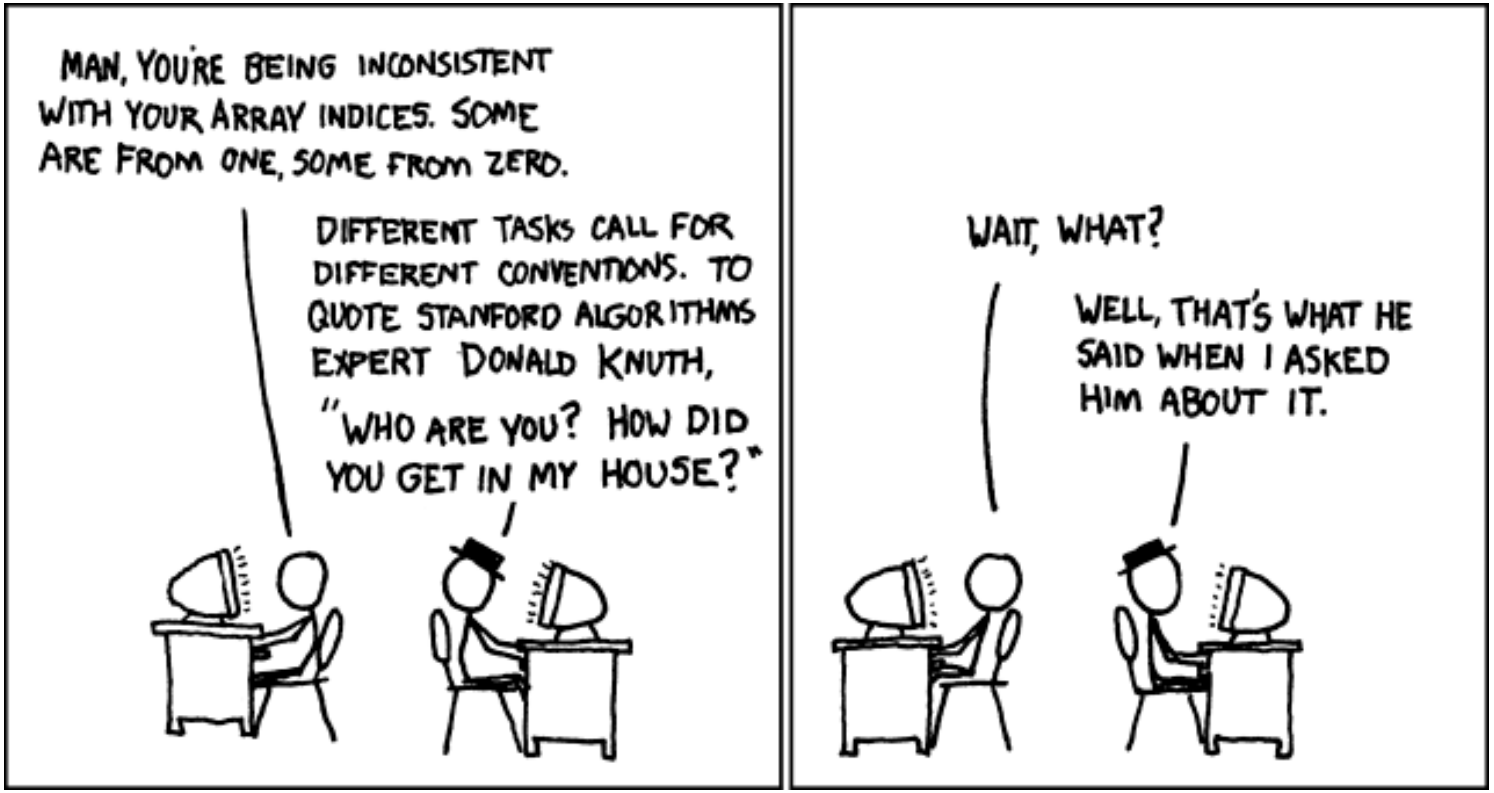
Arrays

CSE 351 Spring 2018



http://xkcd.com/163/

Announcements

See the important email I sent on Friday!!

- Lab 2 Due Soon
- Midterm Friday
  - Reference sheet posted
  - Section this week is [insufficient] review
- I'll be out of town Wednesday-Friday
  - Sam does lecture
  - Eric covers my office hours [different location]
  - I'll be in contact with TAs during the exam

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();
```

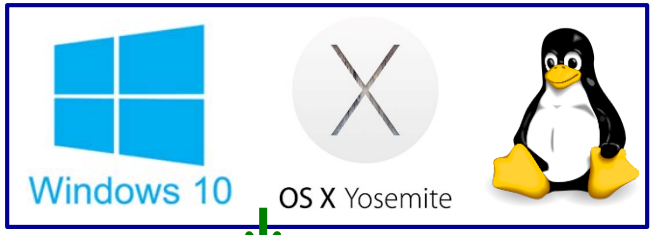
Assembly language:

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

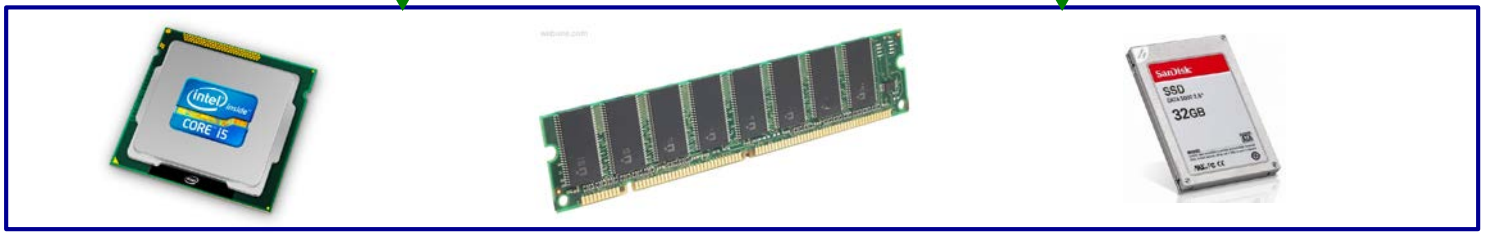
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
11000001111110100011111
```

