Arrays

CSE 351 Autumn 2016

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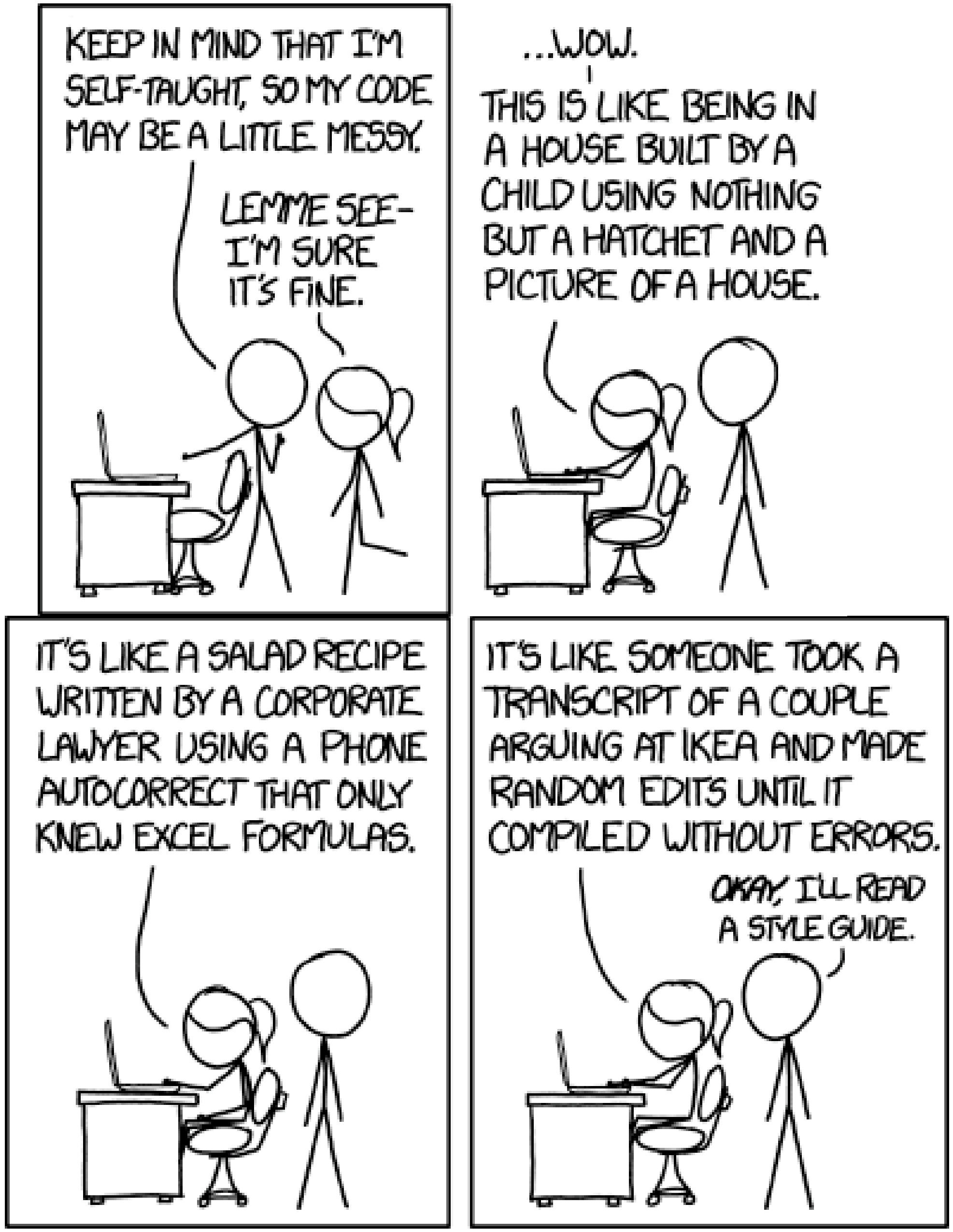


http://xkcd.com/1513/

Administrivia

- Lab 2 due Friday
- Homework 2 released on Friday

- **Midterm** on Nov. 2 in lecture
  - Make a cheat sheet! – two-sided letter page, *handwritten*
  - Midterm details Piazza post: @225
    - Past Num Rep and Floating Point questions posted (solutions tonight)
- **Midterm review session**
  - 5-7pm on Monday, Oct. 31 in EEB 105

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:

Computer system:

