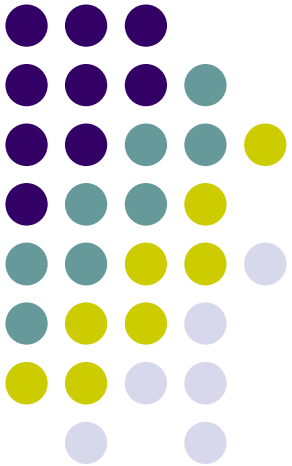
System Programming

08. Machine-Level Programming IV: Data (ch 3.8)



2019. Fall

Instructor: Joonho Kwon

jhkwon@pusan.ac.kr

Data Science Lab @ PNU

datalab

data science laboratory

These slides are based on your text book on the slides prepared by Dan Grossman, Ruth Anderson.

Roadmap

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

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:

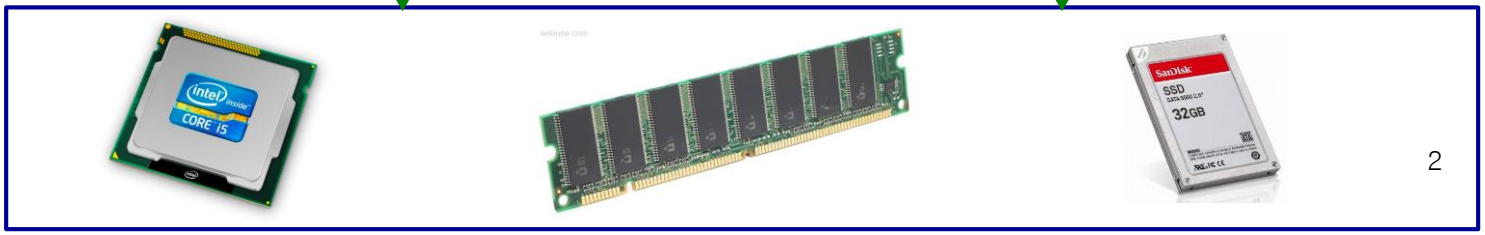
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
11000001111110100001111
```

OS:

Computer system:



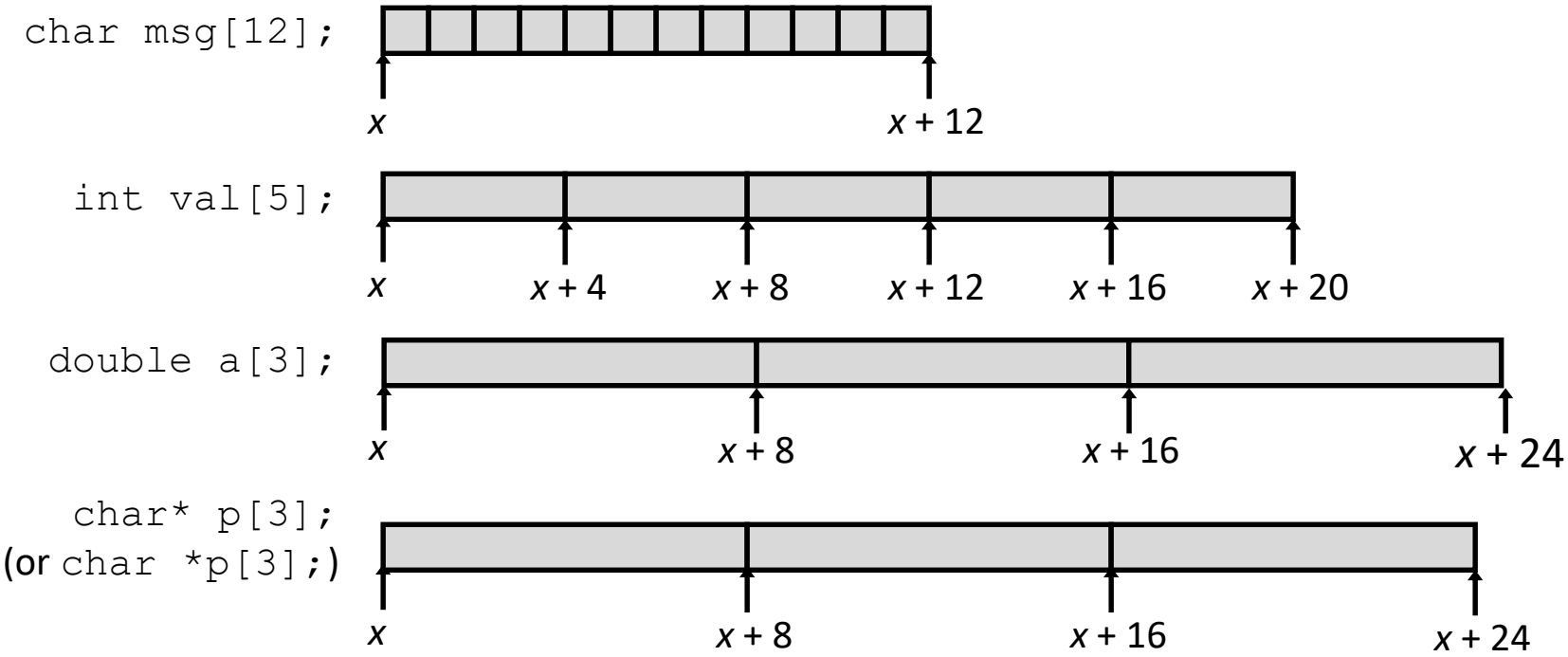
Data Structures in Assembly

- **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

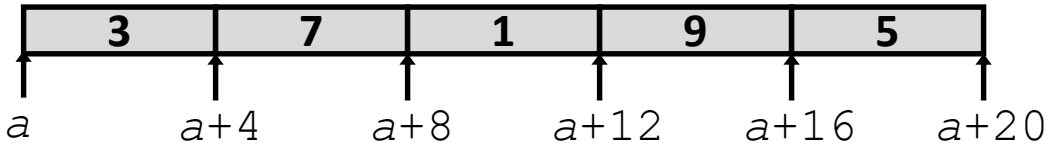
- Basic Principle
  - T A[N];
  - Array of data type T and length N
  - *Contiguously* allocated region of N * sizeof(T) bytes
  - Identifier A can be used as a pointer to array element 0: Type T*



Array Access

- Basic Principle
  - T A[N];
  - Array of data type T and length N
  - Identifier A can be used as a pointer (of type T*) to array element 0:

```
int x[5];
```



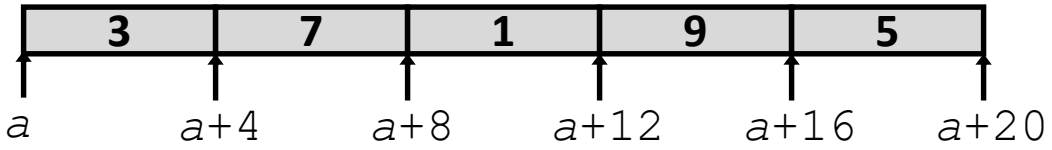
- Reference Type Value

Reference
`x[4]`
`x`
`x+1`
`&x[2]`
`x[5]`
`*(x+1)`
`x+i`

Array Access

- Basic Principle
  - T A[N];
  - Array of data type T and length N
  - Identifier A can be used as a pointer (of type T*) to array element 0:

```
int x[5];
```

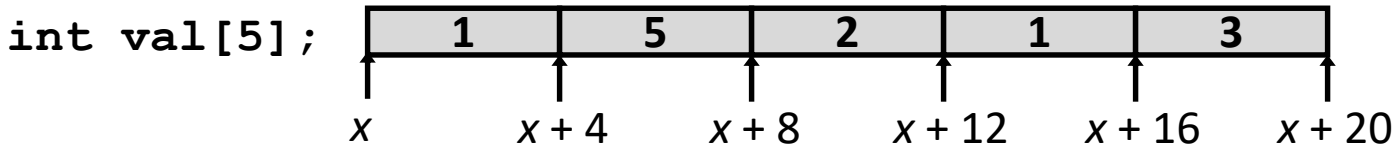


- Reference Type Value

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 Access

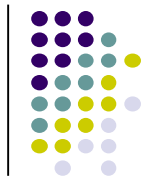
- Basic Principle
  - T A[N];
  - Array of data type T and length N
  - Identifier A can be used as a pointer (of type T*) to array element 0:



- Reference Type Value

Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	?? (whatever is in memory at address *x* + 20)
`*(val+1)`	`int`	5
`val + i`	`int *`	*x* + 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 };
```

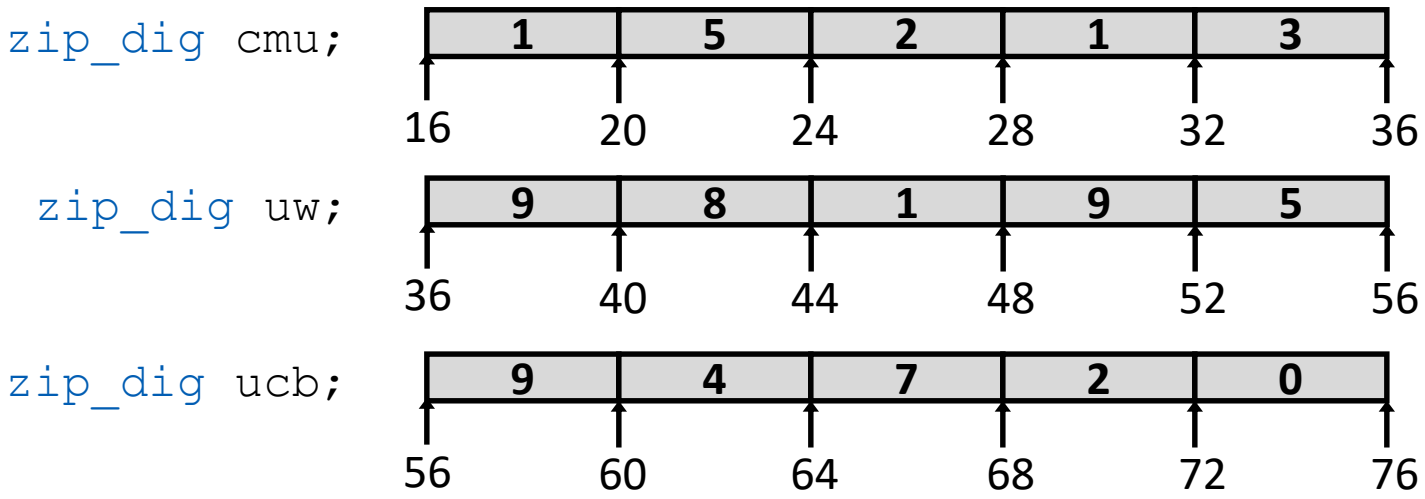
initialization

- `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 };
```

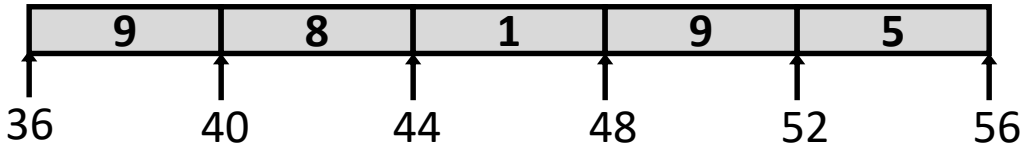


- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

Array Accessing Example

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