OS:



Computer system:



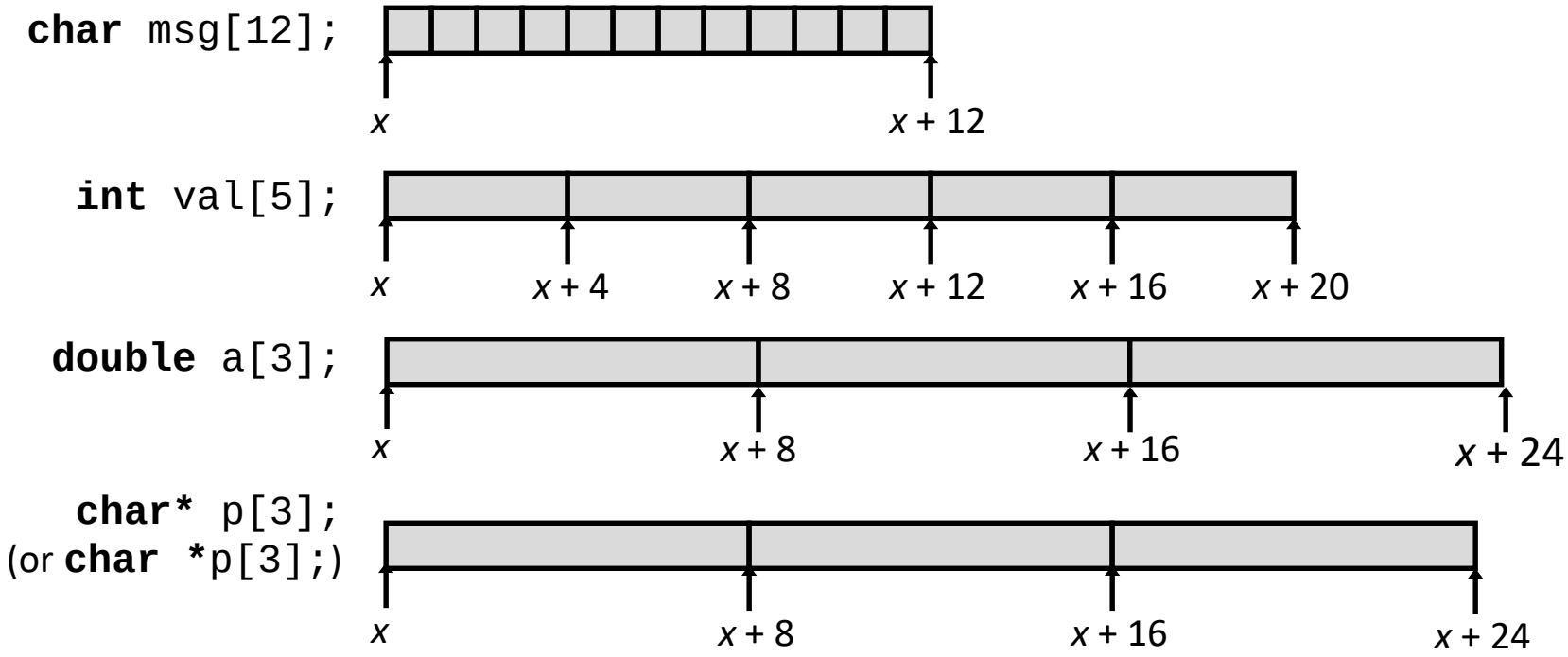
Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Data Structures in Assembly