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

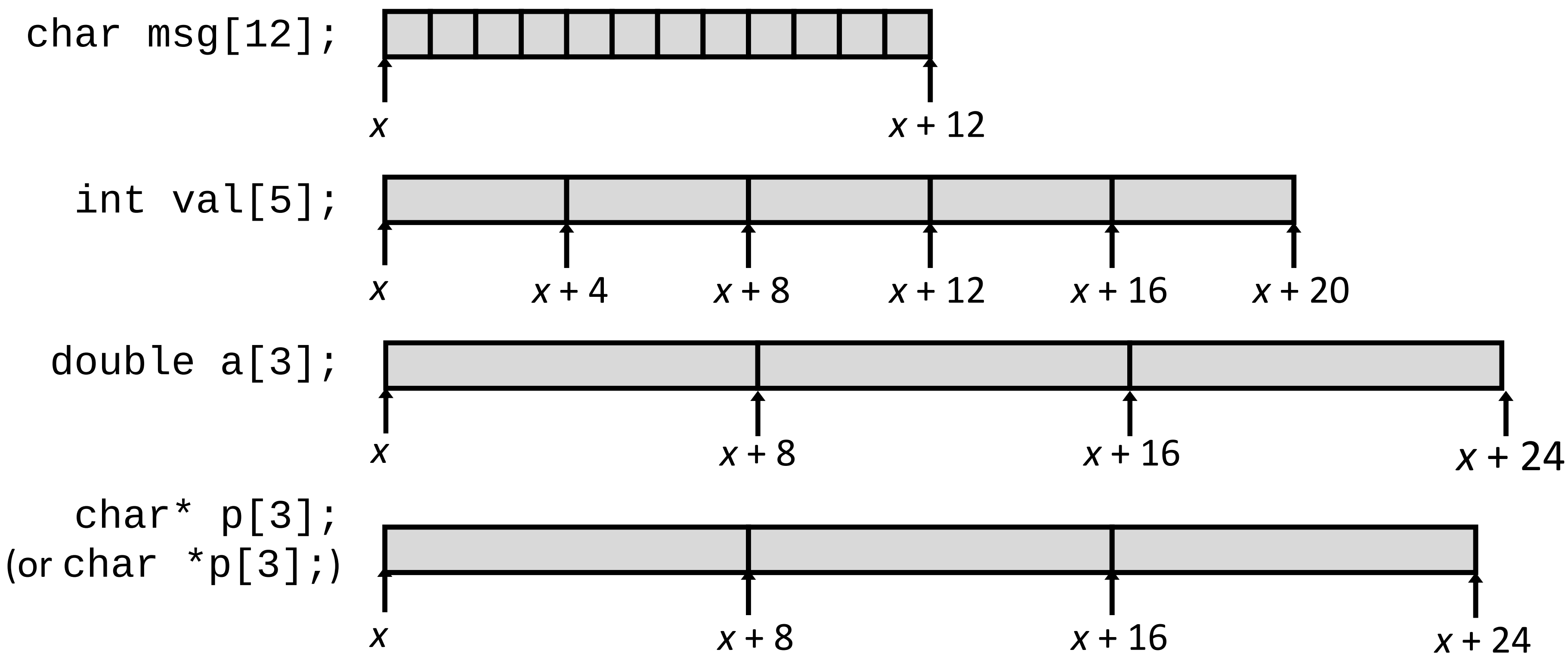
Data Structures in Assembly

- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- Structs
  - Alignment
- Unions

- Also: Some C details and how they relate to Java and assembly
  - C arrays are convenient but with some unique/strange rules

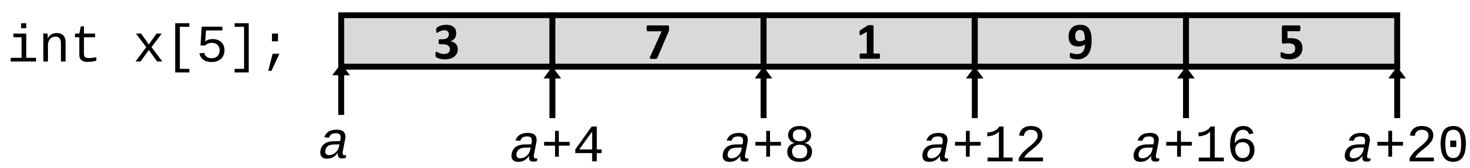
Array Allocation

- 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*`)



Array Access

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



- 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

```
typedef int zip_dig[5];

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

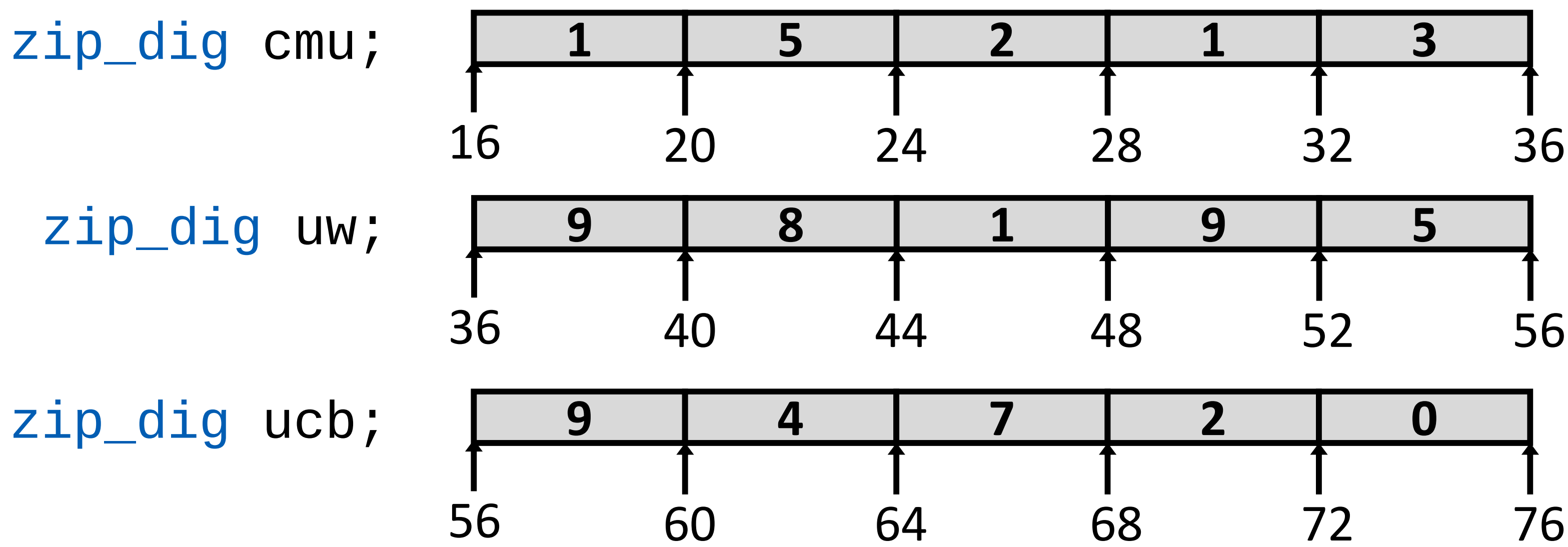
initialization

`int uw[5] …`

Array Example

```
typedef int zip_dig[5];

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

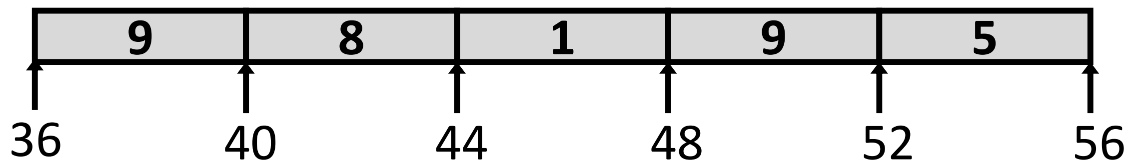


- `typedef`: Declaration "`zip_dig uw`" equivalent to "`int uw[5]`"
- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

```
typedef int zip_dig[5];
```

Array Accessing Example

```
zip_dig uw;
```




```
int get_digit(zip_dig z, int digit)
{
  return z[digit];
}
```

