Executables & Arrays

CSE 351 Spring 2019

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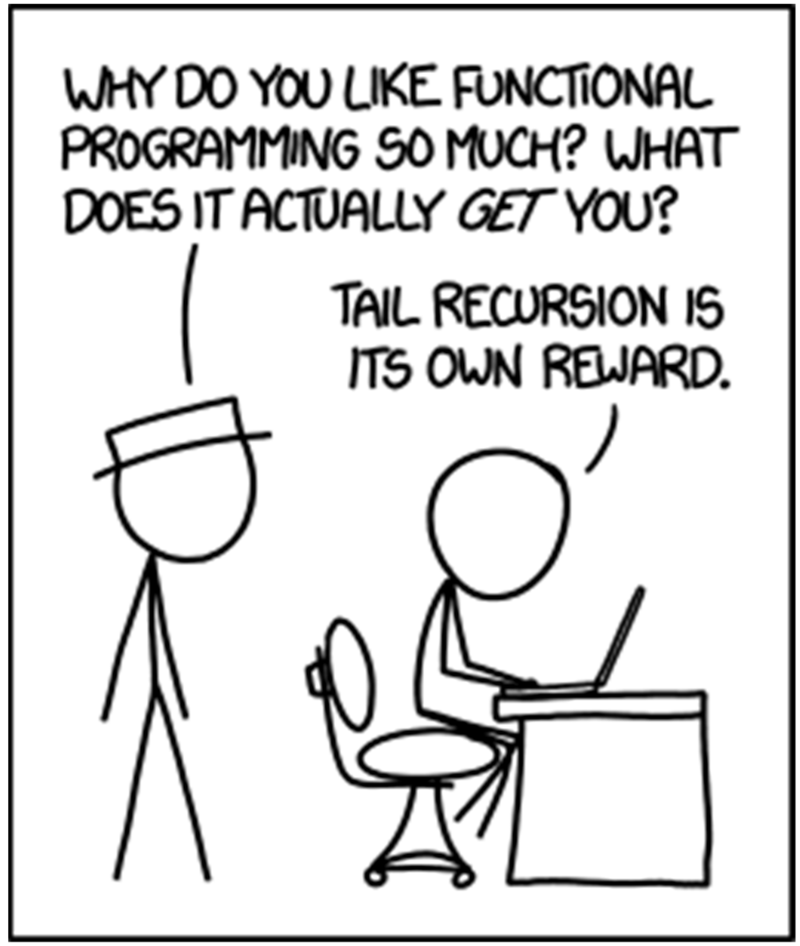


http://xkcd.com/1270/

Administrivia

- Lab 2 (x86-64) due Wednesday (5/01)
- Homework 3, due Wednesday (5/8)
  - On midterm material, but due after the midterm

- **Midterm** (Fri 5/03, 4:30-5:30pm in KNE 130)
  - No lecture on Friday 5/03
  - Ruth will hold office hours instead
    - Fri 11:30am-12:30pm in CSE 460
    - Fri 2:30-3:30pm in CSE 460