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

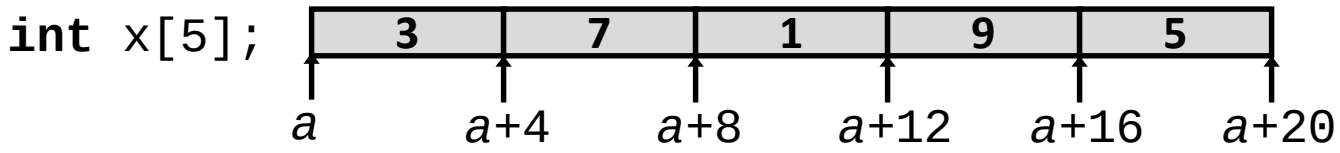
Array Allocation

- 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
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 };
```

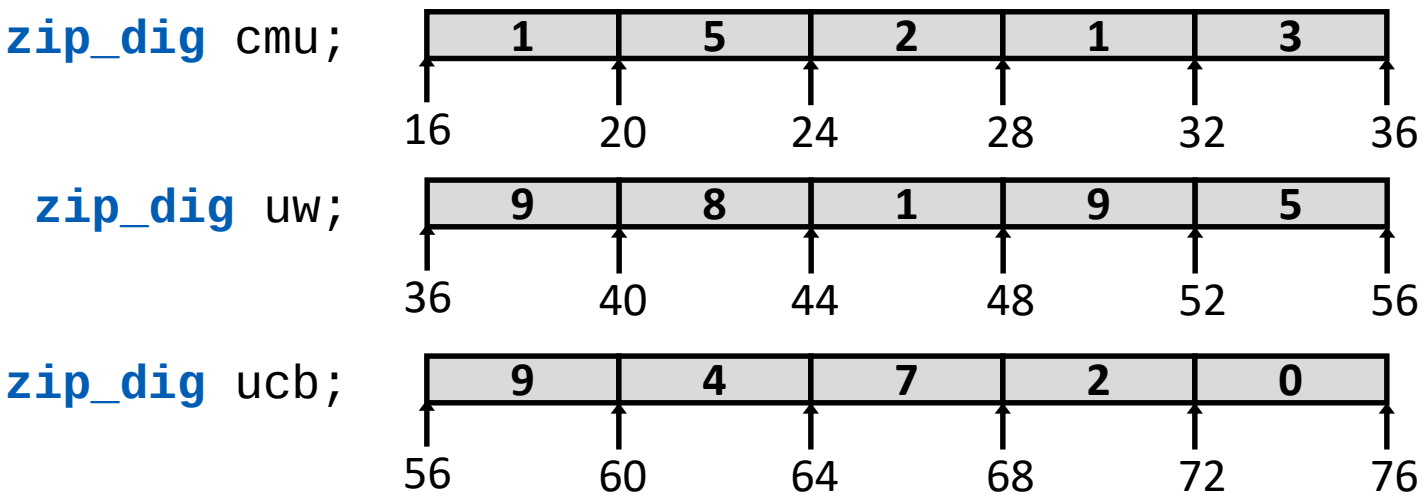
initialization

- `typedef`: Declaration "**`zip_dig`** uw" equivalent to "**`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 };
```

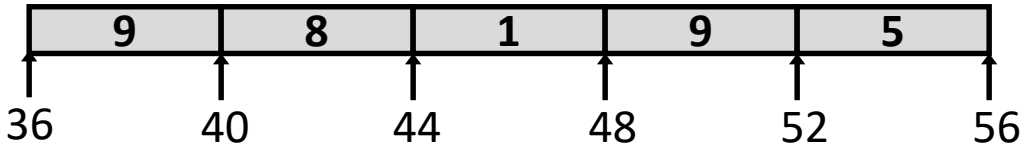


- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

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

Array Accessing Example

```
zip_dig uw;
```




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

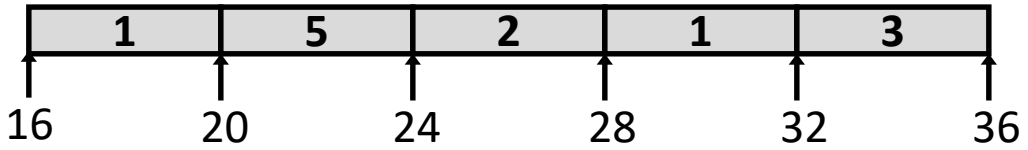
```
get_digit:
  movl (%rdi,%rsi,4), %eax  # z[digit]
```

- 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)`

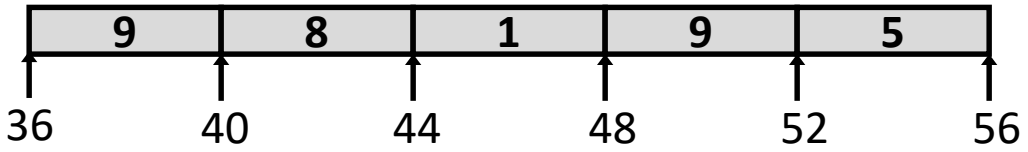
```
typedef int zip_dig[5];
```

Referencing Examples

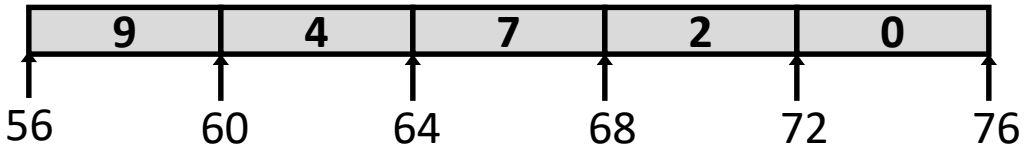
```
zip_dig cmu;
```




```
zip_dig uw;
```




```
zip_dig ucb;
```



Reference	Address	Value	Guaranteed?
uw[3]	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
```

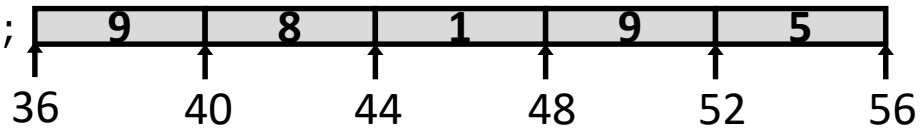
```
zi = 10*98 + 1 = 981
```

```
zi = 10*981 + 9 = 9819
```

```
zi = 10*9819 + 5 = 98195
```

9	8	1	9	5

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

Increments by 4 (size of int)

Array Loop Implementation

gcc with -O1

- Registers:
  - %rdi z
  - %rax zi
  - %rcx zend

- Compiler is rather clever:

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