```
zip_dig uw;
```




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

IA32

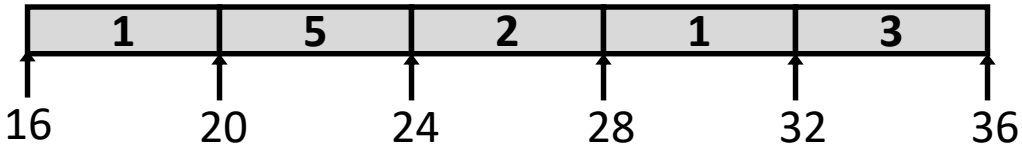
```
get_digit:
  movl (%rdi,%rsi,4), %eax   # z[digit]
```

- 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)`

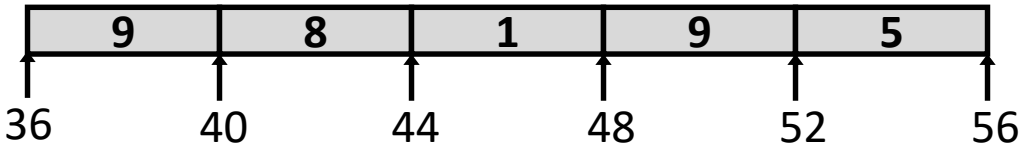
Referencing Examples

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

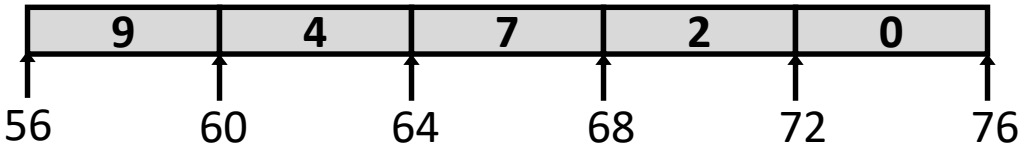
```
zip_dig cmu;
```




```
zip_dig uw;
```




```
zip_dig ucb;
```

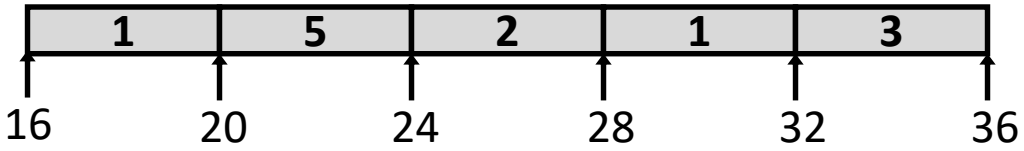


Reference	Address	Value	Guaranteed?
`uw[3]`			
`uw[6]`			
`uw[-1]`			
`cmu[15]`			

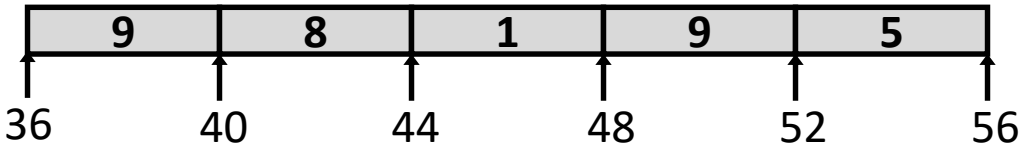
Referencing Examples

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

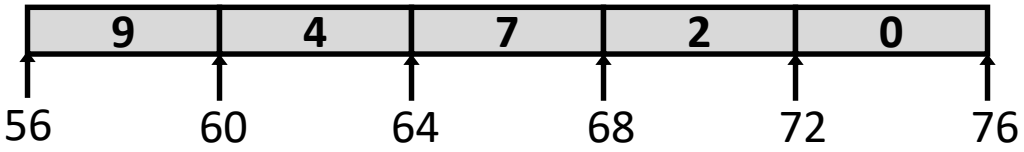
```
zip_dig cmu;
```




```
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

Array Loop Example

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

```
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
```

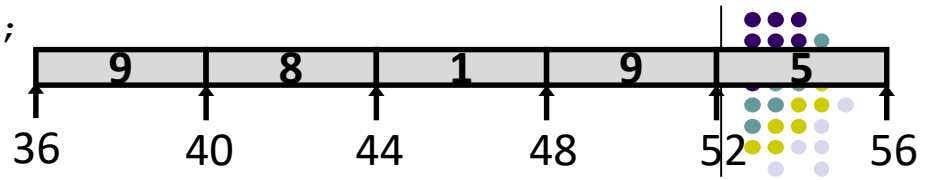
```
zi = 10*9 + 8 = 98
```

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

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

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

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)

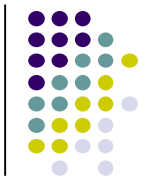
```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 5;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z < zend);
  return zi;
}
```

address just past 5th digit

Increments by 4 (size of int)

Array Loop Implementation

gcc with –O1



- Registers:
  - %rdi z
  - %rax zi
  - %rcx zend
- 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 nearly identical declarations (Remember, no string type in C, here just a variable name)
  - Differ in subtle ways: initialization, sizeof(), etc.
- An array variable looks like a pointer to the first (0^{th}) element
  - `ar[0]` same as `*ar`; `ar[2]` same as `*(ar+2)`
- An array variable 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:

Really `int *ar`

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

Must explicitly pass the size!