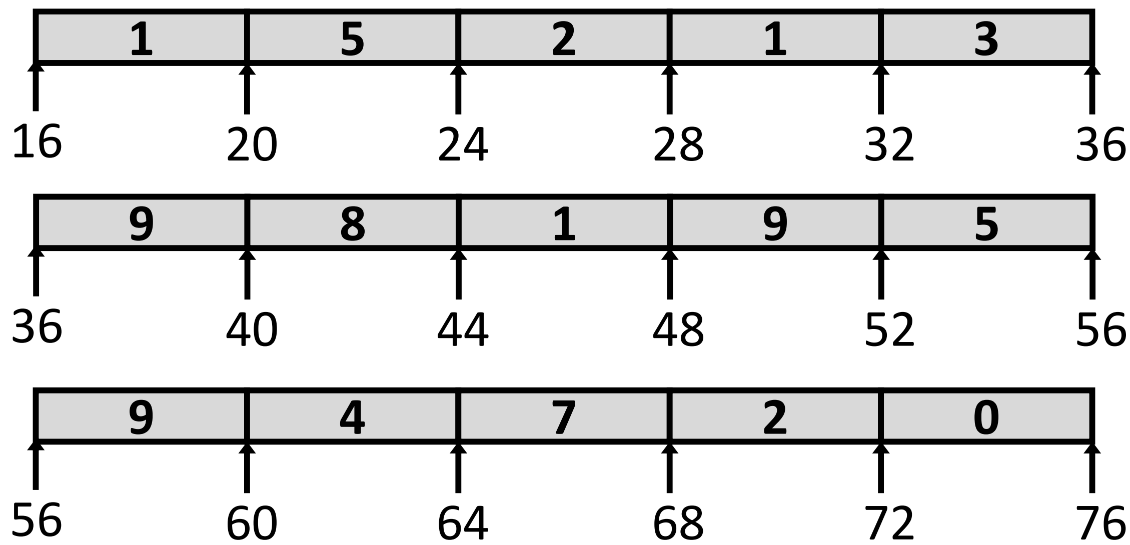
```
get_digit:
  movl (%rdi,%rsi,4), %eax  # z[digit]
```

- 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)`

```
typedef int zip_dig[5];
```

Referencing Examples

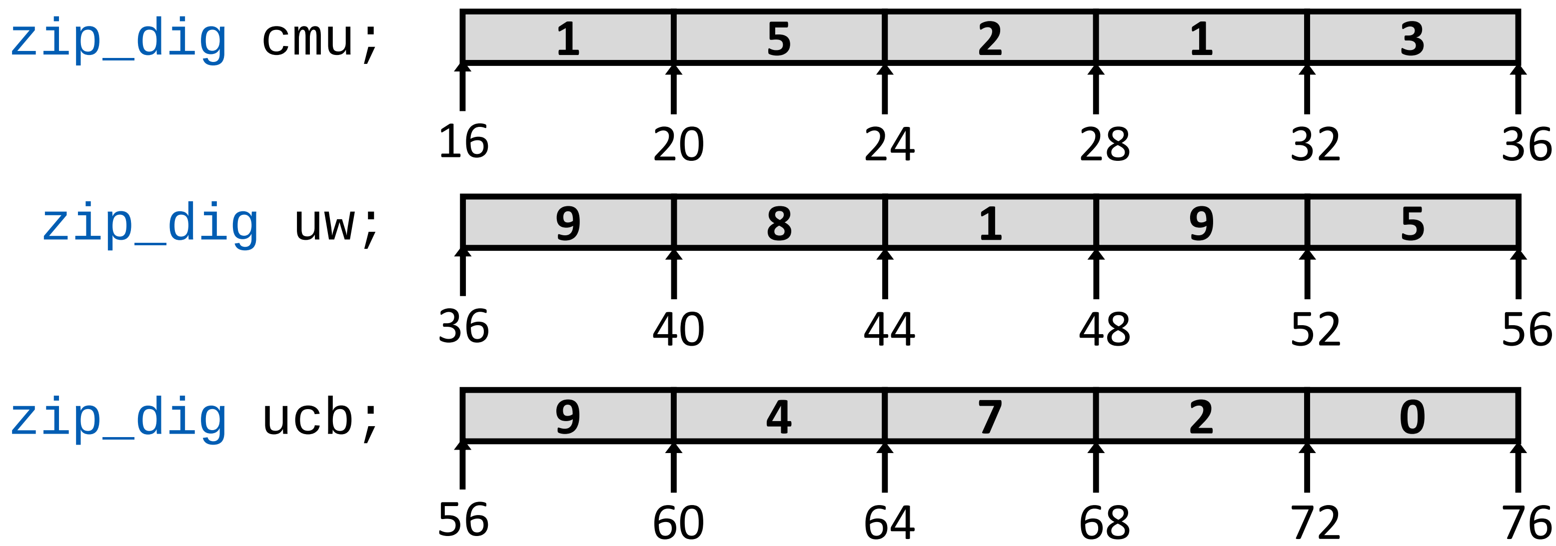
```
zip_dig cmu;
zip_dig uw;
zip_dig ucb;
```



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

```
typedef int zip_dig[5];
```

Referencing Examples



Reference	Address	Value	Guaranteed?
`uw[3]`	`36 + 4* 3 = 48`	9	Yes
`uw[6]`	`36 + 4* 6 = 60`	4	No
`uw[-1]`	`36 + 4*-1 = 32`	3	No
`cmu[15]`	`16 + 4*15 = 76`	??	No

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

```
typedef int zip_dig[5];
```

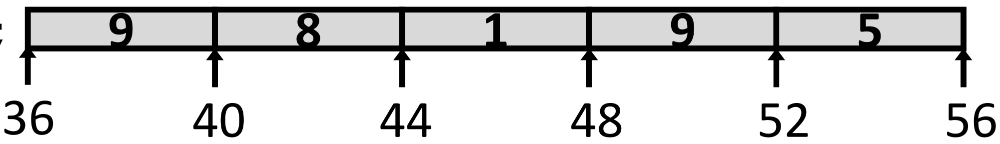
Array Loop Example

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

```
zi = 10*0 + 9 = 9
zi = 10*9 + 8 = 98
zi = 10*98 + 1 = 981
zi = 10*981 + 9 = 9819
zi = 10*9819 + 5 = 98195
```