```
   # %rdi = z
   leaq 20(%rdi),%rcx      #
   movl $0,%eax            #
.L17:
   leal (%rax,%rax,4),%edx #
   movl (%rdi),%eax        #
   leal (%rax,%rdx,2),%eax #
   addq $4,%rdi            #
   cmpq %rdi,%rcx          #
   jne .L17                #
```

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)

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

```
   # %rdi = 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
```

C Details: Arrays and Pointers

- Arrays are (almost) identical to pointers
  - `char *string` and `char string[]` are the *same* as function parameters/results
  - But *different* for local-variable declarations: a pointer variable versus a *stack-allocated array*
    - *Different* for global-variables too

- An array variable acts like a pointer to the first (0^{th}) element *when used in an expression*
  - `ar[0]` same as `*ar`; `ar[2]` same as `*(ar+2)`

- An array variable `ar` is read-only (no assignment)
  - 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
  - **Multi-dimensional (nested)**
  - Multi-level
- Structs
  - Alignment
- Unions

```
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];
```

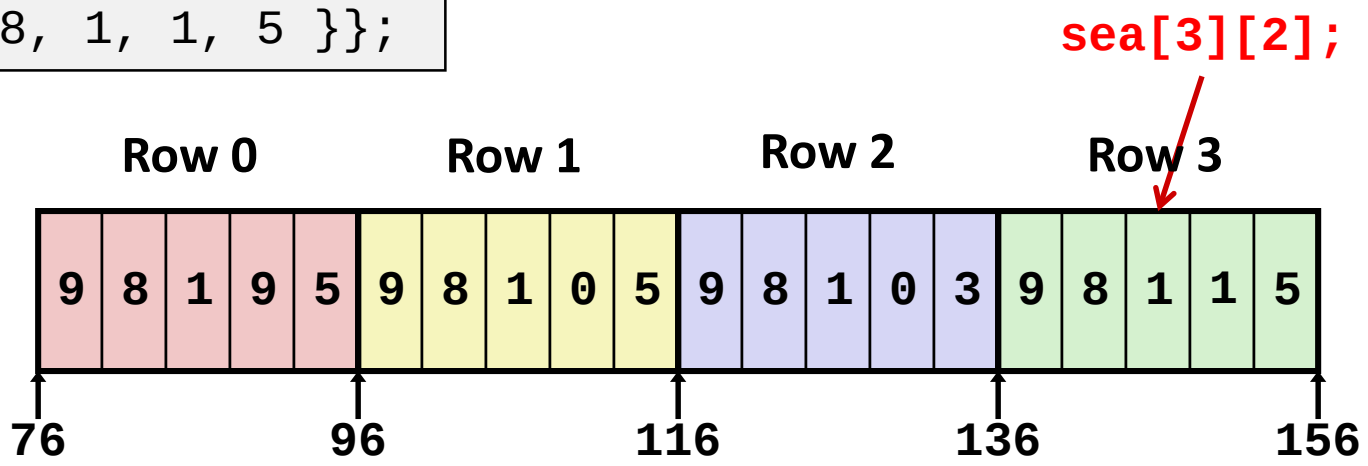
What is the layout in memory?