Details: Arrays and Functions

- Array size gets lost when passed to a function
- What prints in the following code:

```
int foo(int array[], unsigned int size) {
    ...
    printf("%d\n", sizeof(array));
}

int main(void) {
    int a[10], b[5];
    ... foo(a, 10) ...
    printf("%d\n", sizeof(a));
}
```

sizeof(int *)

10*sizeof(int)

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

Nested Array Example

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

```
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];
```

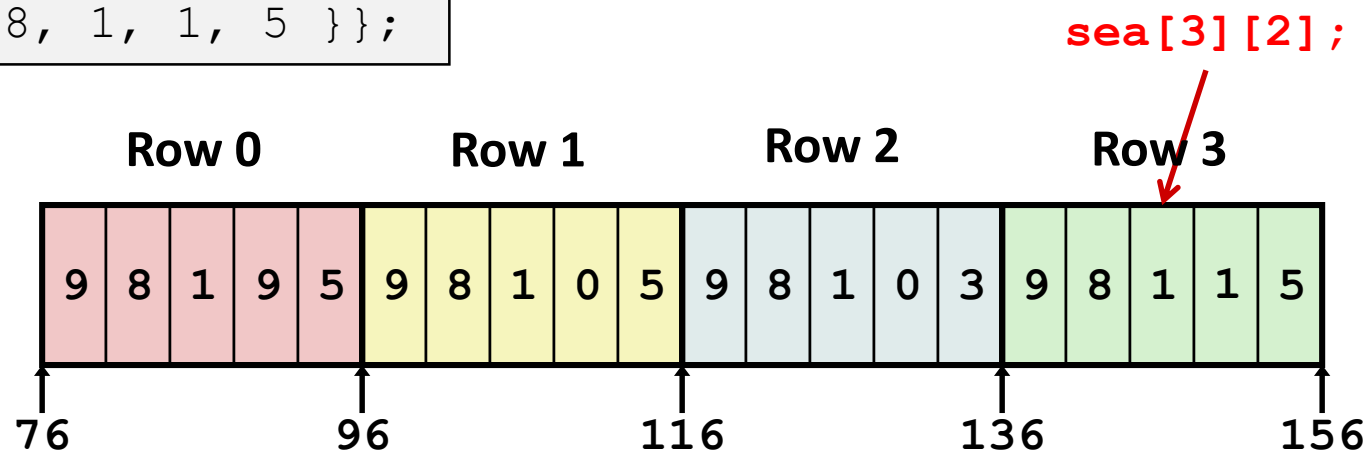
What is the layout in memory?

Nested Array Example

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

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

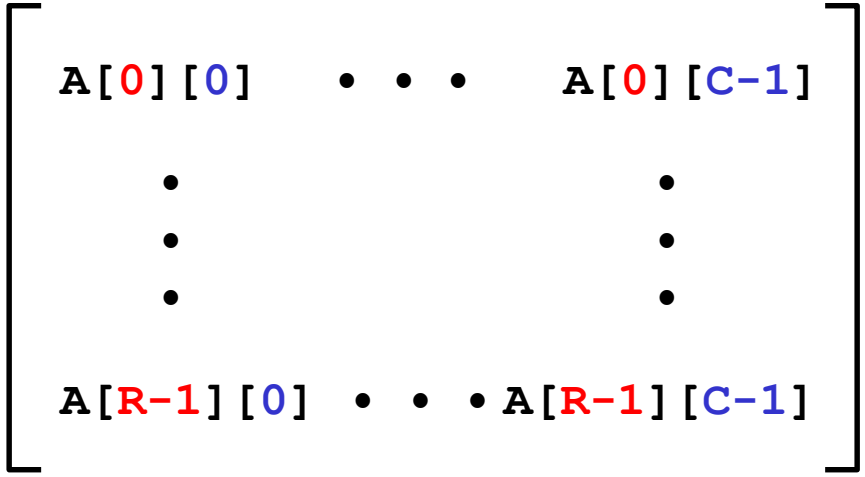
Remember, `T A[N]` is an array with elements of type `T`, with length `N`



- "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?