9	8	1	9	5

`zip_dig uw;`



Array Loop Example

- Original:

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

- Transformed:
  - Eliminate loop variable `i`, use pointer `zend` instead
  - Convert array code to pointer code
    - Pointer arithmetic on z
  - Express in do-while form (no test at entrance)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 5;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z < zend);
  return zi;
}
```

address just past 5th digit (points to `z + 5;`)

Increments by 4 (size of int) (points to `z++;`)

Array Loop Implementation

gcc with –O1

- Registers:
```
%rdi  z
%rax  zi
%rcx  zend
```
- Computations
  - `10*zi + *z` implemented as: `*z + 2*(5*zi)`
  - `z++` increments by 4 (size of `int`)

```c
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 5;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z < zend);
  return zi;
}
```

```
  # %ecx = z
  leaq 20(%rdi),%rcx       # rcx = zend  = z+5
  movl $0,%eax             # rax = zi = 0
.L17:
  leal (%rax,%rax,4),%edx  # zi + 4*zi = 5*zi
  movl (%rdi),%eax         # eax = *z
  leal (%rax,%rdx,2),%eax  # zi = *z + 2*(5*zi)
  addq $4,%rdi             # z++
  cmpq %rdi,%rcx           # zend : z
  jne .L17                 # if != goto loop
```

[[Long Code Demo]]

- See `arrays_in_c.c` for warning-free code that demonstrates:
  - Arrays created on the Heap and on the Stack
  - Reminder of relative positions of Memory sections
  - `typedef`
  - Macro substitution (`#define`)
  - Implicit pass-by-reference of arrays in C
  - `sizeof()` with arrays

Code Demo Takeaways

- Array variables don't have addresses – return address of array
  - Pointers actually have addresses
- Arrays can be created on Stack, Heap, or Static Data
  - Stack (local var) is temporary
  - Heap (`malloc`) is more permanent, but requires memory management
  - Static Data (global var) can have dangerously broad scope
  - Not automatically initialized!
- Passing an array to a procedure actually passes a pointer to the array

```
typedef int zip_dig[5];
```

Nested Array Example

```
zip_dig sea[4] =
  {{ 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

same as:

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

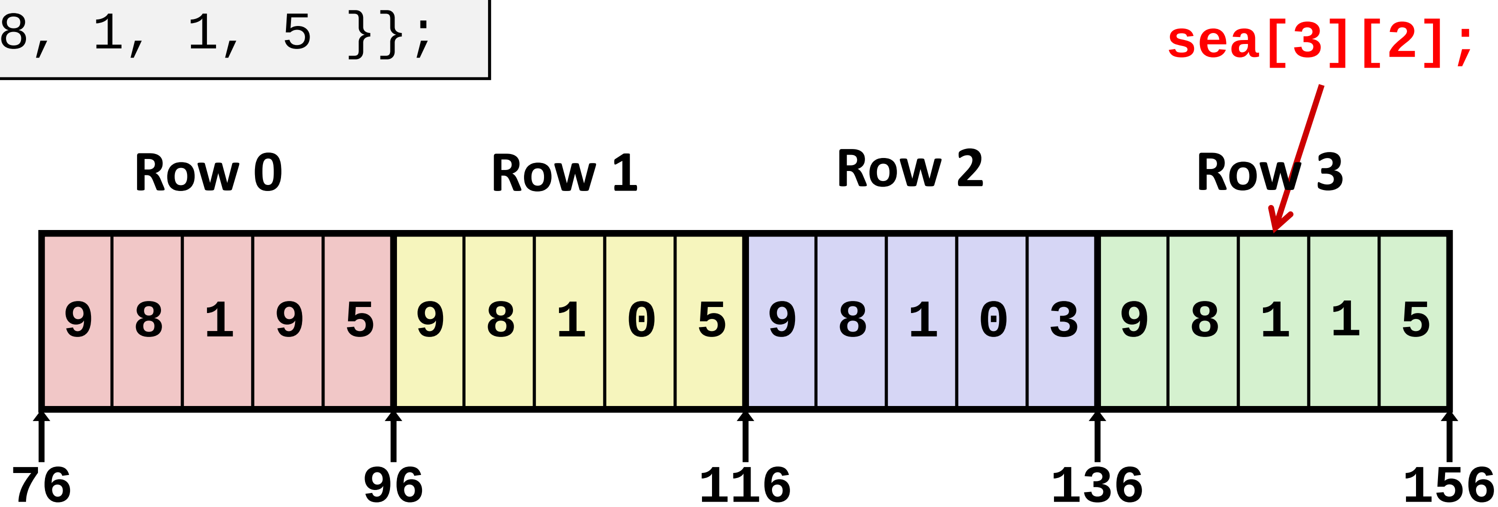
What is the layout in memory?

```
typedef int zip_dig[5];
```

