

Executables & Arrays

CSE 351 Spring 2022

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<http://xkcd.com/1270/>

Relevant Course Information

- ❖ Lab 2 (x86-64) due Friday (4/29)
 - Learn to read x86-64 assembly and use GDB
 - Optional GDB Tutorial on Ed Lessons
 - Since you are submitting a text file (`defuser.txt`), there won't be any Gradescope autograder output this time
- ❖ hw13 – due Monday 5/02
 - Based on the next two lectures, longer than normal
- ❖ Midterm (take home, 5/02-5/04)
 - Midterm review problems in section this week
 - Released 11:59pm on Mon 5/02, due 11:59pm Wed 5/04

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();
```

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

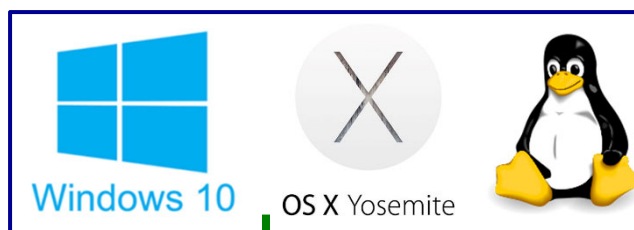
Assembly language:

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

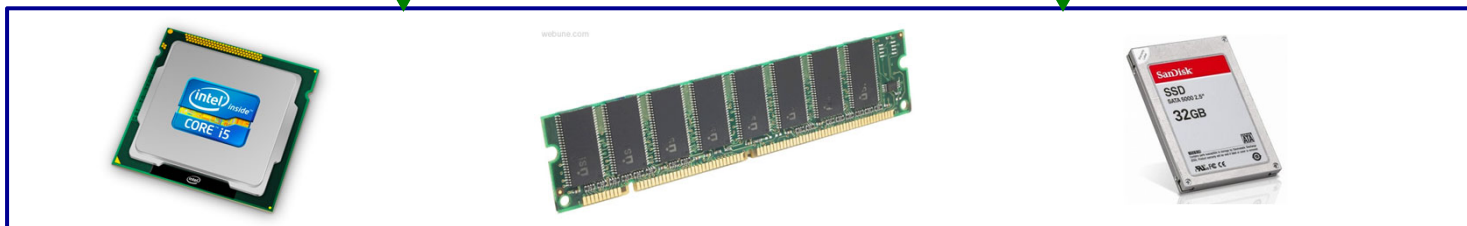
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



Computer system:



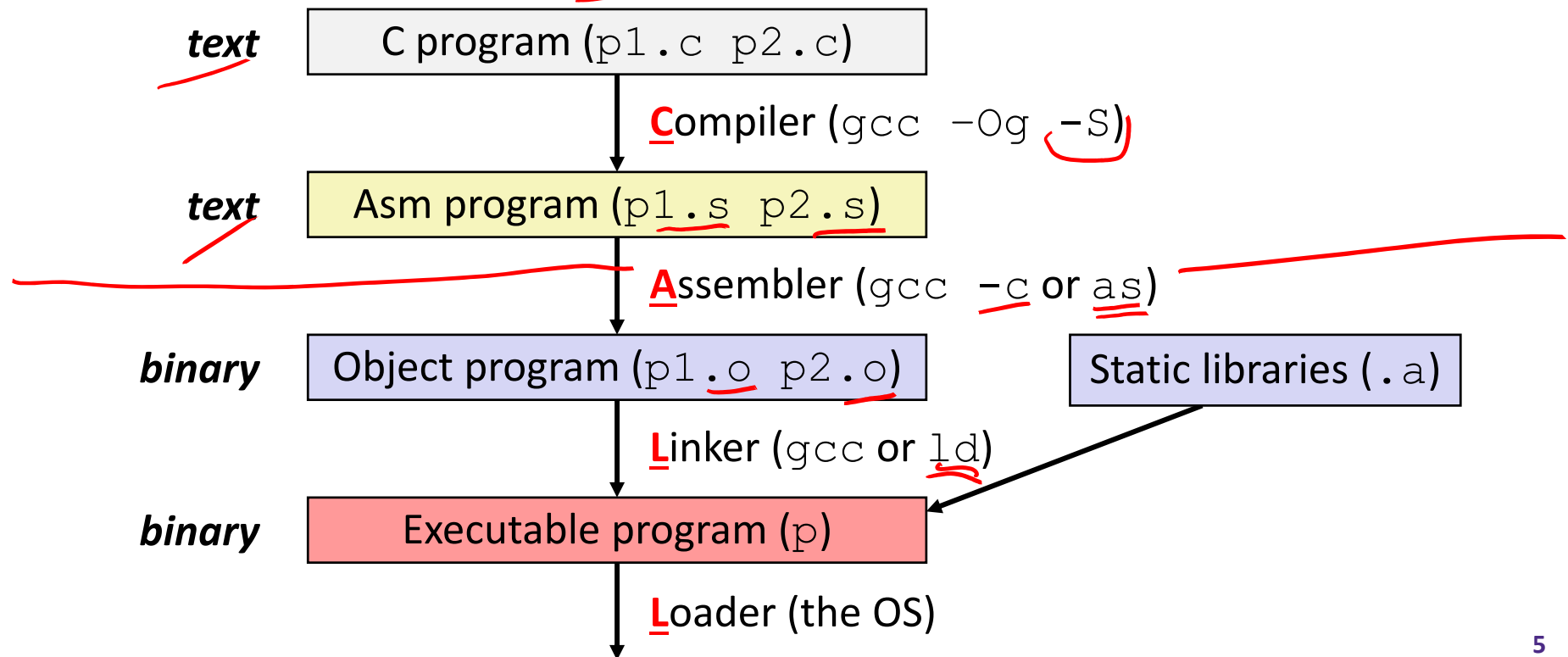
Reading Review

❖ Terminology:

- CALL: compiler, assembler, linker, loader
- Object file: symbol table, relocation table
- Disassembly
- Multidimensional arrays, row-major ordering
- Multilevel arrays

Building an Executable with C (Review)

- ❖ Code in files p1.c p2.c ← can compile multiple source files into a single executable
- ❖ Compile with command: gcc -Og p1.c p2.c -o p
 - Put resulting machine code in file p
- ❖ Run with command: ./p ←



Compiler (Review)

- ❖ **Input:** Higher-level language code (e.g. C, Java)

- `foo.c`

- ❖ **Output:** Assembly language code (e.g. x86, ARM, MIPS)

- `foo.s`

#include "foo"
#define

- ❖ First there's a preprocessor step to handle #directives

- Macro substitution, plus other specialty directives

- If curious/interested: <http://tigcc.ticalc.org/doc/cpp.html>

gcc -E

- ❖ Super complex, whole courses devoted to these!

- ❖ Compiler optimizations

- "Level" of optimization specified by capital 'O' flag (e.g. `-Og`, `-O3`)

- Options: <https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html>

Compiling Into Assembly (Review)

❖ C Code (sum.c)

```
void sumstore(long x, long y, long *dest) {  
    long t = x + y;  
    *dest = t;  
}
```

❖ x86-64 assembly (gcc -Og -S sum.c)

