensional (Nested) Arrays

- Declaration: **`T`** `A[R][C];`
  - 2D array of data type `T`
  - `R` rows, `C` columns
  - Each element requires **`sizeof(T)`** bytes
- Array size?

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

Two-Dimensional (Nested) Arrays

- Declaration: `T A[R][C];`
  - 2D array of data type `T`
  - `R` rows, `C` columns
  - Each element requires `sizeof(T)` bytes
- Array size:
  - `R*C*sizeof(T)` bytes
- Arrangement: **row-major** ordering

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

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

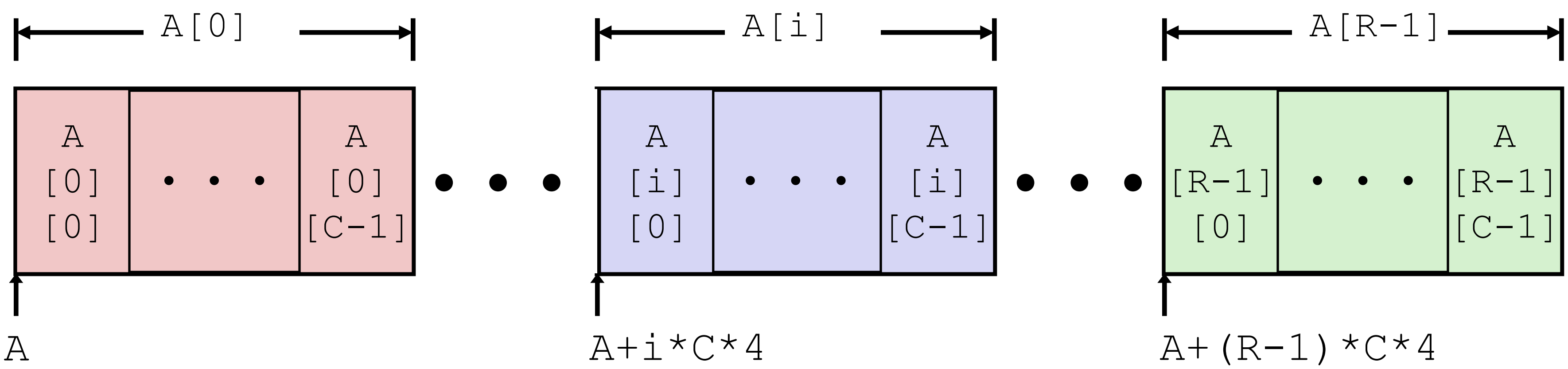
A[0][0]	• • •	A[0][C-1]	A[1][0]	• • •	A[1][C-1]	• • •	A[R-1][0]	• • •	A[R-1][C-1]

4*R*C bytes

Nested Array Row Access

- Row vectors
  - Given **T** `A[R][C]`,
    - `A[i]` is an array of `C` elements ("row `i`")
    - `A` is address of array
    - Starting address of row `i` `= A + i*(C * sizeof(`**T**`))`

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



Nested Array Row Access Code

```
int* get_sea_zip(int index)
{
  return sea[index];
}
```

```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

```
get_sea_zip(int):
    movslq  %edi, %rdi
    leaq    (%rdi,%rdi,4), %rax
    leaq    sea(,%rax,4), %rax
    ret

sea:
    .long   9
    .long   8
    .long   1
    .long   9
    .long   5
    .long   9
    .long   8
...
```

Nested Array Row Access Code

```
int* get_sea_zip(int index)
{
  return sea[index];
}
```

```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

- What data type is `sea[index]`?
- What is its value?

```
  # %rdi = index
  leaq (%rdi,%rdi,4),%rax
  leaq sea(,%rax,4),%rax
```

Translation?