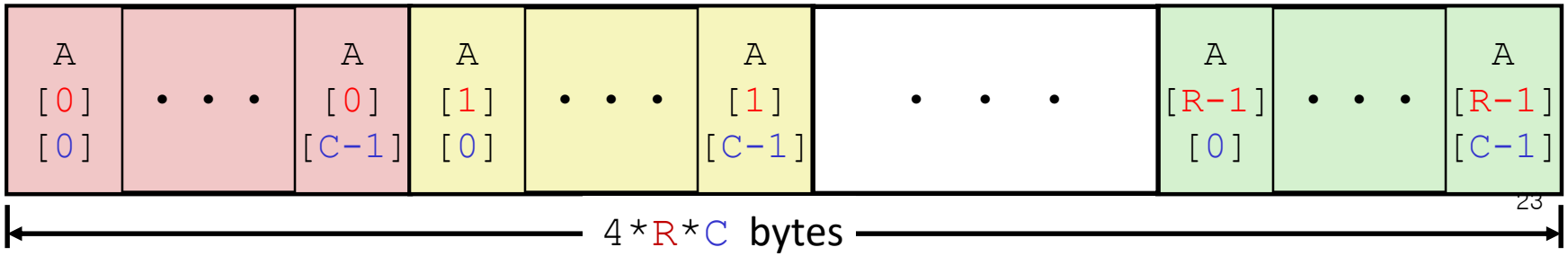


Two-Dimensional (Nested) Arrays

- 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

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

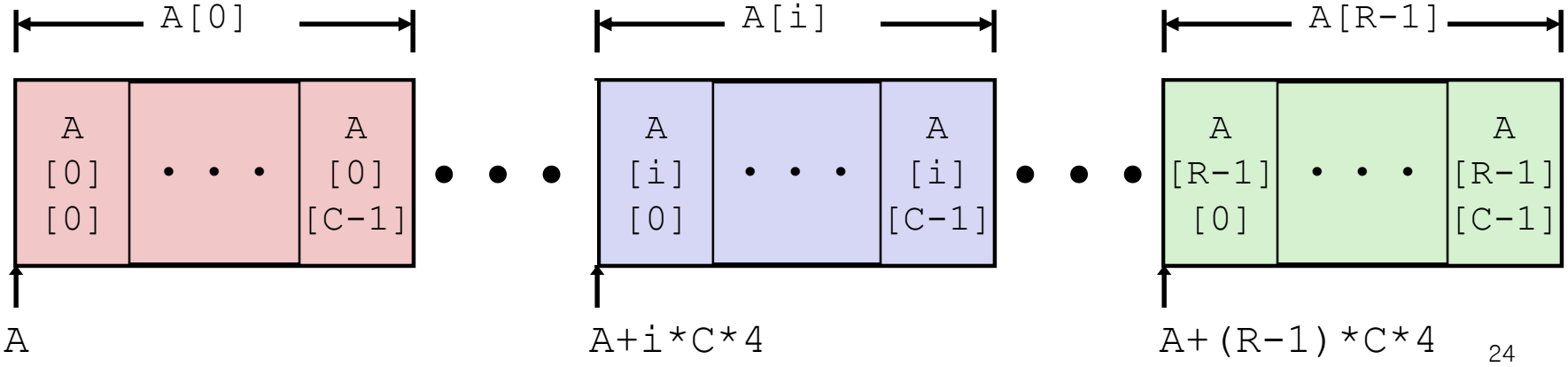
`int A[R][C];`



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 starting 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];
}
```

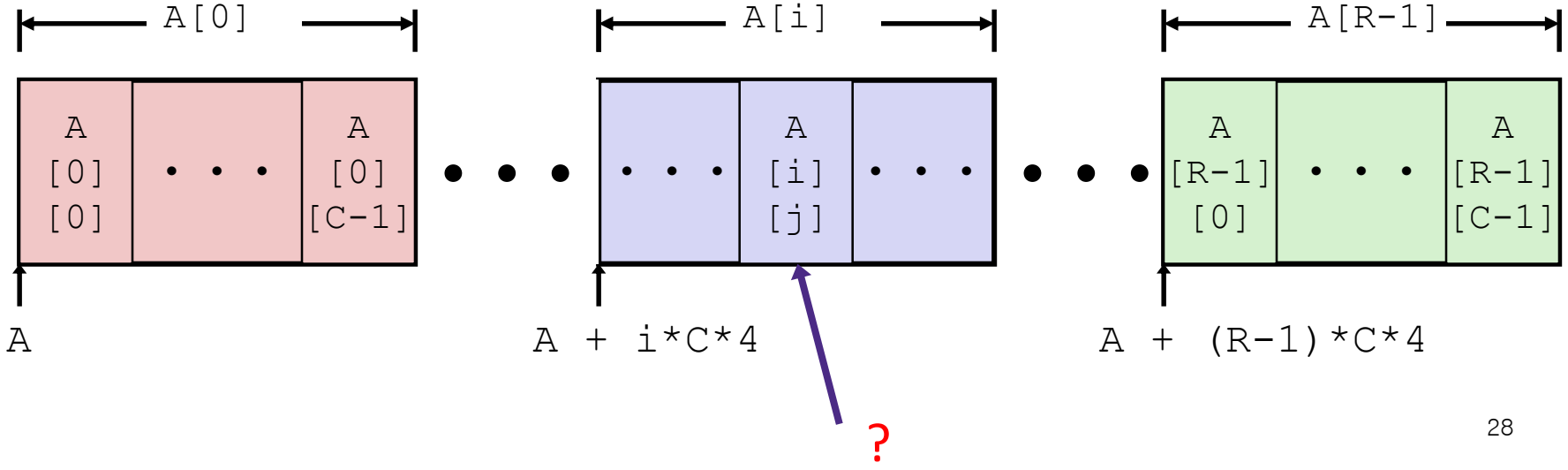
```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

```
# %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];
```