```
sumstore(long, long, long*):  
    addq    %rdi, %rsi  
    movq    %rsi, (%rdx)  
    ret
```

Warning: You may get different results with other versions of gcc and different compiler settings

Assembler (Review)

- ❖ **Input:** Assembly language code (e.g. x86, ARM, MIPS)

- `foo.s`

- ❖ **Output:** Object files (e.g. ELF, COFF)

- `foo.o`

- Contains *object code* and information tables

- ❖ Reads and uses *assembly directives*

- e.g. .text, .data, .quad

- x86: https://docs.oracle.com/cd/E26502_01/html/E28388/eoiyg.html

- ❖ Produces “machine language”

- ★ Does its best, but object file is *not* a completed binary

- ❖ Example: `gcc -c foo.s` → `foo.o`
foo.o.c

Producing Machine Language (Review)

- ❖ **Simple cases:** arithmetic and logical operations, shifts, etc.
 - All necessary information is contained in the instruction itself
- ❖ What about the following?
 - Conditional/unconditional jump *jump done*
 - Accessing static data (e.g. global var or jump table)
 - `call` *to printf*
- ❖ **Addresses and labels are problematic because the final executable hasn't been constructed yet!**
 - So how do we deal with these in the meantime?

Object File Information Tables (Review)

- ❖ Each object file has its own symbol and relocation tables
- ❖ **Symbol Table** holds list of “items” that may be used by other files “what I have”
 - *Non-local labels* – function names for `call`
 - *Static Data* – variables & literals that might be accessed across files
- ❖ **Relocation Table** holds list of “items” that this file needs the address of later (currently undetermined) “What I need”
 - Any *label* or piece of *static data* referenced in an instruction in this file
 - Both internal and external

In .o
file

Object File Format

- 1) object file header: size and position of the other pieces of the object file *"table of contents"*
- 2) text segment: the machine code *(Instructions)*
- 3) data segment: data in the source file (binary) *(Static Data & Literals)*
- 4) relocation table: identifies lines of code that need to be "handled"
- 5) symbol table: list of this file's labels and data that can be referenced
- 6) debugging information *(info for GDB)*

❖ More info: ELF format

- http://www.skyfree.org/linux/references/ELF_Format.pdf

Practice Questions

❖ The following labels/symbols will show up in which table(s) in the object file?

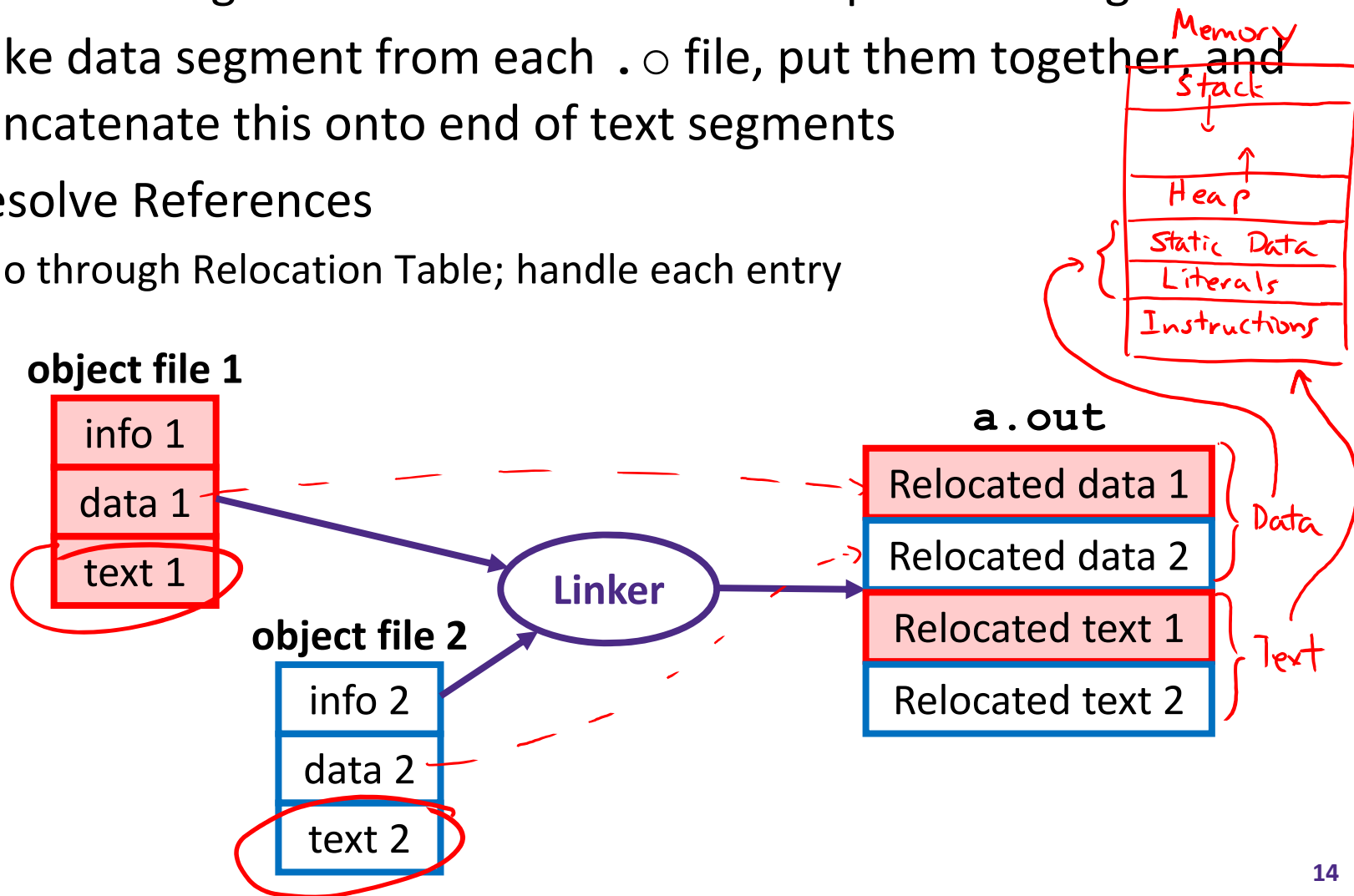
- A **(non-static) user-defined function** (e.g., main, print_r)
Symbol table + relocation table
- A **local variable** (e.g., x, ar)
not in either
- A **library function** (e.g., printf)
not symbol table / relocation table - yes

Linker (Review)

- ❖ **Input:** Object files (e.g. ELF, COFF)
 - `foo.o`
- ❖ **Output:** executable binary program
 - `a.out` ← default name for executable
- ❖ Combines several object files into a single executable (*linking*)
- ❖ Enables separate compilation/assembling of files
 - Changes to one file do not require recompiling of whole program

Linking (Review)

- 1) Take text segment from each .o file and put them together
- 2) Take data segment from each .o file, put them together, and concatenate this onto end of text segments
- 3) Resolve References
 - Go through Relocation Table; handle each entry



Disassembling Object Code (Review)

❖ Disassembled:

```

000000000000400536 <sumstore>:
  400536:  48 01 fe          add    %rdi,%rsi
  400539:  48 89 32         mov   %rsi,(%rdx)
  40053c:  c3              retq
    
```

address of instruction

object code bytes (hex)

interpreted assembly instructions

❖ **Disassembler** (objdump -d sum)

- Useful tool for examining object code (man 1 objdump)
- Analyzes bit pattern of series of instructions
- Produces approximate rendition of assembly code
- Can run on either a complete executable or object file

What Can be Disassembled?