Nested Array Row Access Code

```
int* get_sea_zip(int index)
{
  return sea[index];
}
```

```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

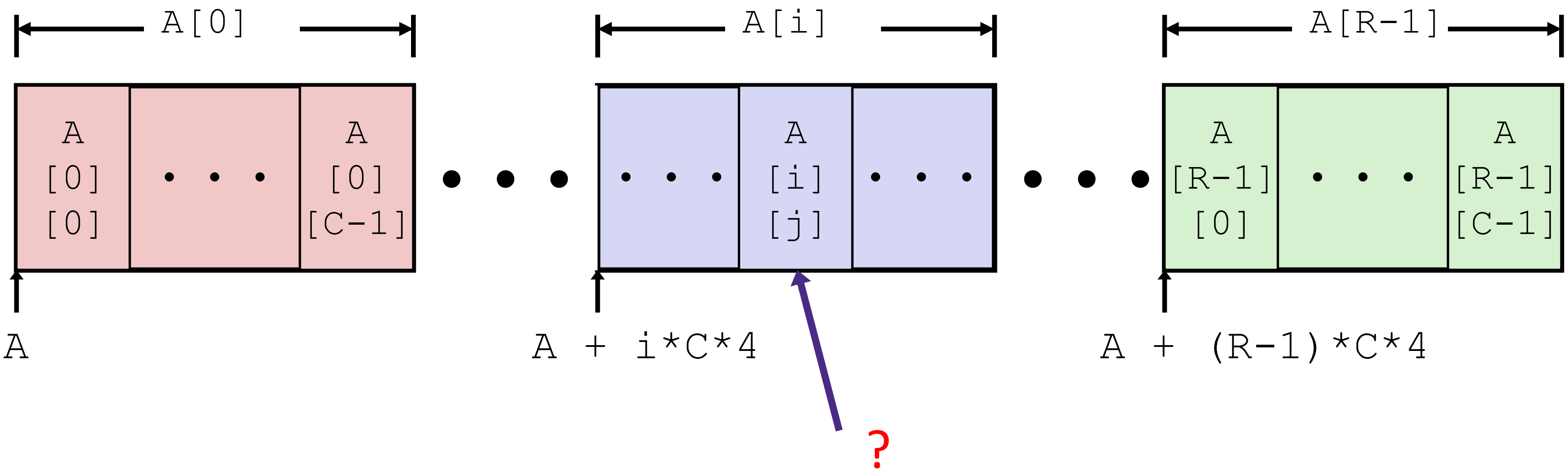
```
  # %rdi = index
  leaq (%rdi,%rdi,4),%rax  # 5 * index
  leaq sea(,%rax,4),%rax   # sea + (20 * index)
```

- Row Vector
  - `sea[index]` is array of 5 `ints`
  - Starting address = `sea+20*index`
- Assembly Code
  - Computes and returns address
  - Compute as: `sea+4*(index+4*index)= sea+20*index`

Nested Array Element Access

- Array Elements
  - `A[i][j]` is element of type **`T`**, which requires K bytes
  - Address of `A[i][j]` is

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

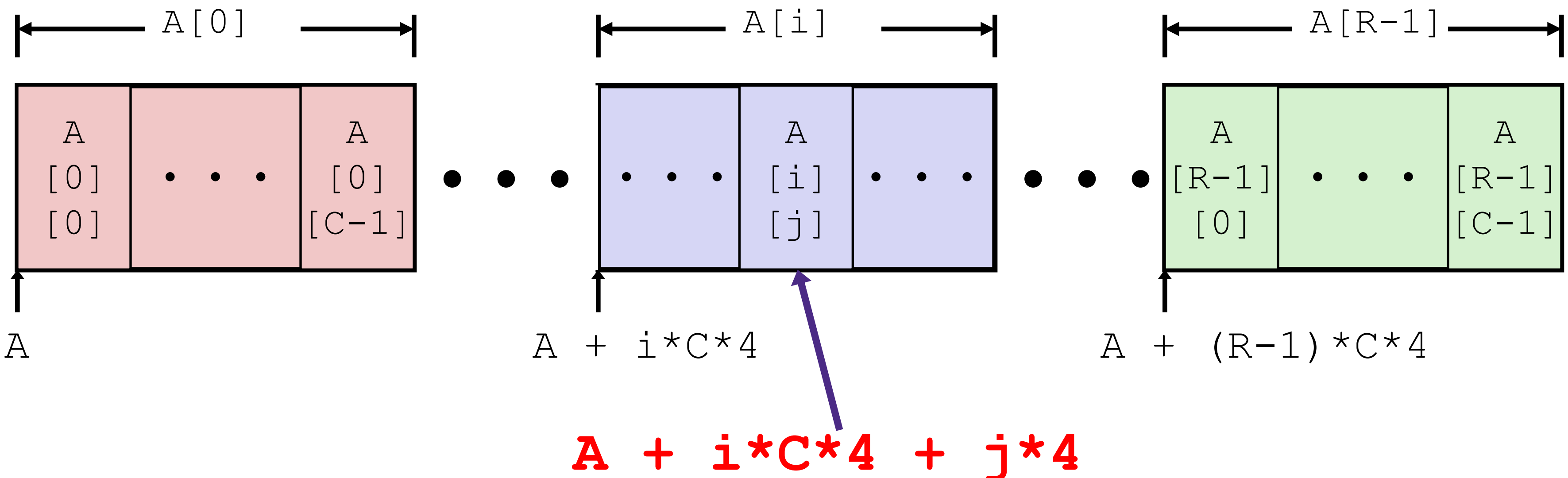


Nested Array Element Access

- Array Elements
  - `A[i][j]` is element of type **`T`**, which requires K bytes
  - Address of `A[i][j]` is

    `A + i*(C*K) + j*K == A + (i*C + j)*K`

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



Nested Array Element Access Code