```
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 }};
```

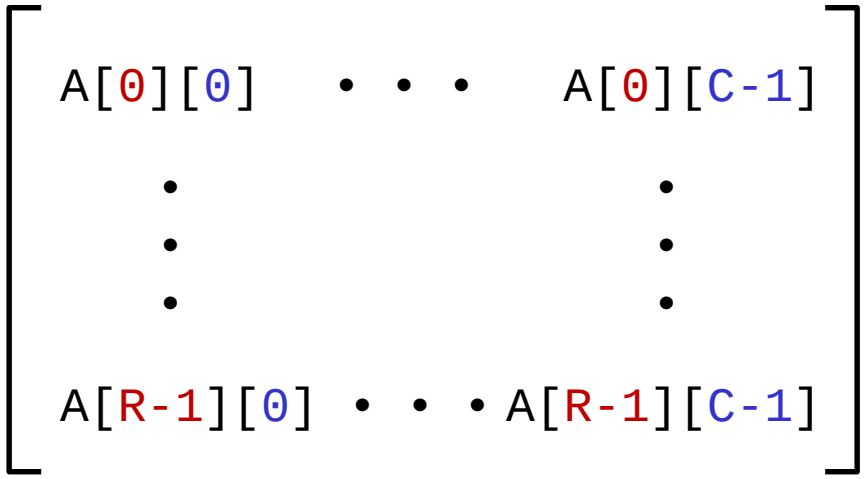
Remember, **T** A[N] is an array with elements of type **T**, with length N



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

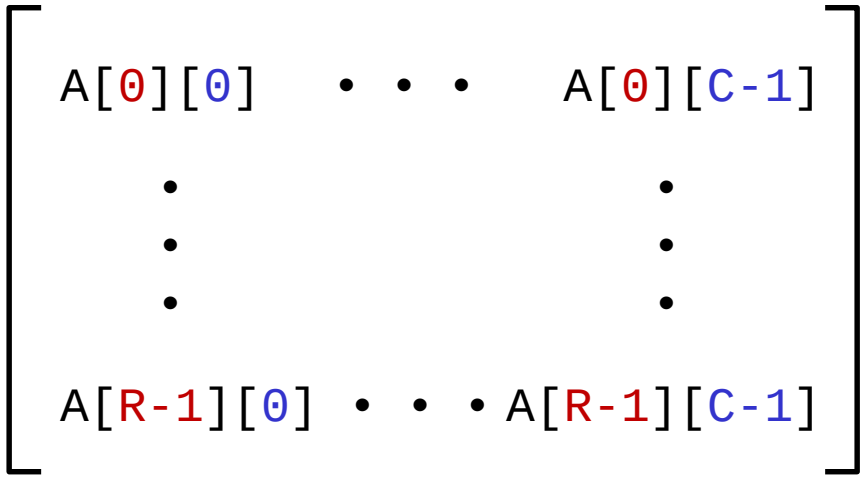
Two-Dimensional (Nested) Arrays

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



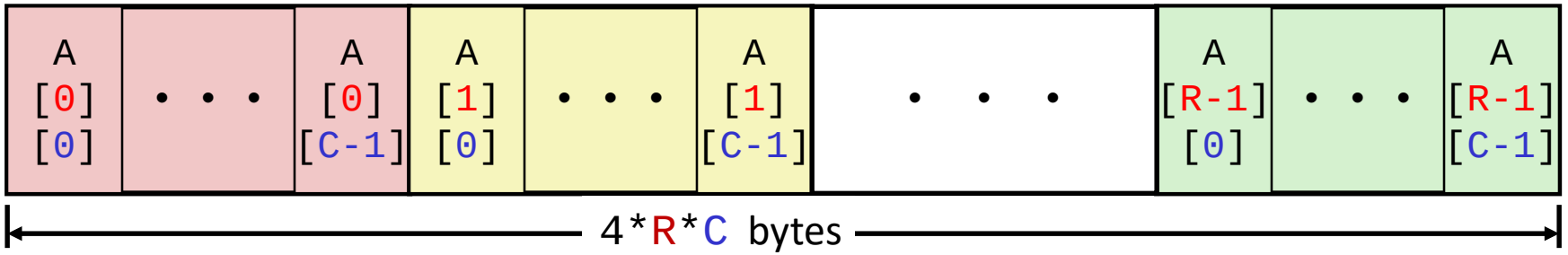
Two-Dimensional (Nested) Arrays

- 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

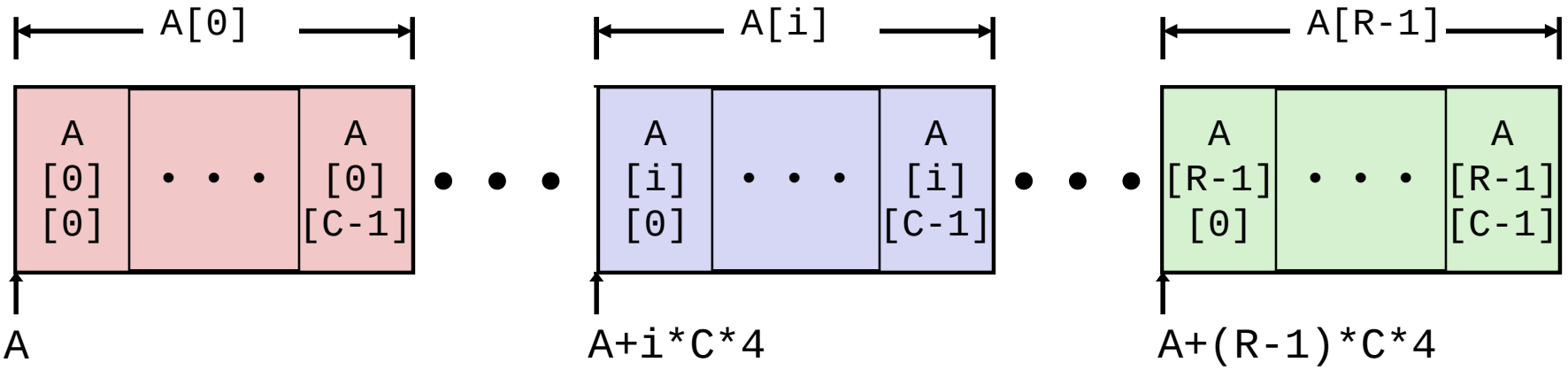
`int A[R][C];`



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):
    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 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 }};
```