```
% objdump -d WINWORD.EXE

WINWORD.EXE:      file format pei-i386

No symbols in "WINWORD.EXE".
Disassembly of section .text:

30001000 <.text>:
30001000:
30001001:
30001003:
30001005:
3000100a:
```

**Reverse engineering forbidden by
Microsoft End User License Agreement**

- ❖ Anything that can be interpreted as executable code
- ❖ Disassembler examines bytes and attempts to reconstruct assembly source

Loader (Review)

- ❖ **Input:** executable binary program, command-line arguments
 - `./a.out arg1 arg2`
- ❖ **Output:** <program is run>

- ❖ Loader duties primarily handled by OS/kernel
 - **More about this when we learn about processes**
- ❖ Memory sections (Instructions, Static Data, Stack) are set up
- ❖ Registers are initialized

Building an Executable Summary

- ❖ Multistep process:
 - compiling, assembling, linking
- ❖ Object code finished by linker
 - using symbol and relocation tables to produce machine code (with finalized addresses)
- ❖ Loader sets up initial memory from executable

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();
```

- Memory & data
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- Memory & caches
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- Java vs. C

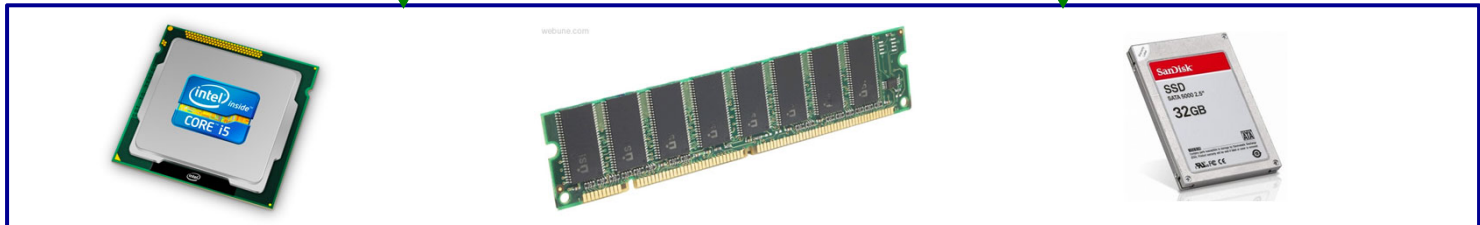
Assembly language:

```
get_mpg:
    pushq    %rbp
    movq    %rsp, %rbp
    ...
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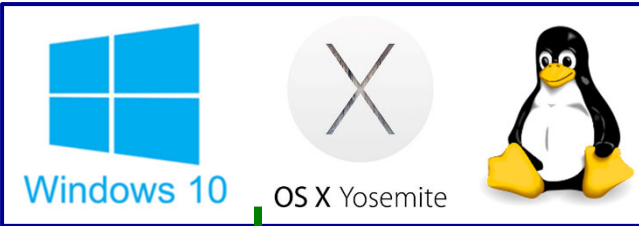
Machine code:

```
0111010000011000
100011010000010000000010
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110000011111101000011111
```

Computer system:



OS:



Data Structures in C

❖ Arrays

- One-dimensional
- Multidimensional (nested)
- Multilevel

❖ Structs

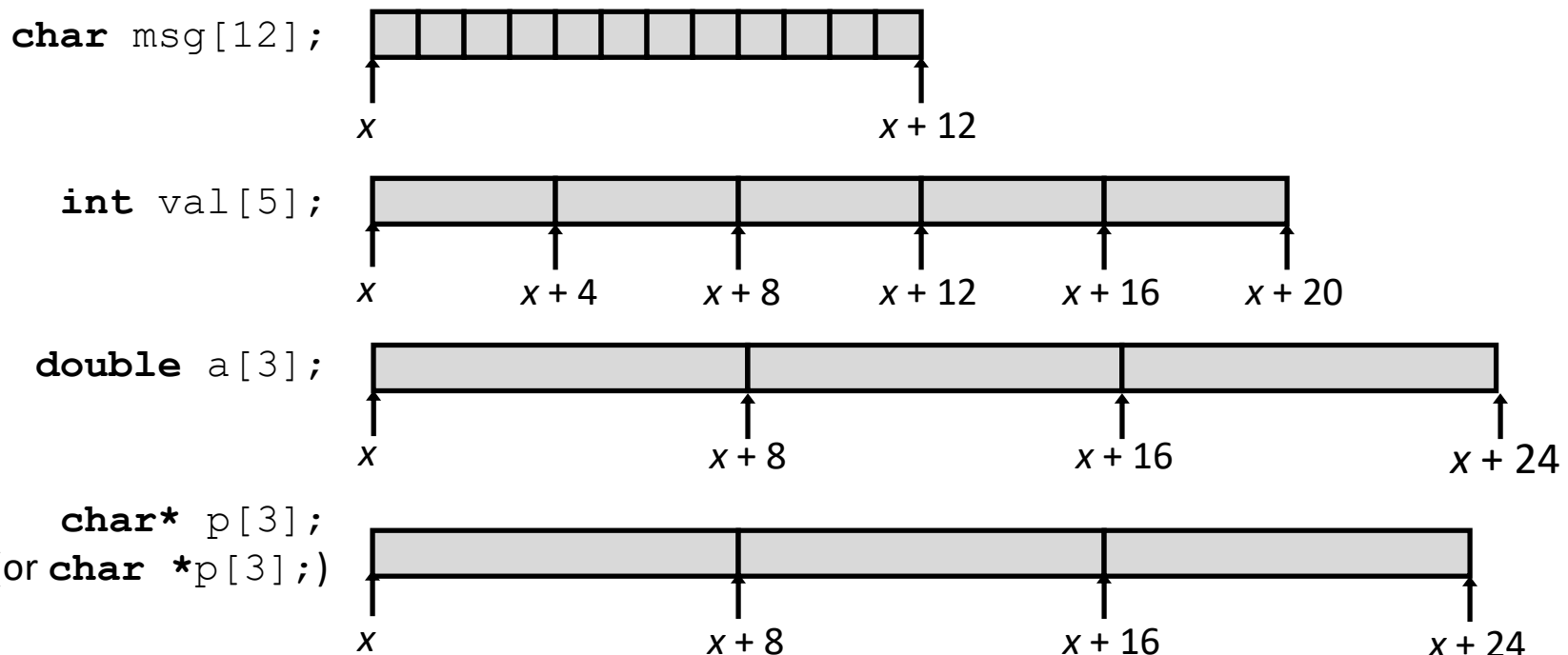
- Alignment

~~❖ Unions~~

Review: Array Allocation (Review)

❖ Basic Principle

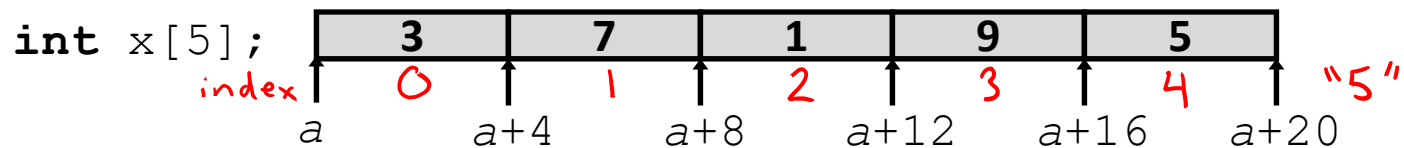
- $\mathbf{T} \ A[N]; \rightarrow$ array of data type \mathbf{T} and length N
- ~~Contiguously~~ *Contiguously* allocated region of $N * \text{sizeof}(\mathbf{T})$ bytes
- Identifier A returns address of array (type \mathbf{T}^*)



Review: Array Access

❖ Basic Principle

- $\mathbf{T} \ A[N]; \rightarrow$ array of data type \mathbf{T} and length N
- Identifier A returns address of array (type \mathbf{T}^*)



❖ Reference

Type

Value

<code>x[4]</code>	<code>int</code>	5
<code>x</code>	<code>int*</code>	<code>a</code>
<code>x+1</code> ← ptr arithmetic	<code>int*</code>	<code>a + 4</code>
<code>&x[2]</code>	<code>int*</code>	<code>a + 8</code>
<code>x[5]</code>	<code>int</code>	?? (whatever's in memory at addr <code>x+20</code>)
<code>*(x+1)</code>	<code>int</code>	7
<code>x+i</code>	<code>int*</code>	<code>a + 4*i</code>

Array Example

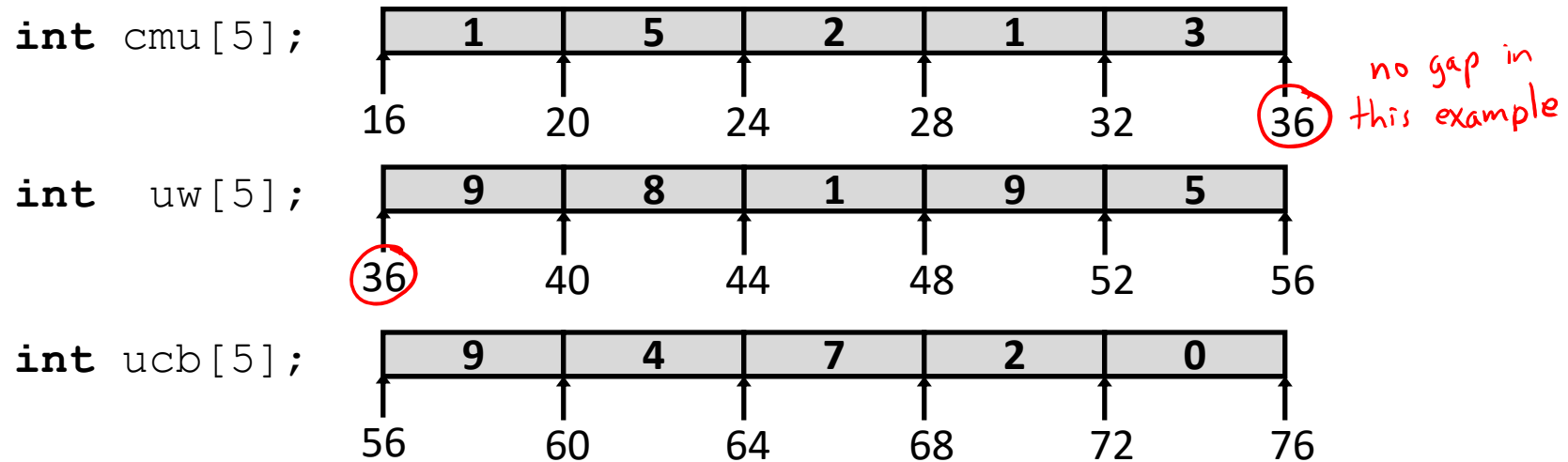
```
// arrays of ZIP code digits  
int cmu[5] = { 1, 5, 2, 1, 3 };  
int  uw[5] = { 9, 8, 1, 9, 5 };  
int ucb[5] = { 9, 4, 7, 2, 0 };
```

← brace-enclosed
list initialization

Array Example

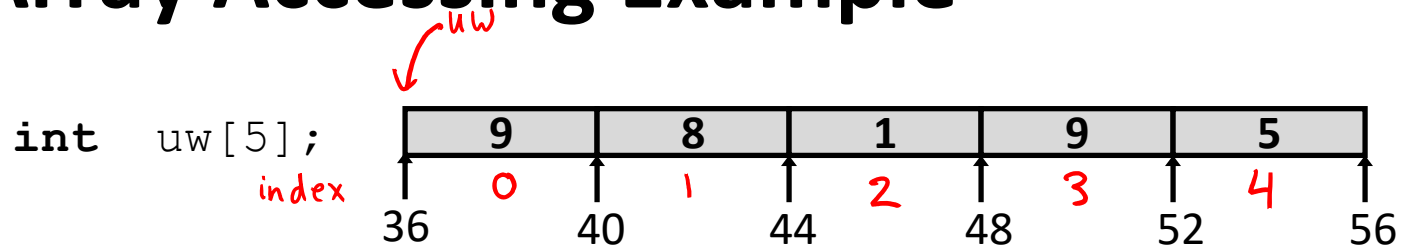
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// arrays of ZIP code digits
int cmu[5] = { 1, 5, 2, 1, 3 };
int uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

} 20 B each



- ❖ Example arrays happened to be allocated in successive 20 byte blocks
 - Not guaranteed to happen in general (could have allocated variables in-between)

Array Accessing Example



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

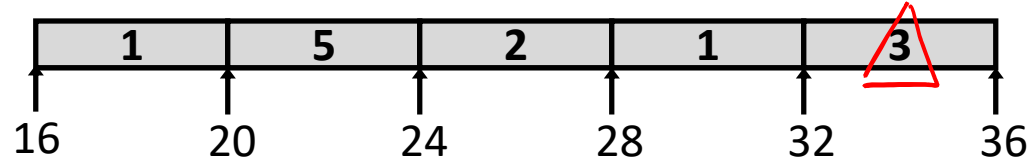
```
get_digit:
    movl (%rdi,%rsi,4), %eax # z[digit]
```

Handwritten annotations:
 - R_b (base reg) points to `%rdi`
 - R_i (index reg) points to `%rsi`
 - S (scale factor (sizeof)) points to `4`

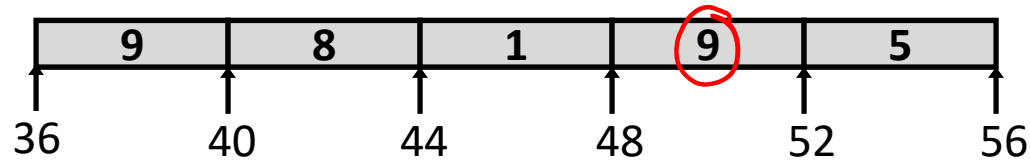
- Register `%rdi` contains starting address of array
- Register `%rsi` contains array index
- Desired digit at `%rdi+4*%rsi`, so use memory reference `(%rdi,%rsi,4)`

Referencing Examples

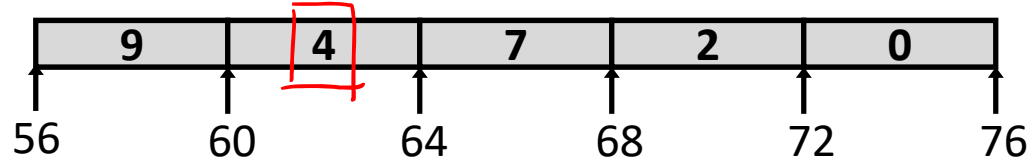
```
int cmu[5];
```



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