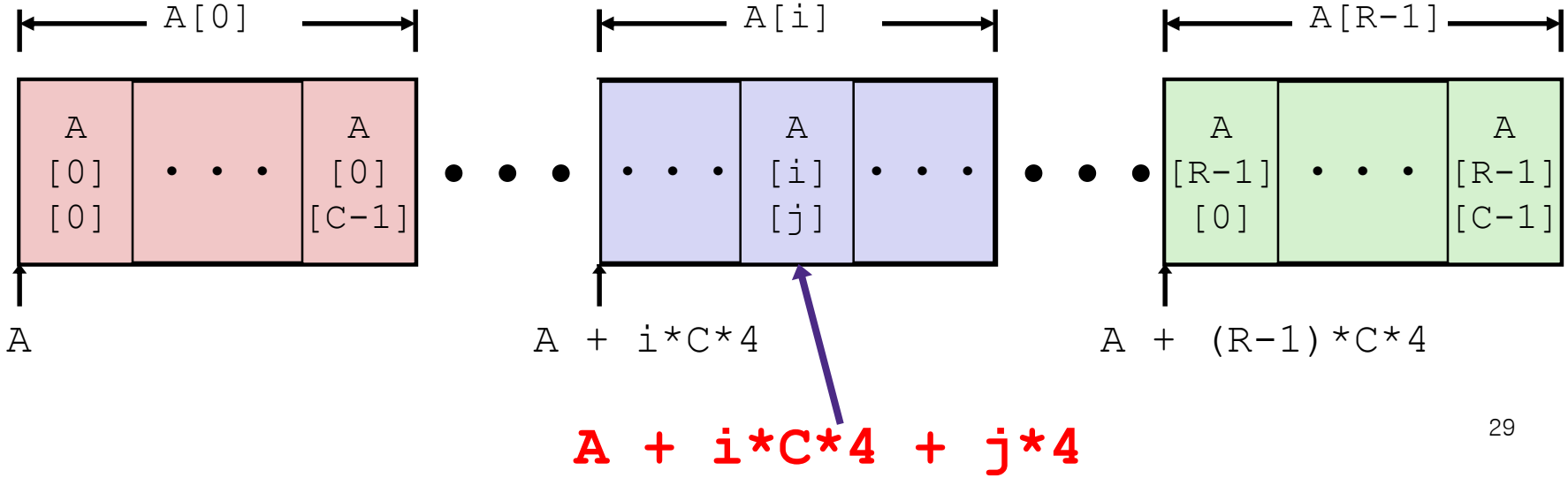


Nested Array Element Access

- 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 }};
```

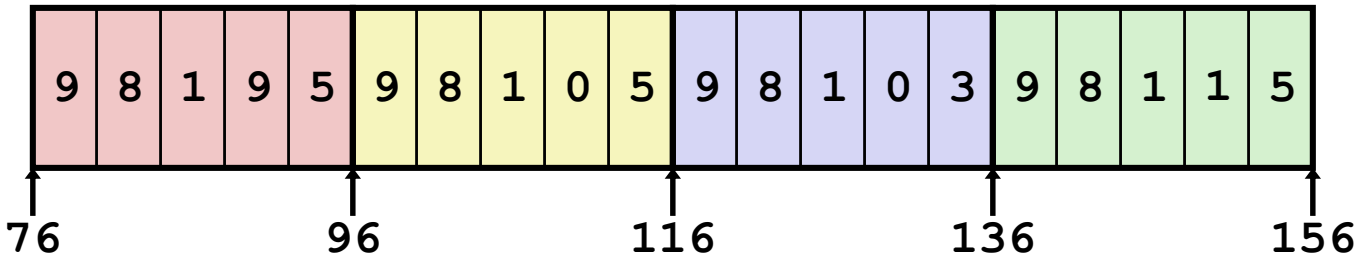
```
leaq   (%rdi,%rdi,4), %rax   # 5*index
addl   %rax, %rsi            # 5*index+digit
movl   sea(,%rsi,4),  %eax   # *(sea + 4*(5*index+digit))
```

- 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];
```



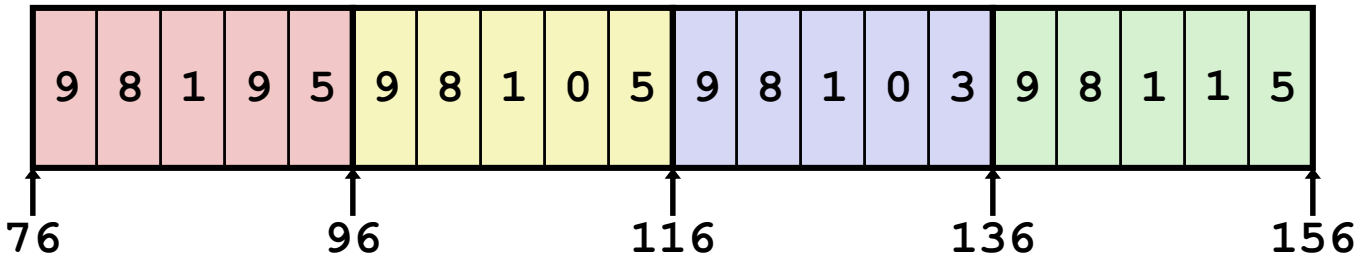
Reference	Address	Value Guaranteed?
`sea[3][3]`		
`sea[2][5]`		
`sea[2][-1]`		
`sea[4][-1]`		
`sea[0][19]`		
`sea[0][-1]`		