Nested Array Example

```
zip_dig sea[4] =
  {{ 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)

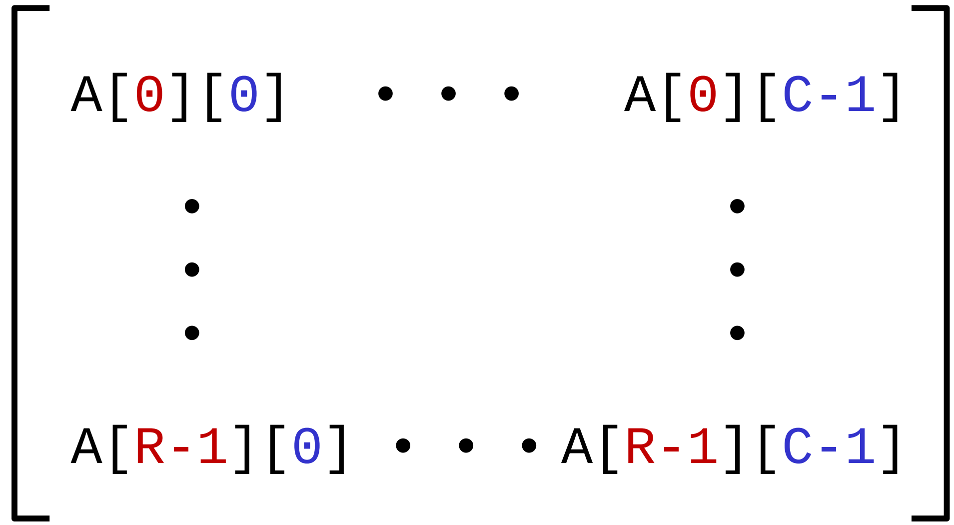
Two-Dimensional (Nested) Arrays

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

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

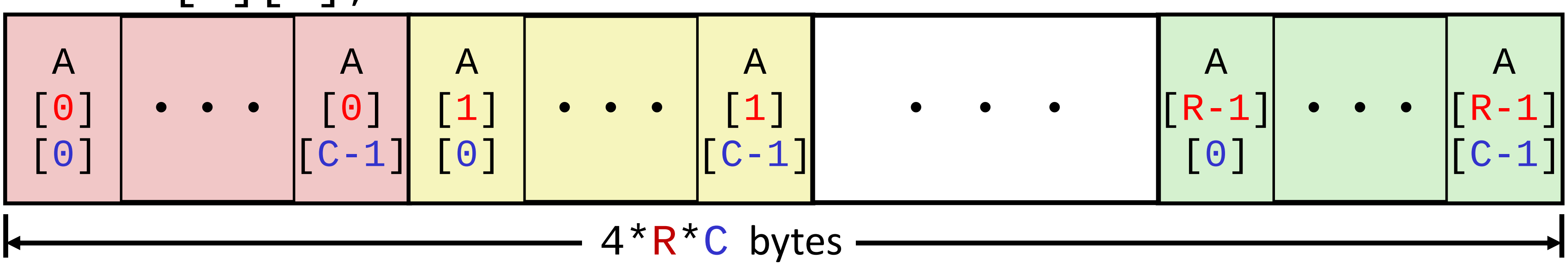
Two-Dimensional (Nested) Arrays

- 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

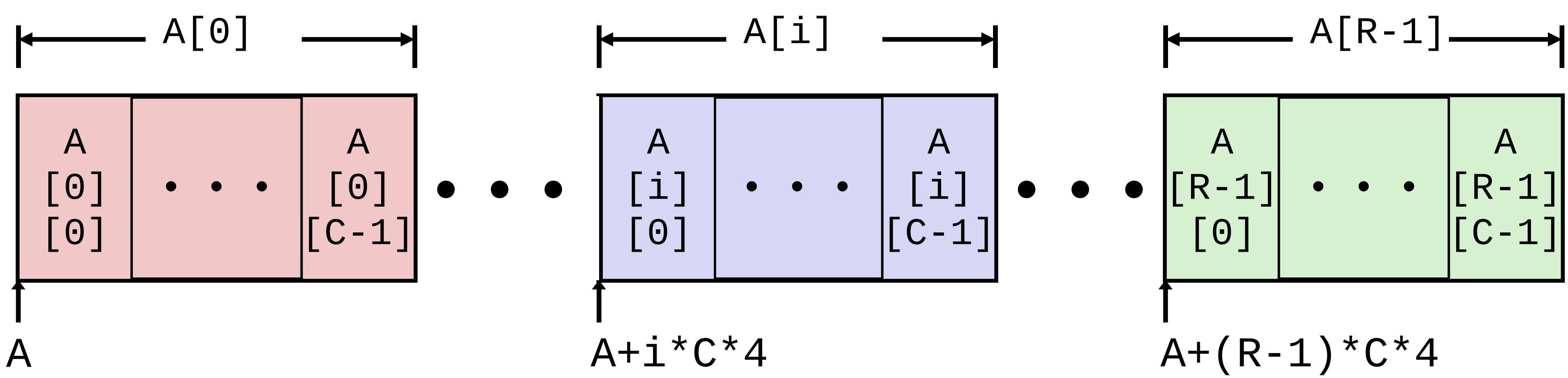
```
int A[R][C];
```



Nested Array Row Access

- Row vectors
  - Given `T A[R][C]`,
    - `A[i]` is an array of C elements ("row `i`")
    - Each element of type T requires *K* bytes
    - A is address of array
    - Starting address of row `i = A + i*(C * K)`

```
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 }};
```

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

```
get_sea_zip(int):
	movslq  %edi, %rdi
	leaq    (%rdi,%rdi,4), %rdx
	leaq    0(,%rdx,4), %rax
	addq    $sea, %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 starting address?

```
# %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];
}
```

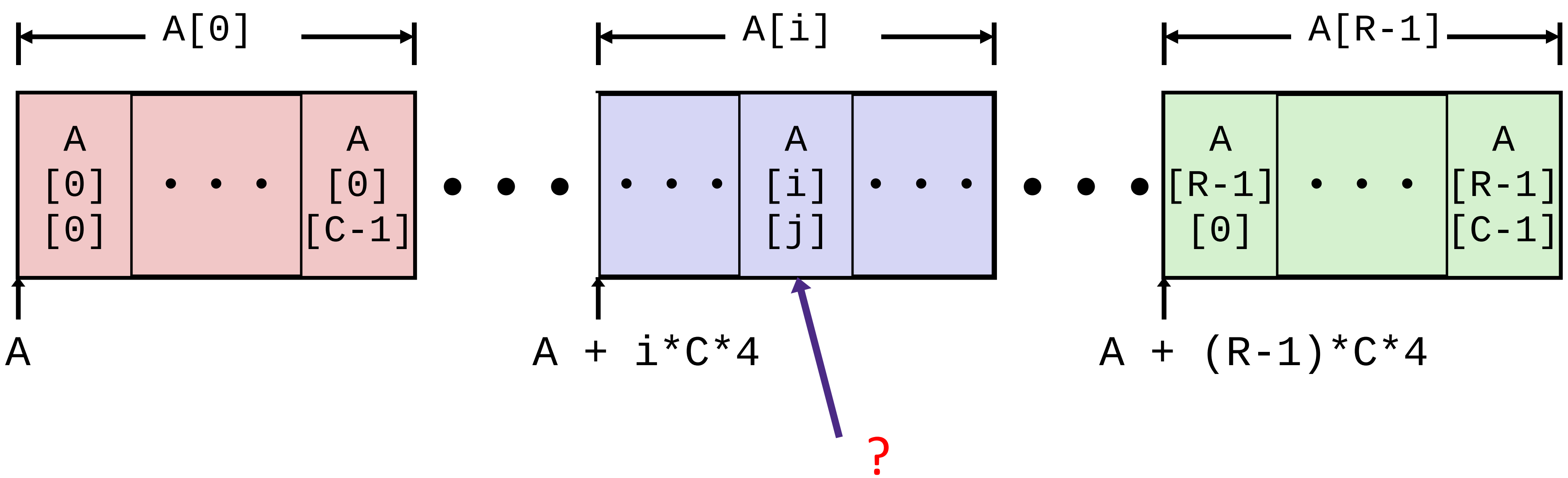
```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