```
int get_sea_digit
  (int index, int digit)
{
  return sea[index][digit];
}
```

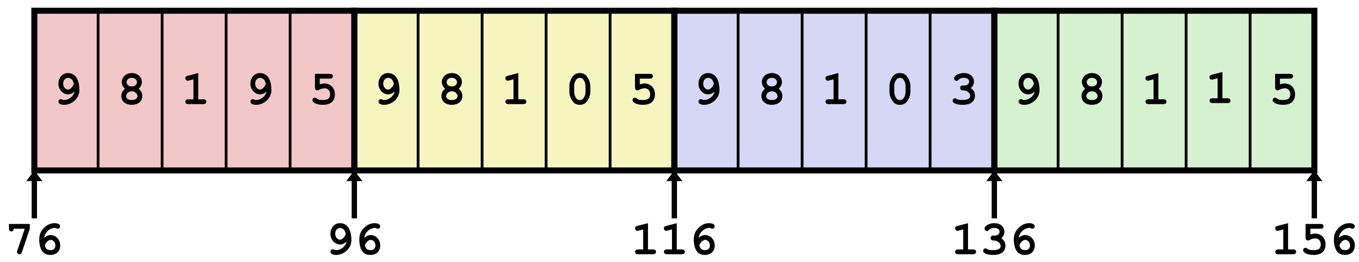
```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

```
leaq   (%rdi,%rdi,4), %rax   # 5*index
addl   %rax, %rsi            # 5*index+digit
movl   sea(,%rsi,4),  %eax   # *(sea + 4*(5*index+digit))
```

- Array Elements
  - `sea[index][digit]` is an **`int`** (**`sizeof`**`(`**`int`**`)=4`)
  - Address = `sea + 5*4*index + 4*digit`
- Assembly Code
  - Computes address as: `sea + ((index+4*index) + digit)*4`
  - `movl` performs memory reference

Multidimensional Referencing Examples

```
int sea[4][5];
```



Reference	Address	Value	Guaranteed?
`sea[3][3]`			
`sea[2][5]`			
`sea[2][-1]`			
`sea[4][-1]`			
`sea[0][19]`			
`sea[0][-1]`			

- Code does not do any bounds checking
- Ordering of elements within array guaranteed

Data Structures in Assembly

- **Arrays**
  - One-dimensional
  - Multidimensional (nested)
  - **Multilevel**
- Structs
  - Alignment
- ~~Unions~~

Multilevel Array Example

Multilevel Array Declaration(s):

```
int cmu[5] = { 1, 5, 2, 1, 3 };
int  uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

```
int* univ[3] = {uw, cmu, ucb};
```

Is a multilevel array the same thing as a 2D array?

NO

2D Array Declaration:

```
int univ2D[3][5] = {
  { 9, 8, 1, 9, 5 },
  { 1, 5, 2, 1, 3 },
  { 9, 4, 7, 2, 0 }
};
```

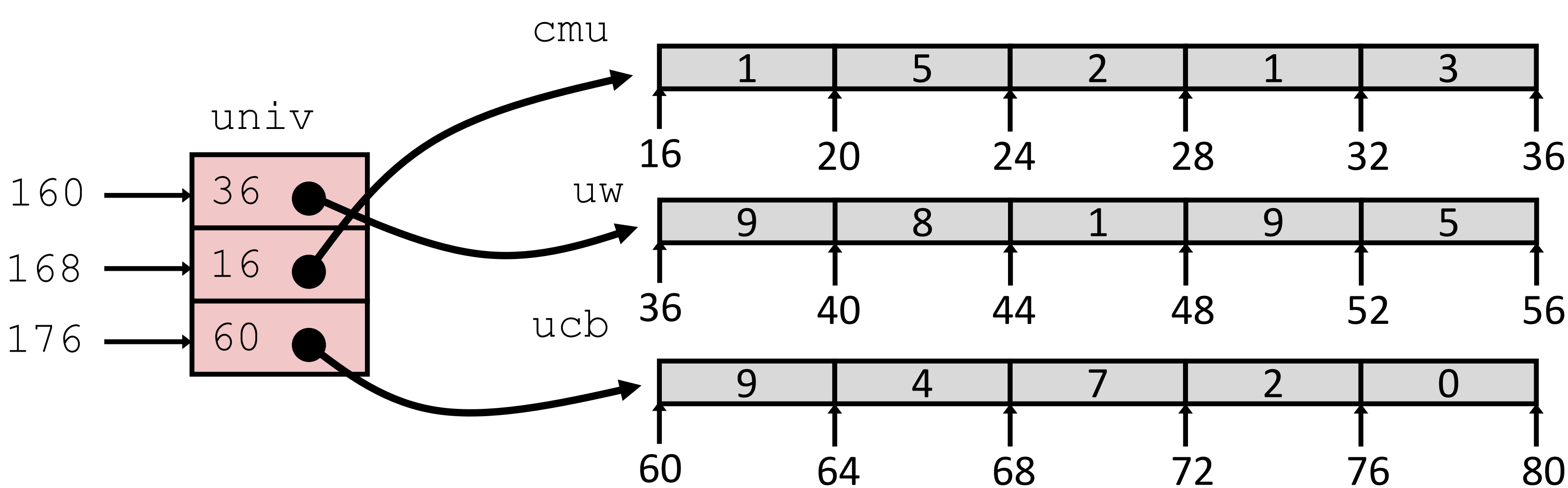
One array declaration = one contiguous block of memory

Multilevel Array Example

```
int cmu[5] = { 1, 5, 2, 1, 3 };
int  uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

```
int* univ[3] = {uw, cmu, ucb};
```

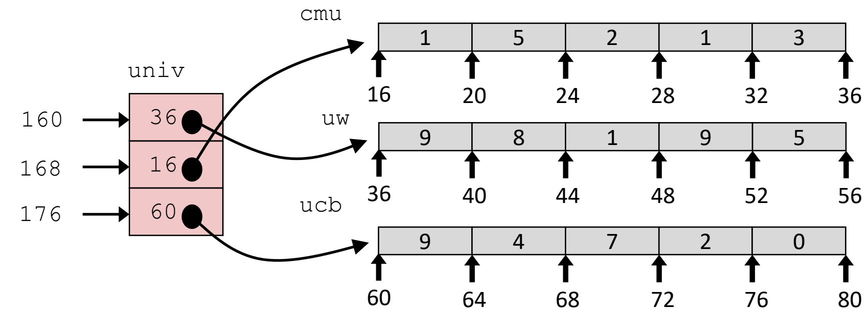
- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 8 bytes each
- Each pointer points to array of `int`s



Note: this is how Java represents multidimensional arrays

Element Access in Multilevel Array

```
int get_univ_digit
  (int index, int digit)
{
  return univ[index][digit];
}
```



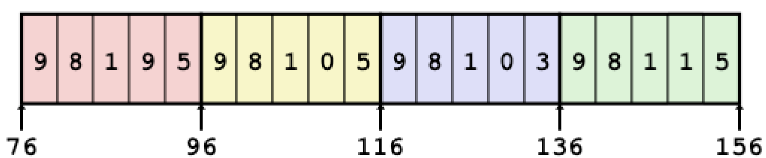

```
salq    $2, %rsi             # rsi = 4*digit
addq    univ(,%rdi,8), %rsi  # p = univ[index] + 4*digit
movl    (%rsi), %eax         # return *p
ret
```

- Computation
  - Element access Mem[Mem[univ+8*index]+4*digit]
  - Must do **two memory reads**
    - First get pointer to row array
    - Then access element within array
  - But allows inner arrays to be different lengths (not in this example)