```
int ucb[5];
```



Rb Ri S
uw 3 4

Reference

Address

Value

Guaranteed?

uw[3]

$36 + 3 * 4 = 48$

9

Yes

uw[6]

$36 + 6 * 4 = 60$

4

No

uw[-1]

$36 + (-1) * 4 = 32$

3

No

cmu[15]

$16 + 15 * 4 = 76$

?

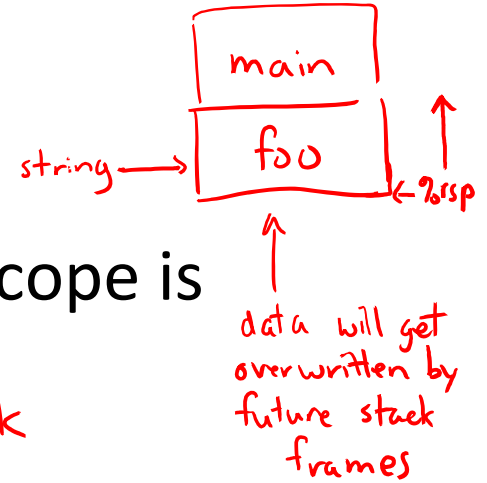
No

- ❖ 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 (0th) 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;
}
```

array is allocated on stack

BAD!

returns stack addr that is < %rsp

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

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

*Really int *ar (%rdi can only fit 8 bytes)*

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 }};
```

2D array

Remember, $\mathbf{T} \ A[N]$ is an array with elements of type \mathbf{T} , with length N

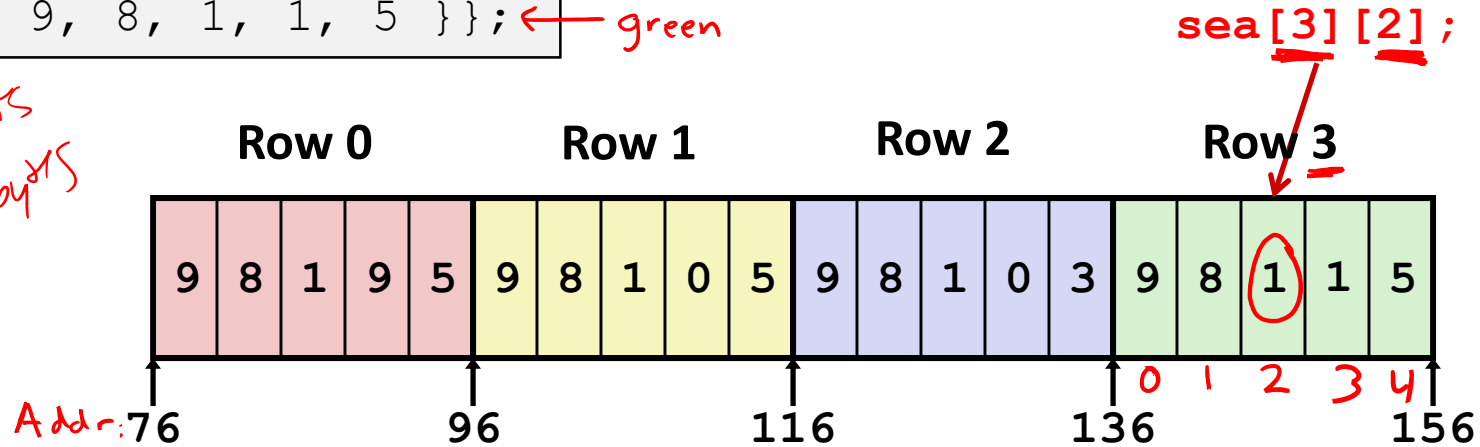
- ❖ What is the layout in memory?

Nested Array Example