```
# %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 `int`s
  - 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

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

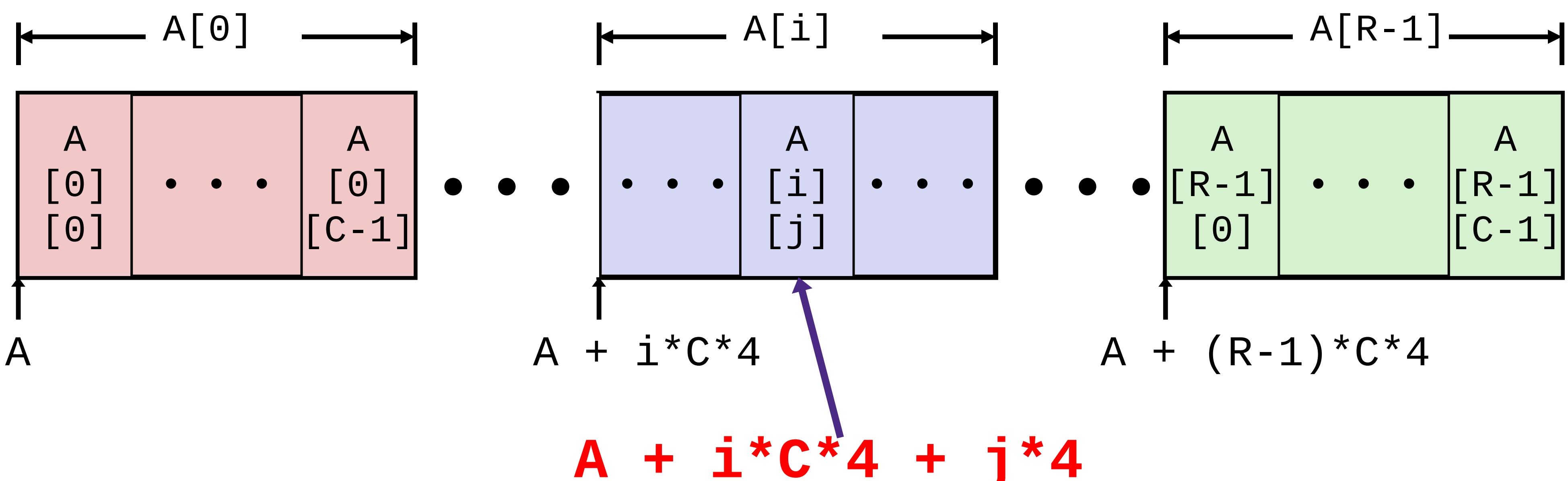


Nested Array Element Access

- 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 }};
```

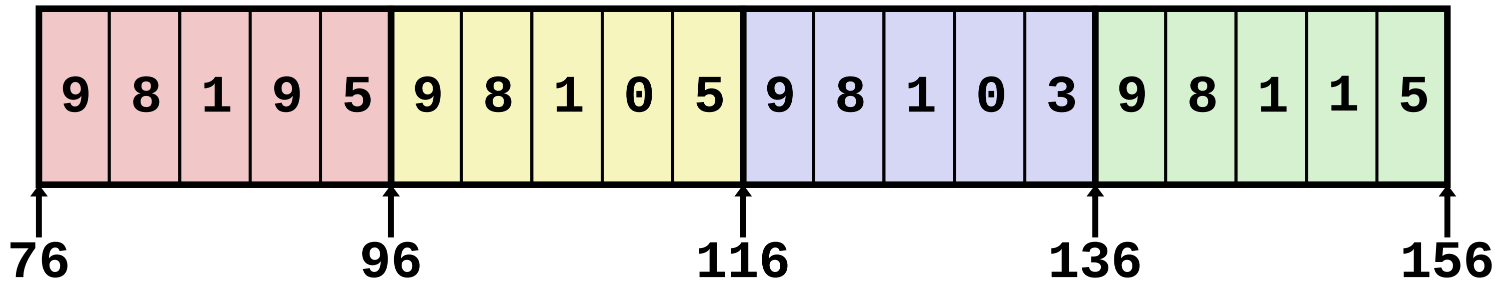
```
leaq   (%rdi,%rdi,4), %rax   # 5*index
addl   %rax, %rsi            # 5*index+digit
movl   sea(,%rsi,4),  %eax   # *(sea + 4*(5*index+digit))
```

- 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

```
typedef int zip_dig[5];
```

Strange Referencing Examples

```
zip_dig sea[4];
```



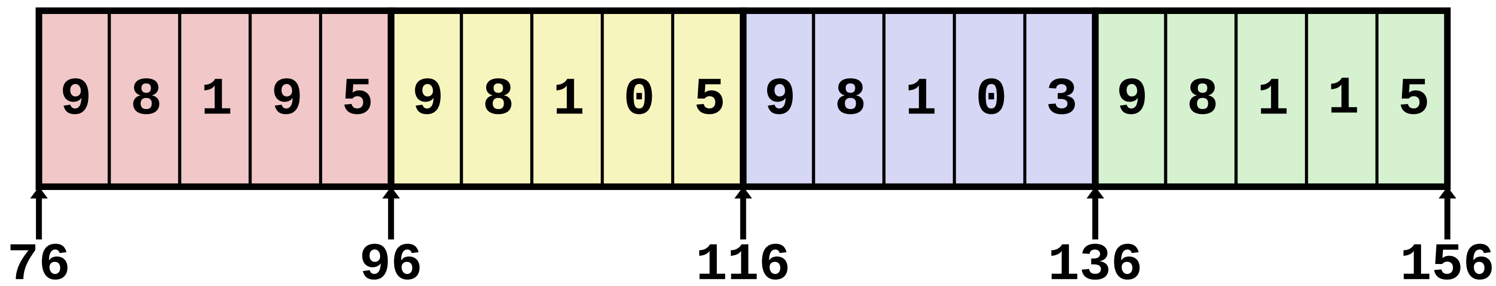
Reference	Address	Value	Guaranteed?
`sea[3][3]`			
`sea[2][5]`			
`sea[2][-1]`			
`sea[4][-1]`			
`sea[0][19]`			
`sea[0][-1]`			

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