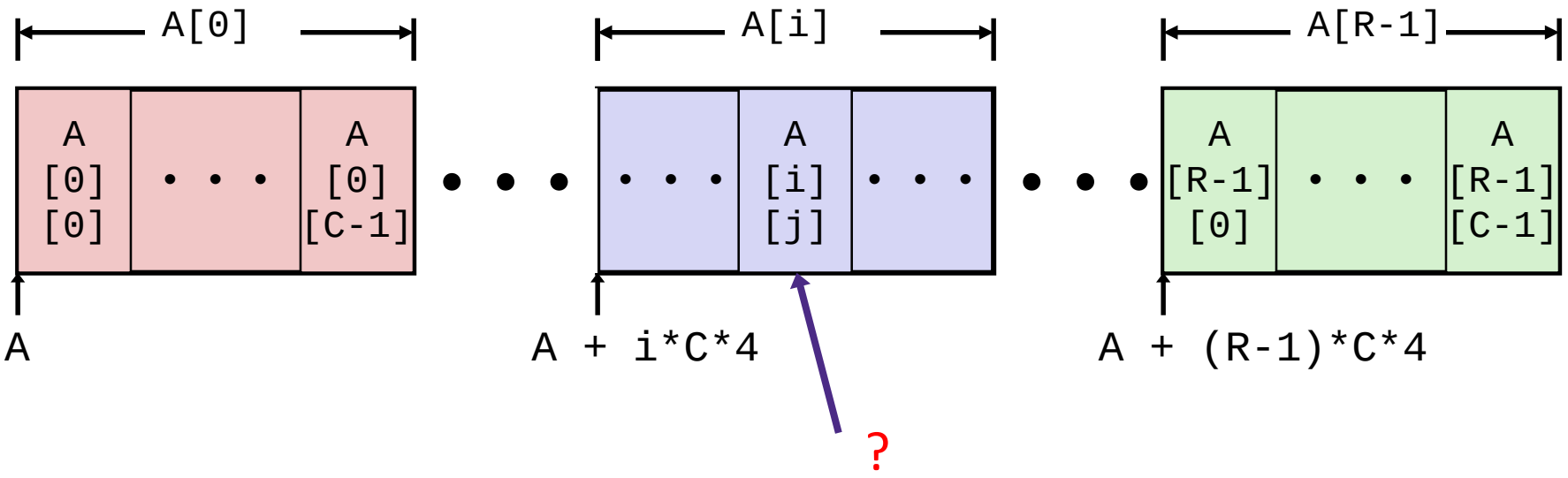
```
# %rdi = index
  leaq (%rdi,%rdi,4),%rax # 5 * index
  leaq sea(,%rax,4),%rax  # sea + (20 * index)
```

- 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

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

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



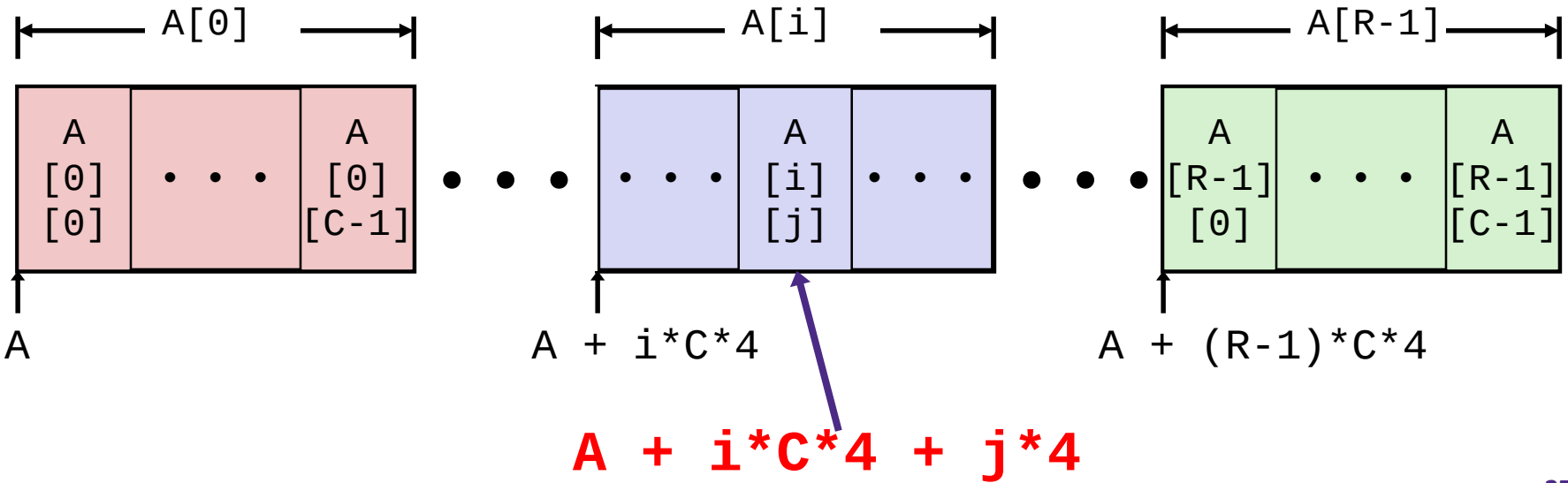
Nested Array Element Access

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

$$\texttt{A + i*(C*}K\texttt{) + j*}K\texttt{ == A + (i*C + j)*}K$$

Size of 1 row

```
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 }};
```

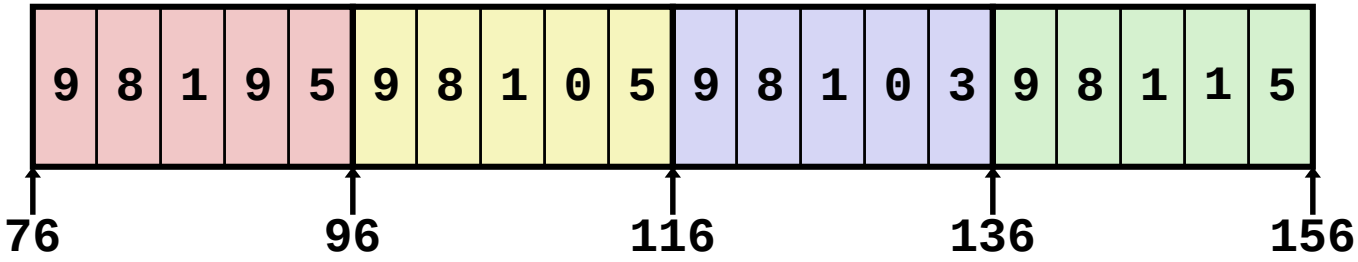
```
leaq   (%rdi,%rdi,4), %rax   # 5*index
addl   %rax, %rsi            # 5*index+digit
movl   sea(,%rsi,4),  %eax   # *(sea + 4*(5*index+digit))
```