```
int sea[4][5] =
  { { 9, 8, 1, 9, 5 }, ← red
    { 9, 8, 1, 0, 5 }, ← yellow
    { 9, 8, 1, 0, 3 }, ← blue
    { 9, 8, 1, 1, 5 } }; ← green
```

Remember, $\mathbf{T} \ A[N]$ is an array with elements of type \mathbf{T} , with length N

20 ints
80 bytes



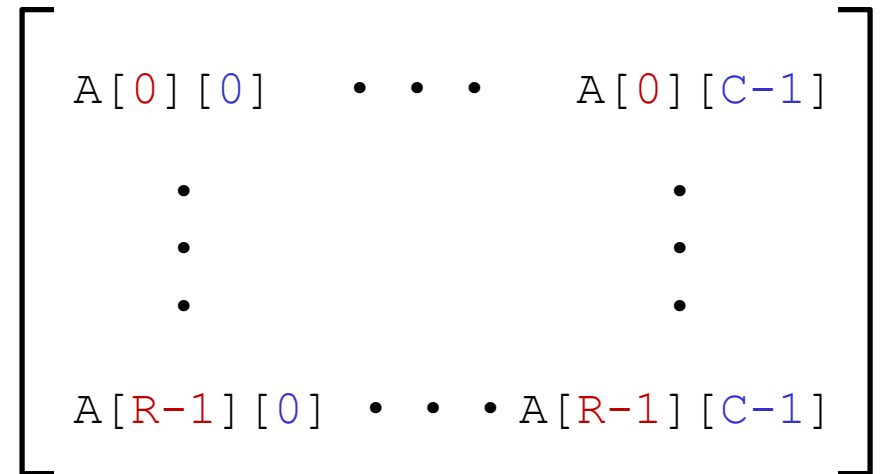
- ❖ “Row-major” ordering of all elements
- ❖ Elements in the same row are contiguous
- ❖ Guaranteed (in C)

Two-Dimensional (Nested) Arrays

❖ Declaration: $\mathbf{T} \ A[\mathbf{R}][\mathbf{C}];$

- 2D array of data type \mathbf{T}
- \mathbf{R} rows, \mathbf{C} columns
- Each element requires $\mathbf{sizeof}(\mathbf{T})$ bytes

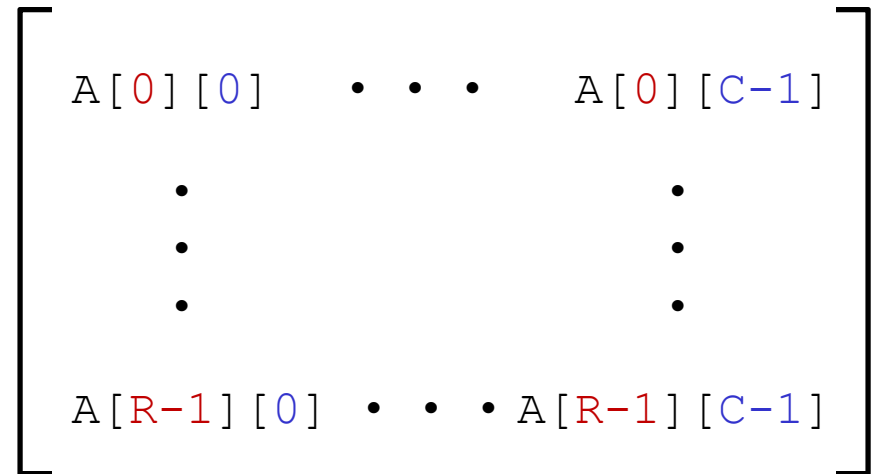
❖ Array size?



Two-Dimensional (Nested) Arrays

❖ Declaration: $\mathbf{T} \ A[R][C];$

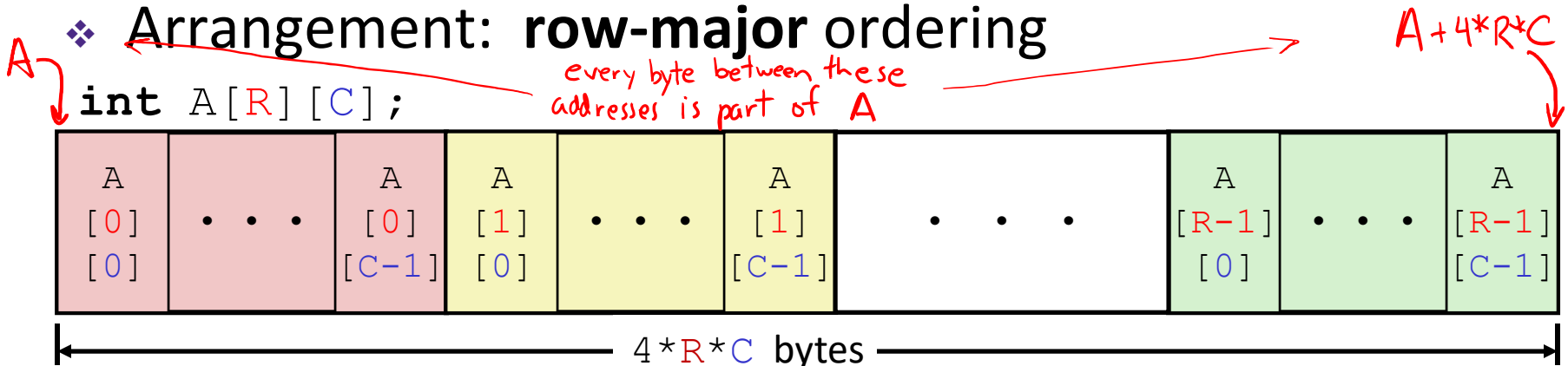
- 2D array of data type T
- R rows, C columns
- Each element requires **sizeof(T)** bytes



❖ Array size:

- $R * C * \mathbf{sizeof(T)}$ bytes

❖ Arrangement: **row-major** ordering



Nested Array Row Access

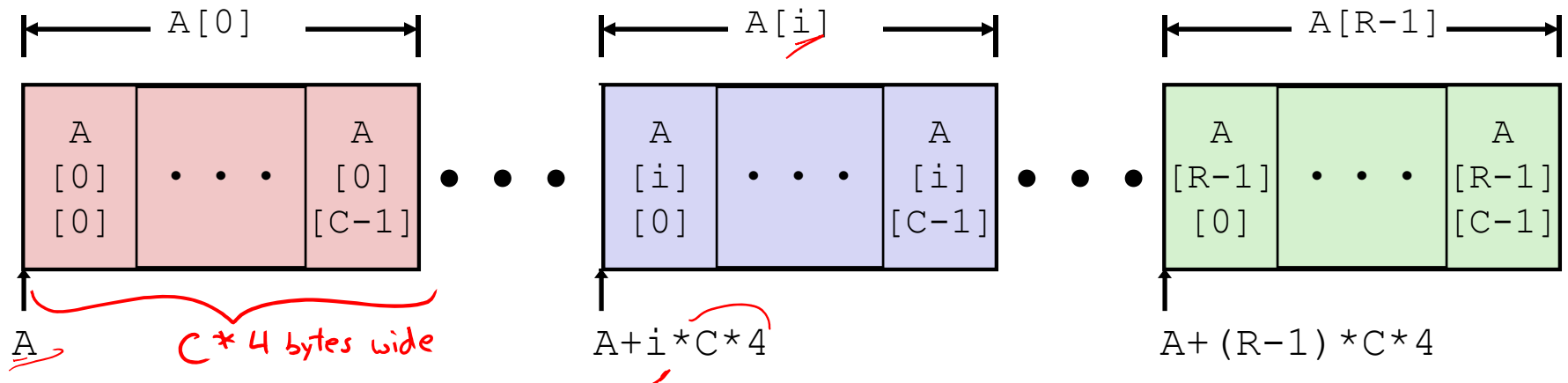
❖ Row vectors

■ Given \mathbf{T} $A[R][C]$,

- $A[i]$ is an array of C elements ("row i ") → *just an address!*
- A is address of array
- Starting address of row $i = A + i * (C * \text{sizeof}(\mathbf{T}))$

size of row
0, 1

```
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
    ...
```

address of array →

ends up in memory!

Nested Array Row Access Code

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

```
int seaR[4]C[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]? *address*
- What is its value? $A + C * \text{sizeof}(T) * i \rightarrow \text{sea} + 5 * 4 * \text{index}$

<pre># %rdi = index leaq (%rdi,%rdi,4),%rax leaq sea(,%rax,4),%rax</pre>	<h2>Translation?</h2>
--	-----------------------