- 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

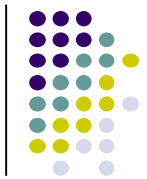
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

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

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 }
};
```

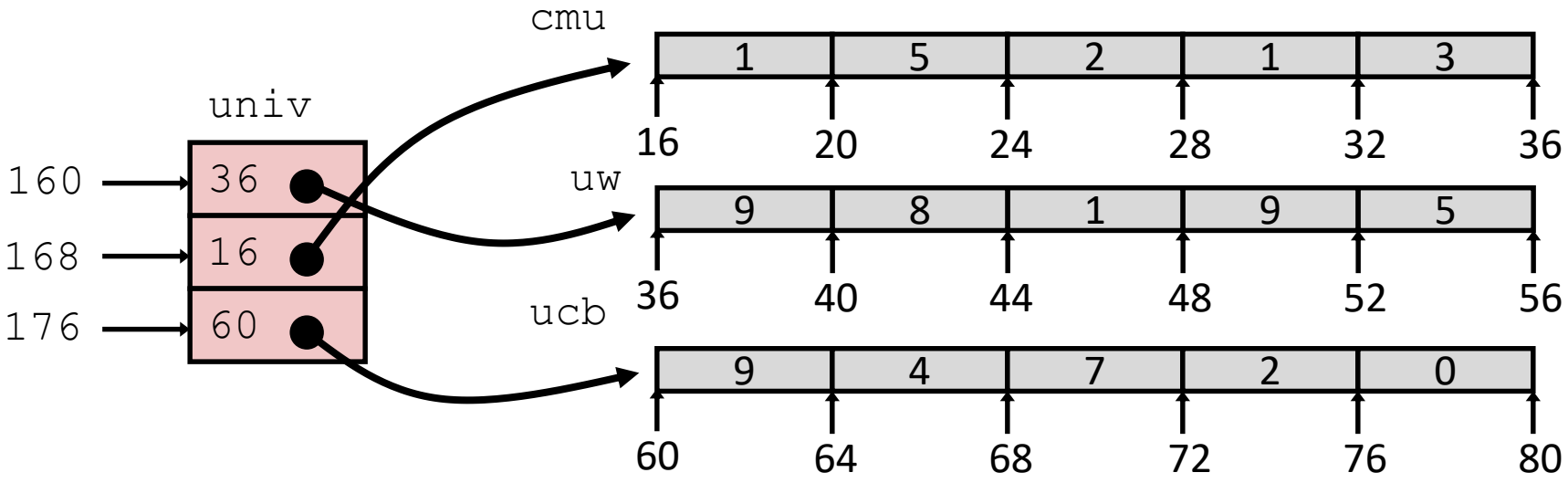
One array declaration = one contiguous block of memory

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};
```

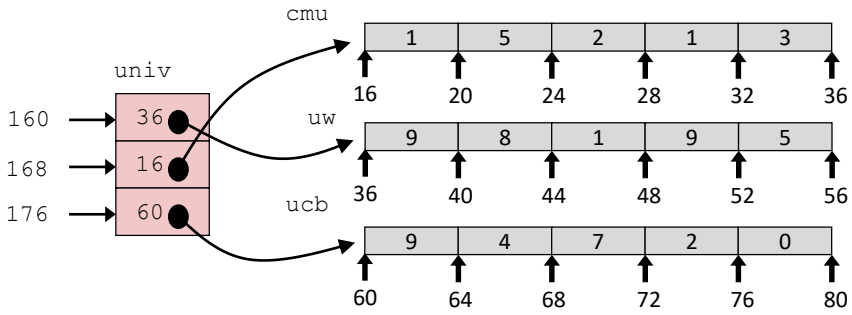
- Variable univ denotes array of 3 elements
- Each element is a pointer
  - 8 bytes each
- Each pointer points to array of ints



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];
}
```



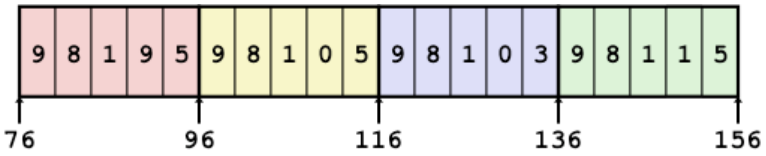

```
salq    $2, %rsi                # rsi = 4*digit
addq    univ(,%rdi,8), %rsi     # p = univ[index] + 4*digit
movl    (%rsi), %eax            # return *p
ret
```

- 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

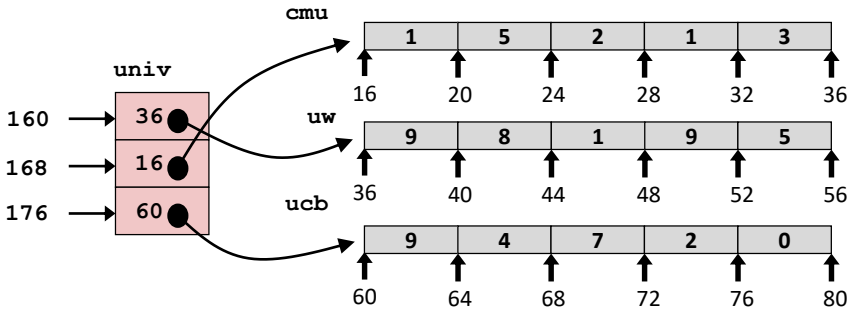
Nested array