- 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]	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

Data Structures in Assembly

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

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};
```

2D Array Declaration:

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

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

NO

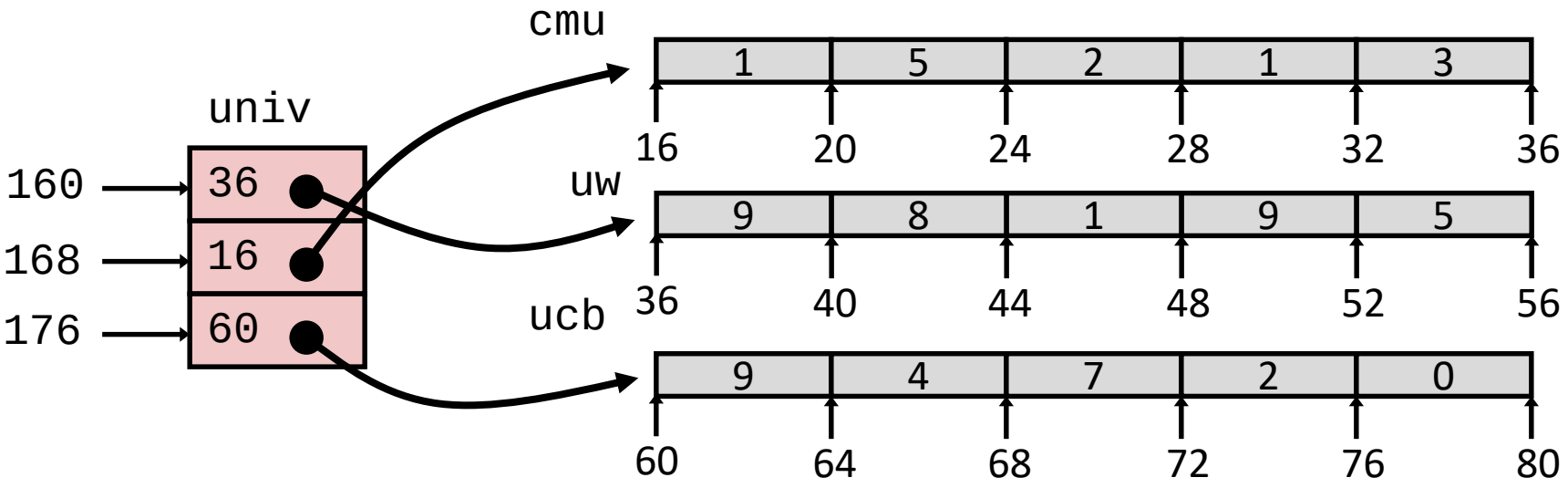
One array declaration = one contiguous block of memory

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};
```

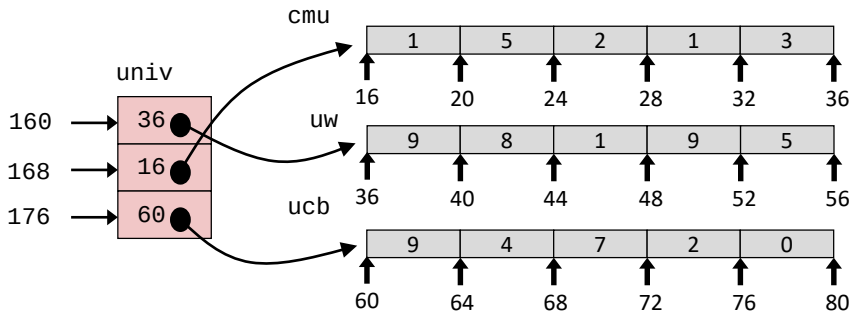
- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 8 bytes each
- Each pointer points to array of `ints`



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];
}
```



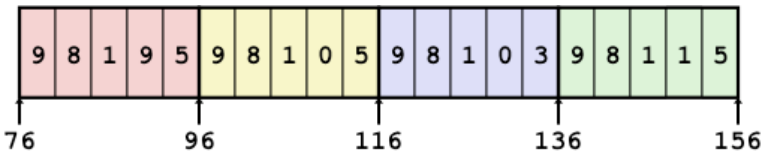

```
salq    $2, %rsi              # rsi = 4*digit
addq    univ(,%rdi,8), %rsi   # p = univ[index] + 4*digit
movl    (%rsi), %eax          # return *p
ret
```

- 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

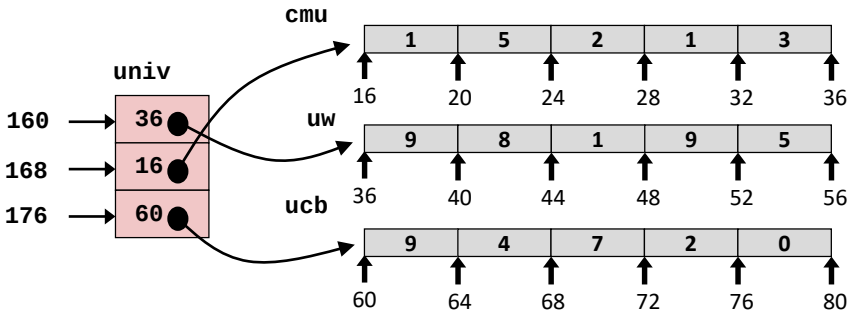
Nested array