using a label as D

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)
```

just calculating an address, so no memory access

❖ 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

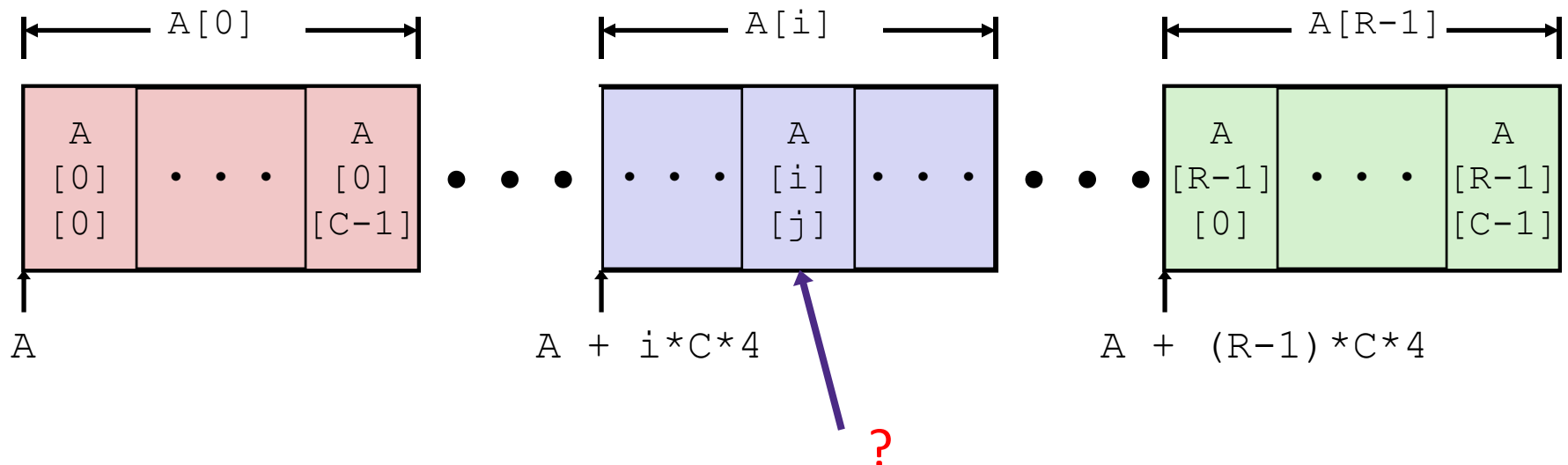
Nested Array Element Access

*reminder: $ar[j] = *(ar + j)$*

❖ Array Elements

- $A[i][j]$ is element of type T , which requires K bytes
- Address of $(A[i])$ _{address} $[j]$ is $(A + i * C * \text{sizeof}(T)) + j * \text{sizeof}(T)$

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



Nested Array Element Access

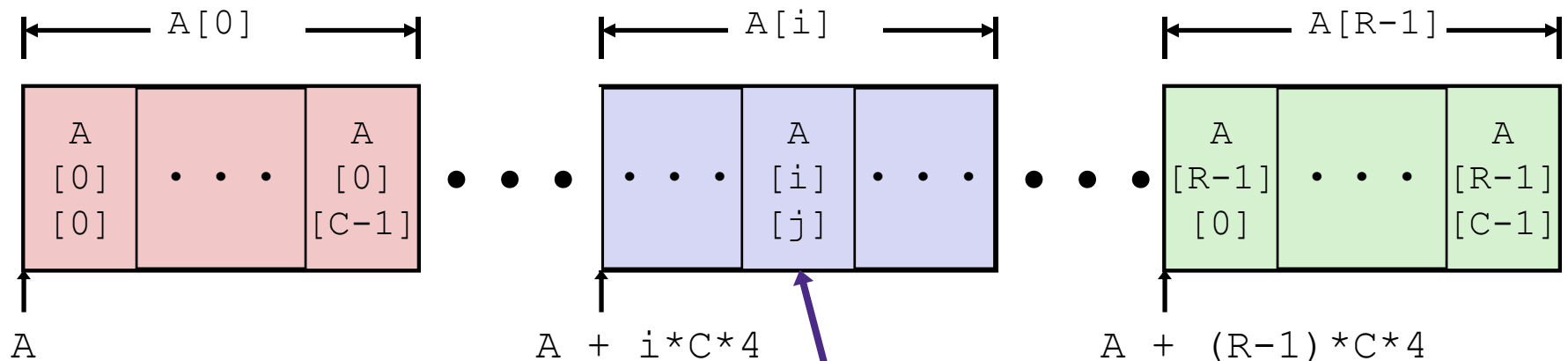
❖ Array Elements

- $A[i][j]$ is element of type \mathbf{T} , which requires K bytes
- Address of $A[i][j]$ is

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

*Handwritten notes: "Size of row" under $(C * K)$; a red arrow points from K in the second term to K in the first term.*

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



$A + i * C * 4 + j * 4$

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))
```

mov gets data

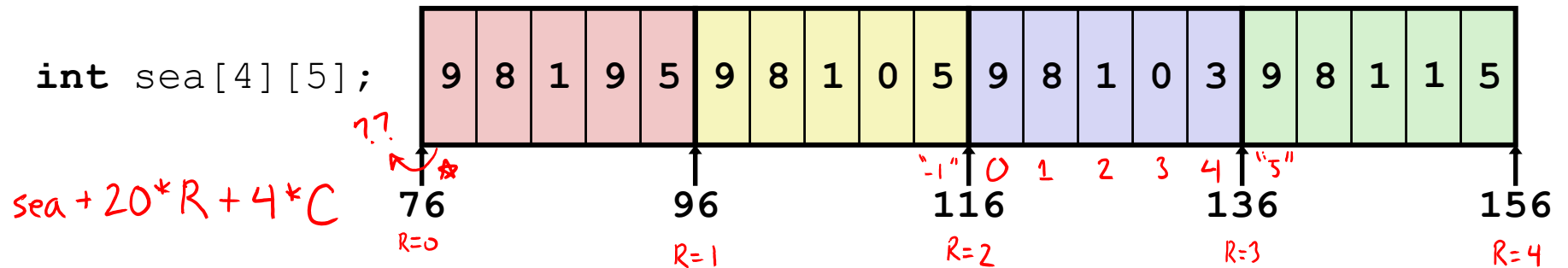
❖ Array Elements

- `sea[index][digit]` is an **int** (**sizeof(int)**=4)
- Address = `sea + 5*4*index + 4*digit`
start of array ↗ *start of row* ↗ *column of interest* ↗

❖ Assembly Code

- Computes address as: `sea + ((index+4*index) + digit)*4`
- `movl` performs memory reference

Multidimensional Referencing Examples



<u>Reference</u>	<u>Address</u>	<u>Value</u>	<u>Guaranteed?</u>
------------------	----------------	--------------	--------------------

<code>sea[3][3]</code>	$76 + 20 \cdot 3 + 4 \cdot 3 = 148$	1	Yes
<code>sea[2][5]</code>	$76 + 20 \cdot 2 + 4 \cdot 5 = 136$	9	Yes
<code>sea[2][-1]</code>	$76 + 20 \cdot 2 + 4 \cdot (-1) = 112$	5	Yes
<code>sea[4][-1]</code>	$76 + 20 \cdot 4 + 4 \cdot (-1) = 152$	5	Yes
<code>sea[0][19]</code>	$76 + 20 \cdot 0 + 4 \cdot (19) = 152$	5	Yes
<code>* sea[0][-1]</code>	$76 + 20 \cdot 0 + 4 \cdot (-1) = 72$??	No

- 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 };
```

} could be apart
4 arrays

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

univ[2][2] == 7

2D Array Declaration:

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

} guaranteed contiguous

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

NO

univ2D[2][2] == 7

1 array

One array declaration = one contiguous block of memory

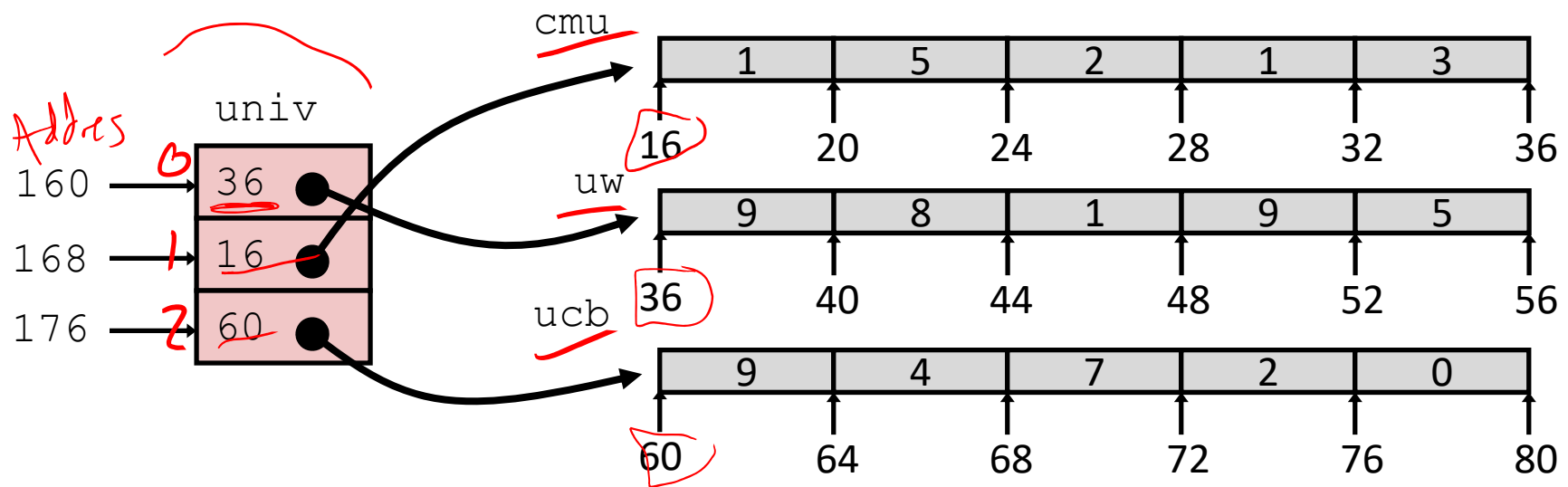
Multilevel Array Example