```
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];
}
```

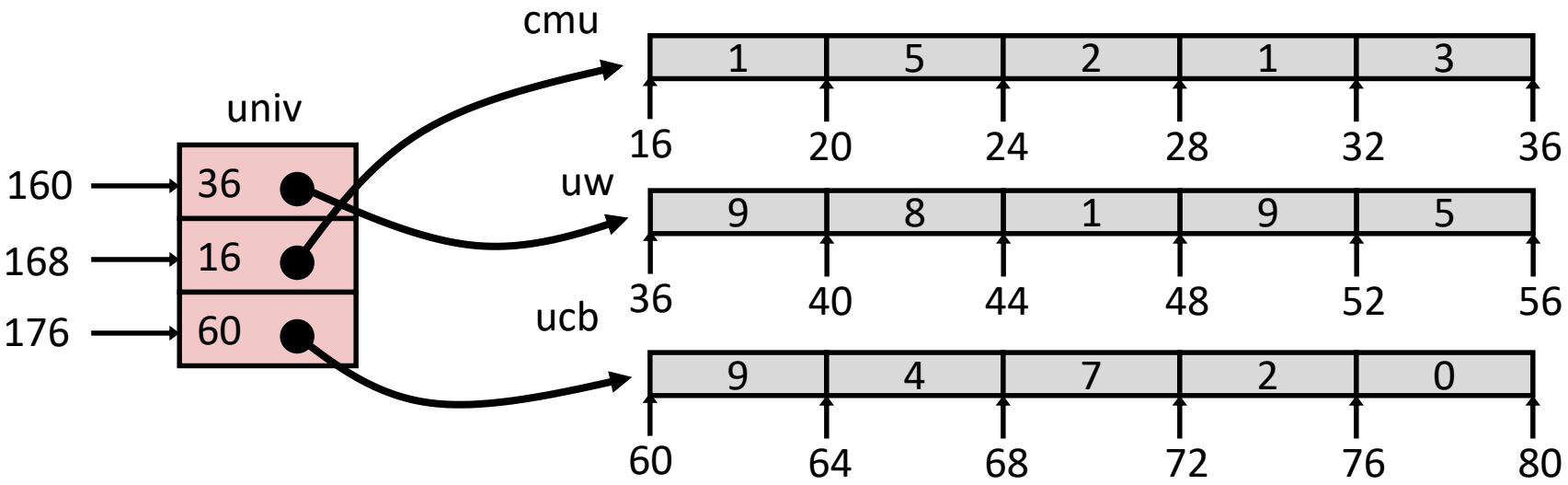


Access *looks* the same, but it isn't:

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

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

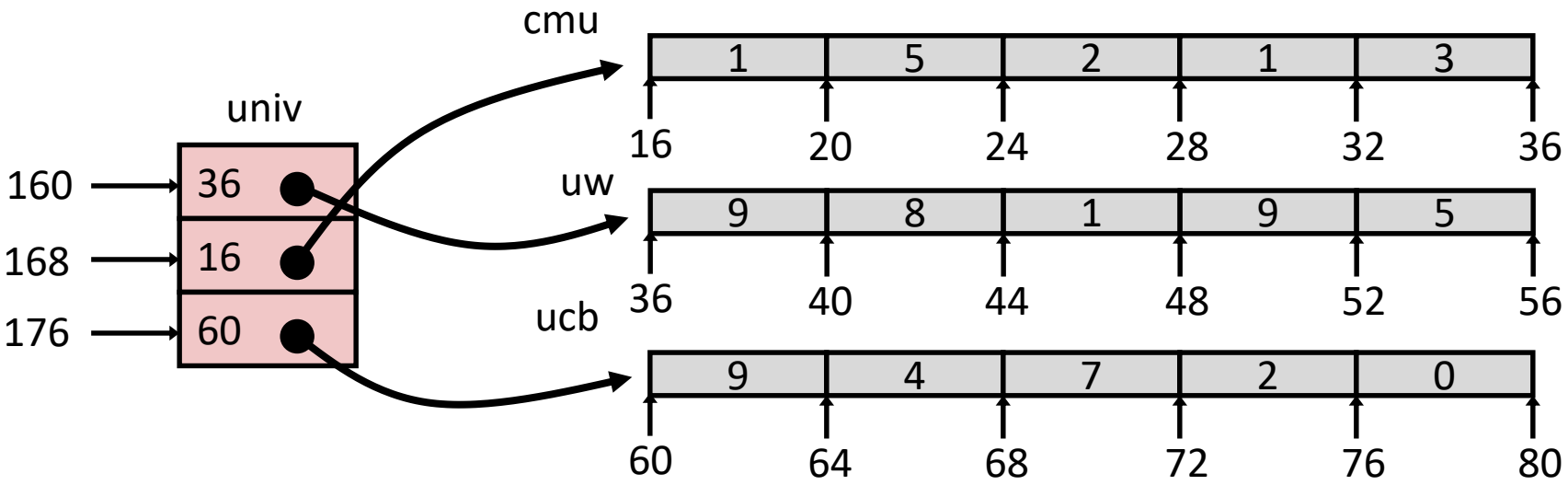
Strange Referencing Examples (1/2)



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 (2/2)



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: Arrays in C

- 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
  - Need to allocate sub-arrays separately
  - Sub-arrays anywhere in memory

Q&A