Array Element Accesses

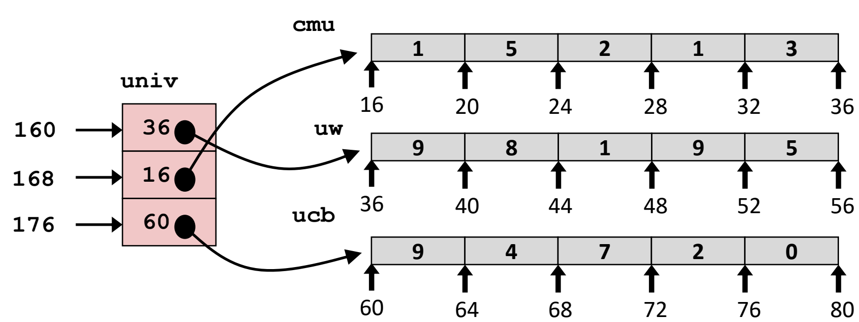
Multidimensional array

```
int get_sea_digit
  (int index, int digit)
{
  return sea[index][digit];
}
```



Multilevel array

```
int get_univ_digit
  (int index, int digit)
{
  return univ[index][digit];
}
```

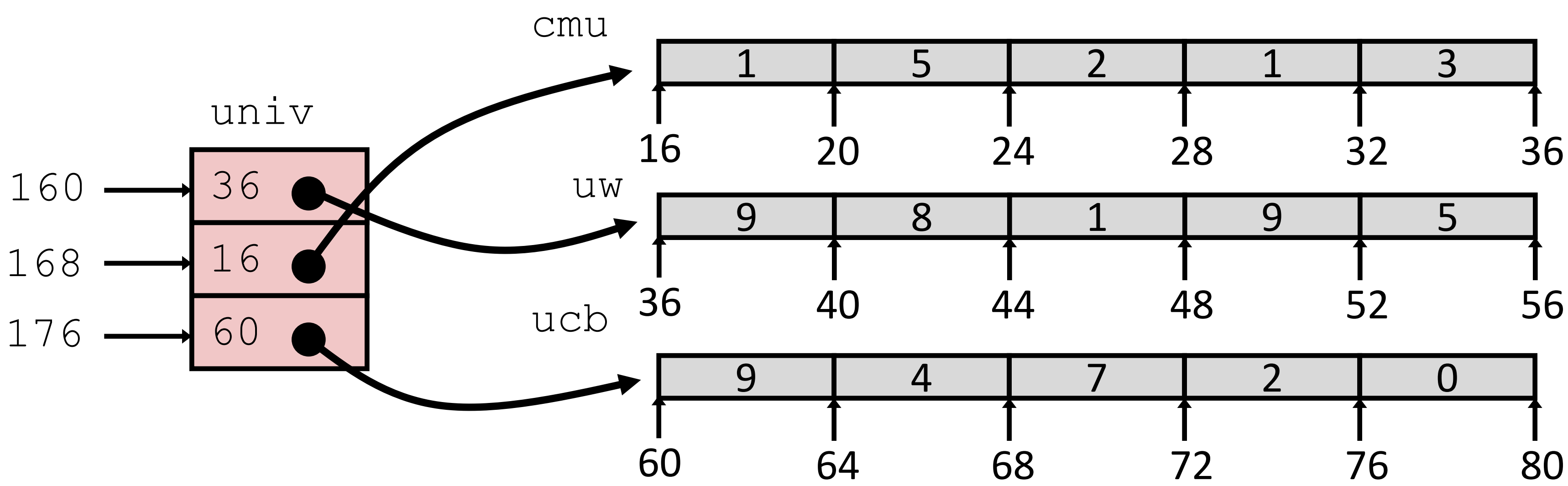


Access *looks* the same, but it isn't:

Mem[sea+20*index+4*digit]

Mem[Mem[univ+8*index]+4*digit]

Multilevel Referencing Examples



Reference	Address	Value	Guaranteed?
`univ[2][3]`			
`univ[1][5]`			
`univ[2][-2]`			
`univ[3][-1]`			
`univ[1][12]`			

- C code does not do any bounds checking
- Location of each lower-level array in memory is *not* guaranteed

Summary

- Contiguous allocations of memory
- No bounds checking (and no default initialization)
- Can usually be treated like a pointer to first element
- `int a[4][5];` → array of arrays
  - all levels in one contiguous block of memory
- `int* b[4];` → array of pointers to arrays
  - First level in one contiguous block of memory
  - Each element in the first level points to another "sub" array
  - Parts anywhere in memory