```
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];
}
```

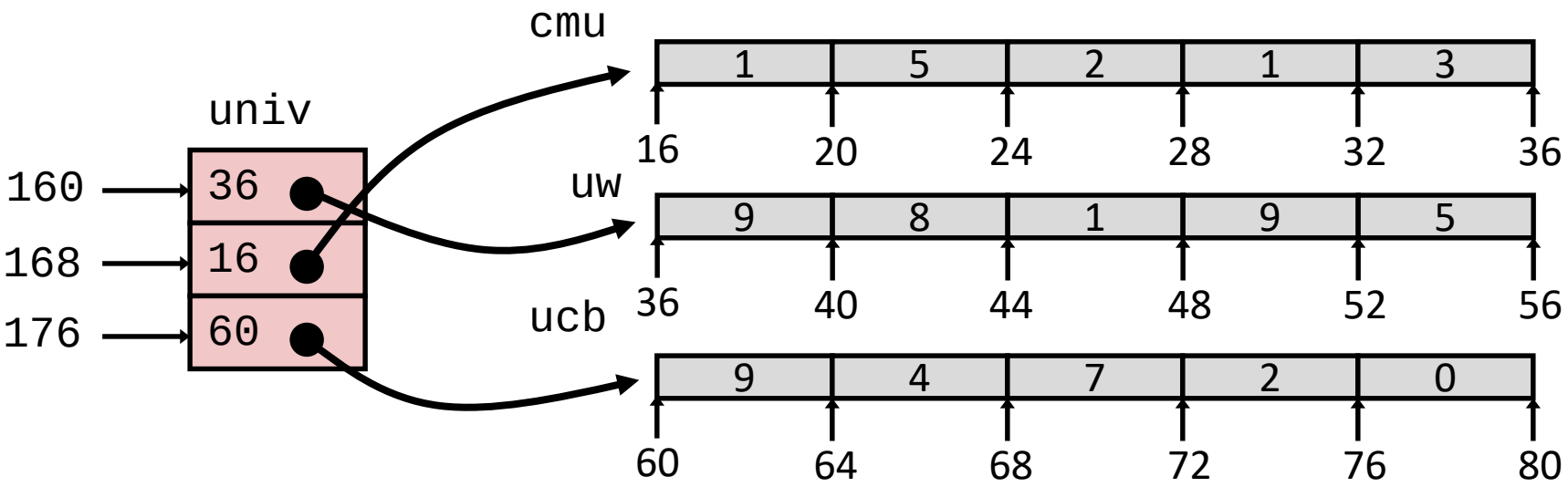


Access *looks* the same, but it isn't:

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

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

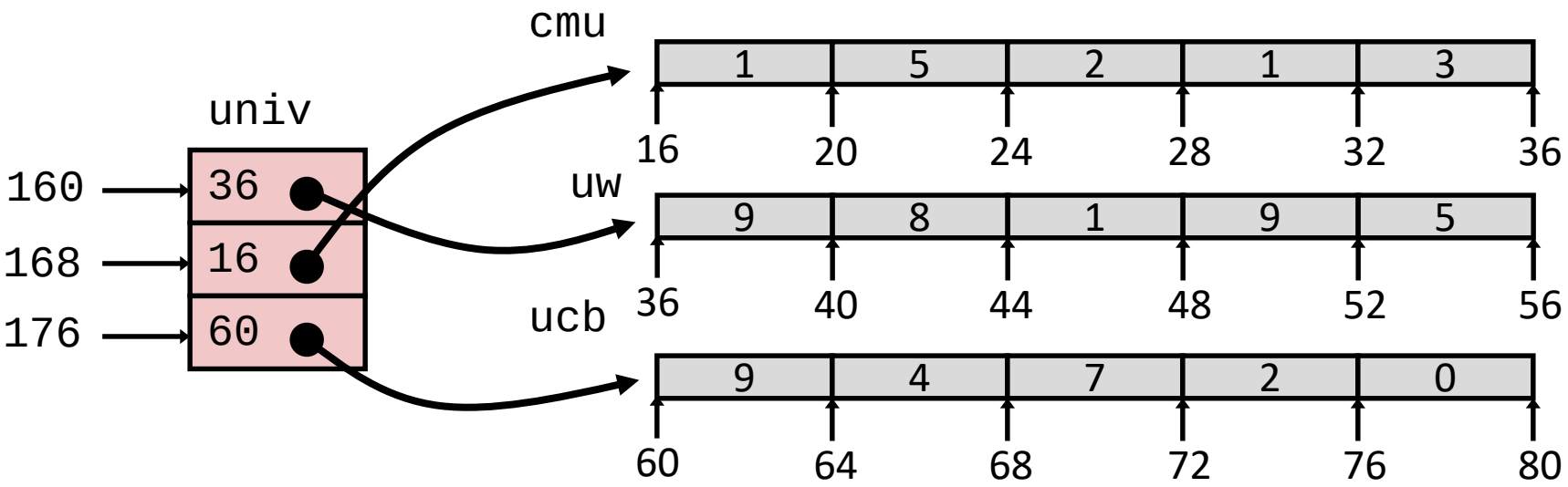
Strange Referencing Examples



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