```
typedef int zip_dig[5];
```

Strange Referencing Examples

```
zip_dig sea[4];
```



Reference	Address	Value	Guaranteed?
`sea[3][3]`	`76+20*3+4*3 = 148`	1	Yes
`sea[2][5]`	`76+20*2+4*5 = 136`	9	Yes
`sea[2][-1]`	`76+20*2+4*-1 = 112`	5	Yes
`sea[4][-1]`	`76+20*4+4*-1 = 152`	5	Yes
`sea[0][19]`	`76+20*0+4*19 = 152`	5	Yes
`sea[0][-1]`	`76+20*0+4*-1 = 72`	??	No

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

Multi-Level Array Example

Multi-Level 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 multi-level array the same thing as a 2D array?

NO

2D Array Declaration:

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

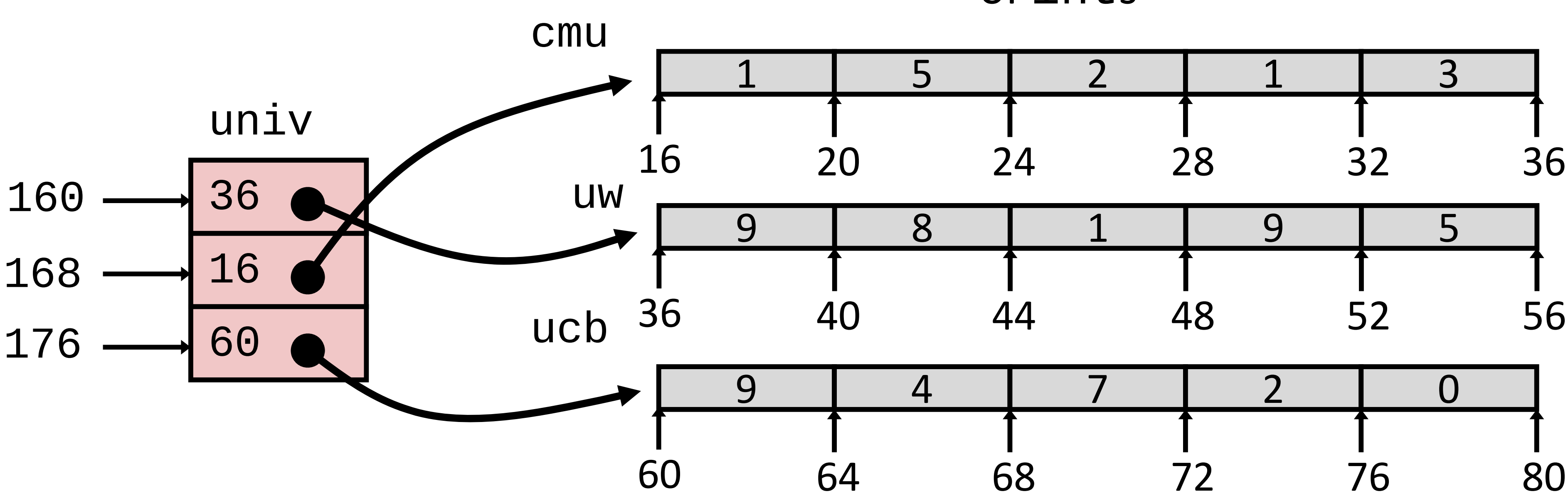
One array declaration = one contiguous block of memory

Multi-Level 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};
```

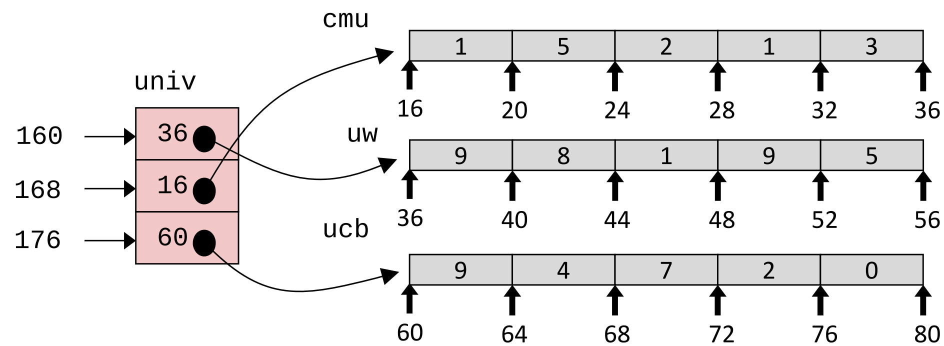
- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 8 bytes each
- Each pointer points to array of `int`s



Note: this is how Java represents multi-dimensional arrays

Element Access in Multi-Level Array

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



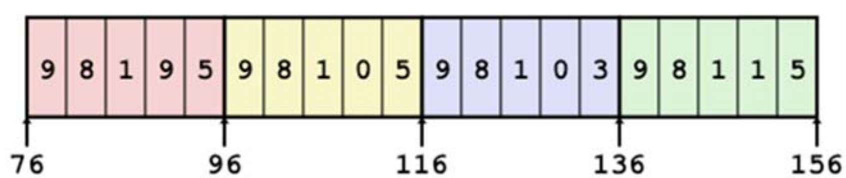

```
salq    $2, %rsi              # rsi = 4*digit
addq    univ(,%rdi,8), %rsi   # p = univ[index] + 4*digit
movl    (%rsi), %eax          # return *p
ret
```