```

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};
    
```

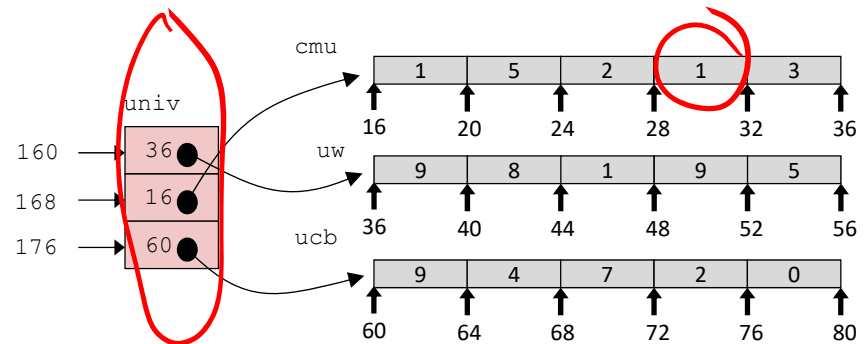
- ❖ Variable `univ` denotes array of 3 elements
 - ❖ Each element is a pointer
 - 8 bytes each
- ❖ Each pointer points to array of `ints`



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
```

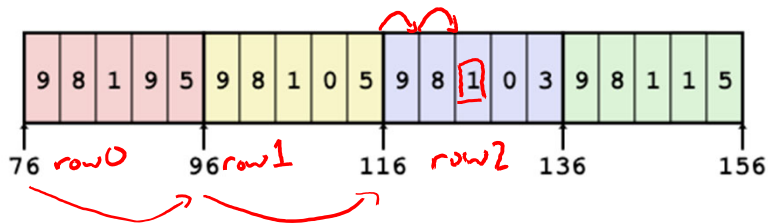
❖ Computation

- Element access $\text{Mem}[\text{Mem}[\text{univ} + 8 * \text{index}] + 4 * \text{digit}]$
- 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

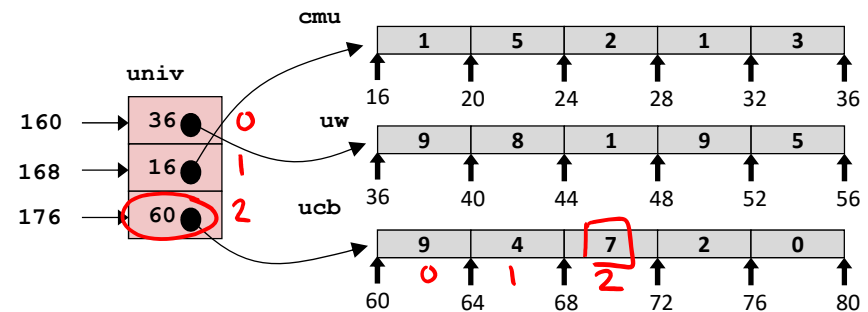
Multidimensional array

```
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:

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

more efficient:

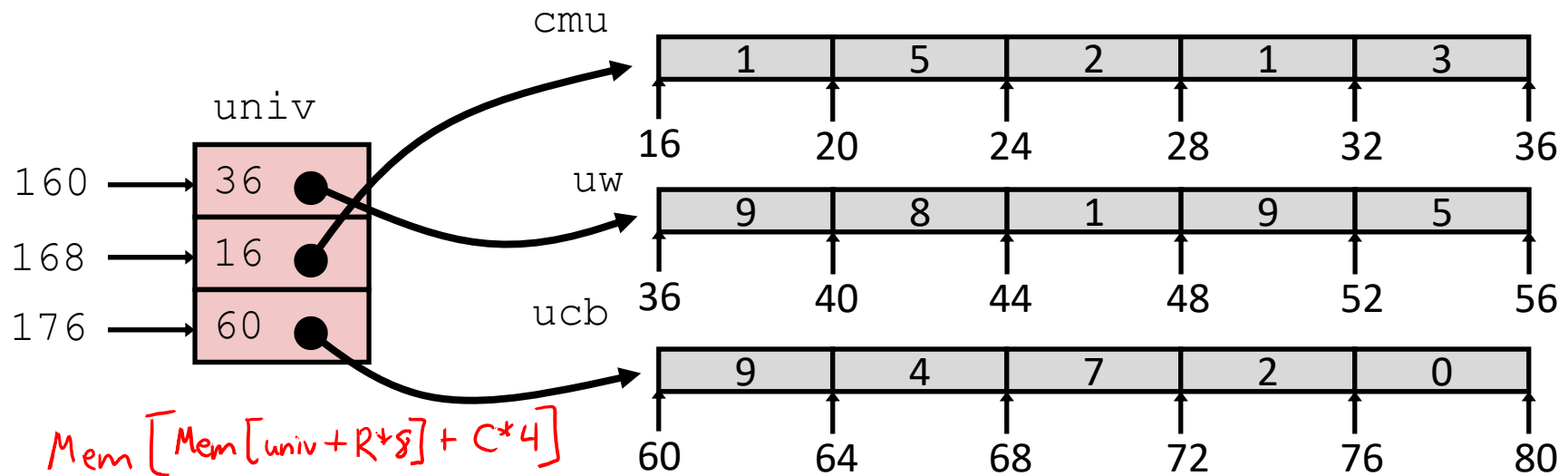
- less overall memory
- faster to access

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

more flexible:

- easier to "fit" smaller arrays in memory
- can swap out rows (and resize)
- can have rows of different lengths

Multilevel Referencing Examples



<u>Reference</u>	<u>Address</u>	<u>Value</u>	<u>Guaranteed?</u>
<code>univ[2][3]</code>	$Mem[176] + 3 * 4 = 60 + 12 = 72$	2	Yes
<code>univ[1][5]</code>	$Mem[168] + 5 * 4 = 16 + 20 = 36$	9	No
<code>univ[2][-2]</code>	$Mem[176] + (-2) * 4 = 60 - 8 = 52$	5	No
<code>univ[3][-1]</code>	$Mem[184] + (-1) * 4 = ?? - 4 = ??$???	No
<code>univ[1][12]</code>	$Mem[168] + 12 * 4 = 16 + 48 = 64$	4	No

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

Arrays 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