- 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

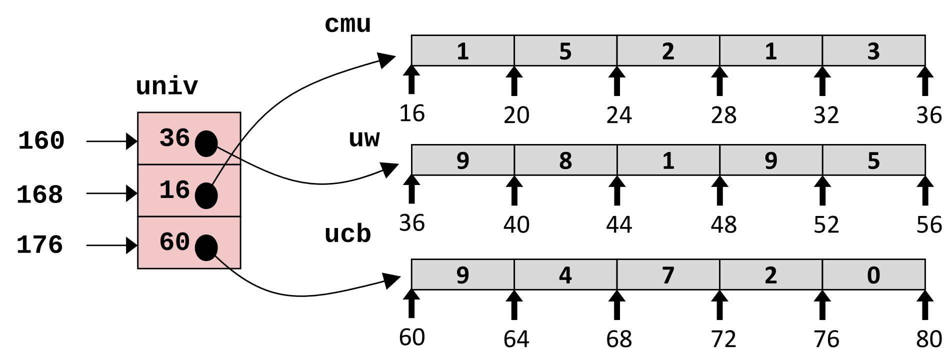
Nested array

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



Multi-level array

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

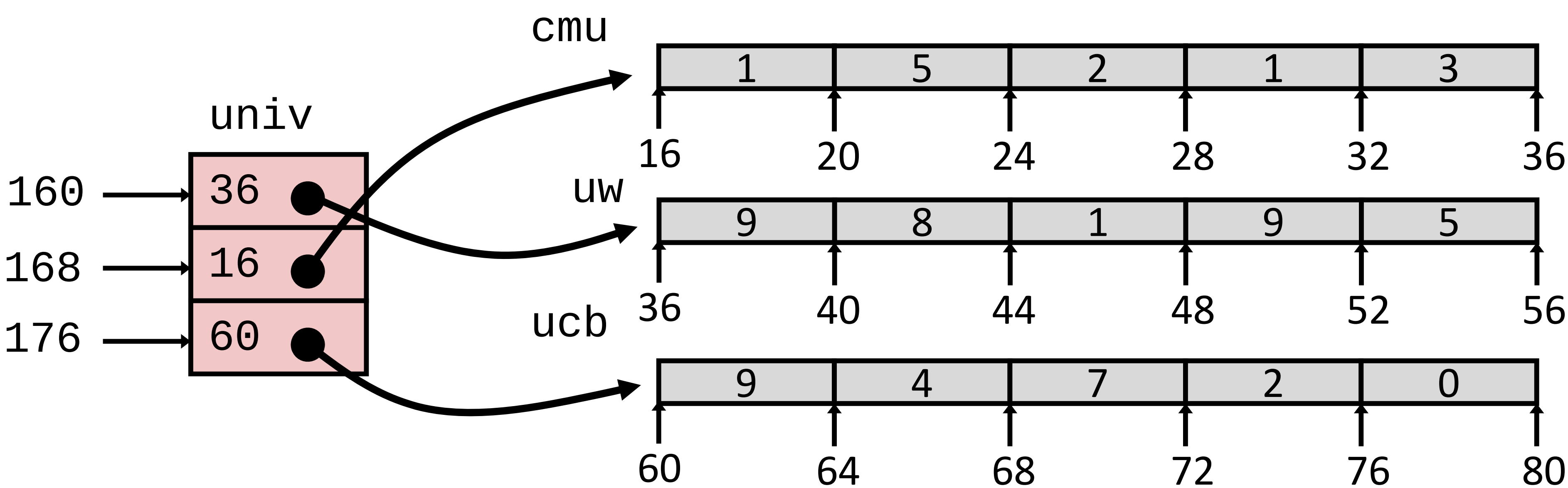


Access *looks* the same, but it isn't:

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

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

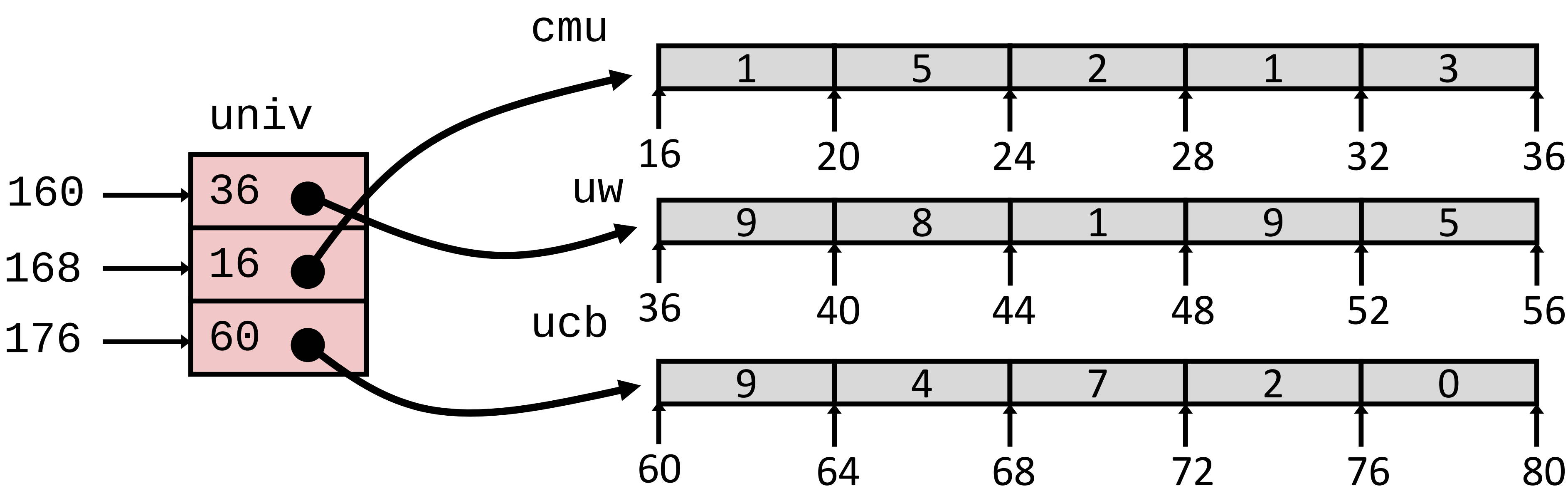
Strange Referencing Examples



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

Strange Referencing Examples



Reference	Address	Value	Guaranteed?
univ[2][3]	60+4*3 = 72	2	Yes
univ[1][5]	16+4*5 = 36	9	No
univ[2][-2]	60+4*-2 = 52	5	No
univ[3][-1]	#@%!^??	??	No
univ[1][12]	16+4*12 = 64	4	No

- 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