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
```

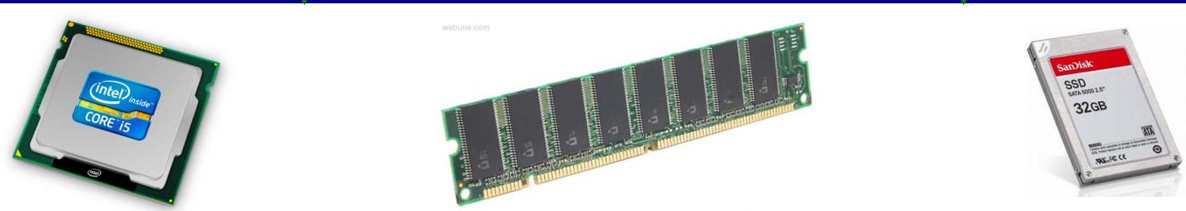
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

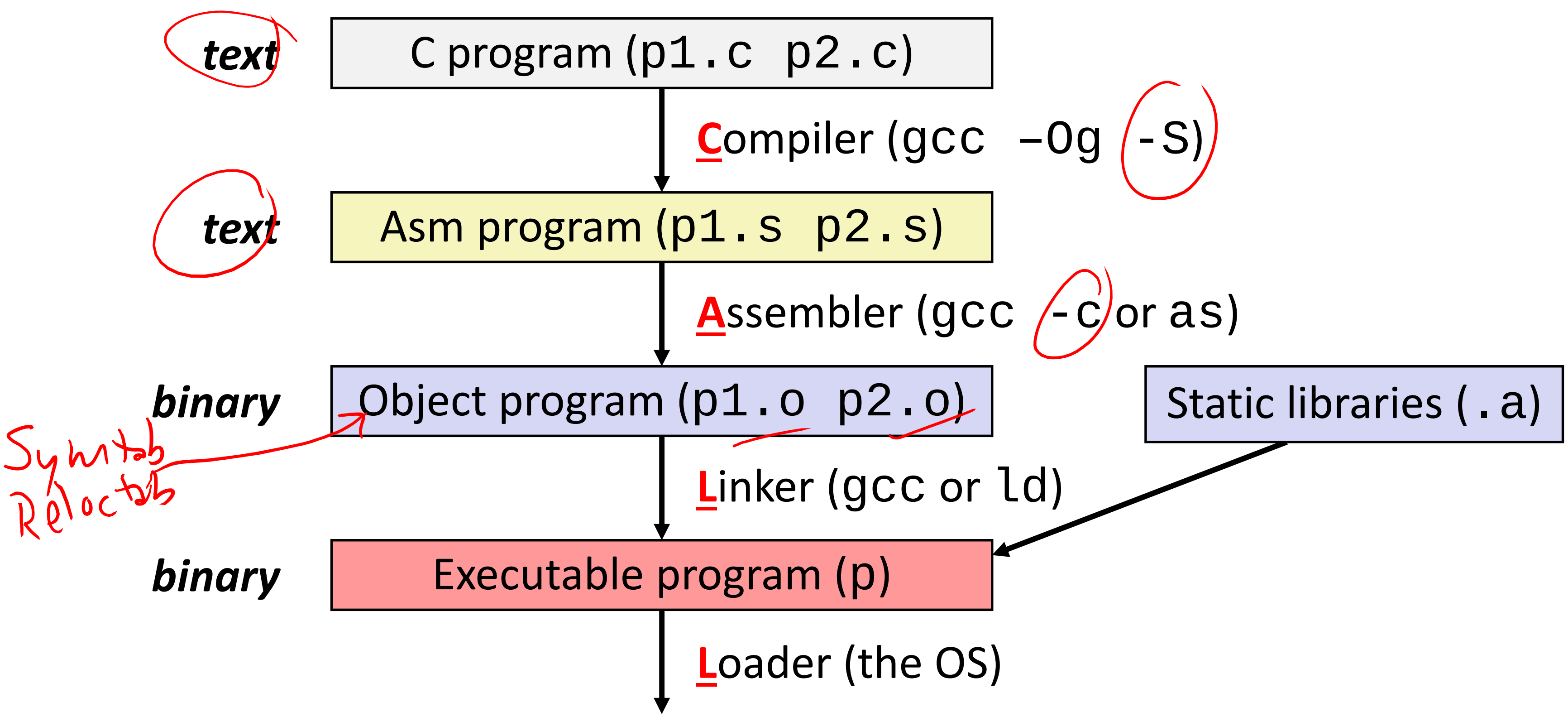
Windows 10
OS X Yosemite

Computer system:



Building an Executable from a C File

- Code in files `p1.c p2.c`
- Compile with command: `gcc -Og p1.c p2.c -o p`
  - Put resulting machine code in file p
- Run with command: `./p`



Compiler

- **Input:** Higher-level language code (*e.g.* C, Java)
  - `foo.c`
- **Output:** Assembly language code (*e.g.* x86, ARM, MIPS)
  - `foo.s`

- 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
- 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

- 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

- **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`

Producing Machine Language

Assembler

addq %rdi, %rsi

- **Simple cases:** arithmetic and logical operations, shifts, etc.
  - All necessary information is contained in the instruction itself

- What about the following?
  - Conditional jump addr/label
  - Accessing static data (*e.g.* global var or jump table)
  - `call` addr/label

- 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

Assembler puts in object file

- **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)
  - Any *label* or piece of *static data* referenced in an instruction in this file
    - Both internal and external "What I need"

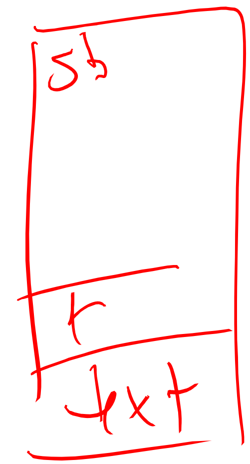
- Each file has its own symbol and relocation tables

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

Linker

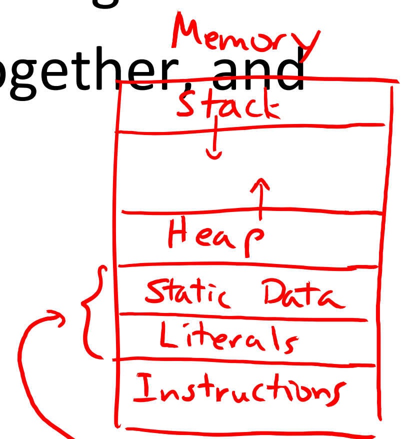


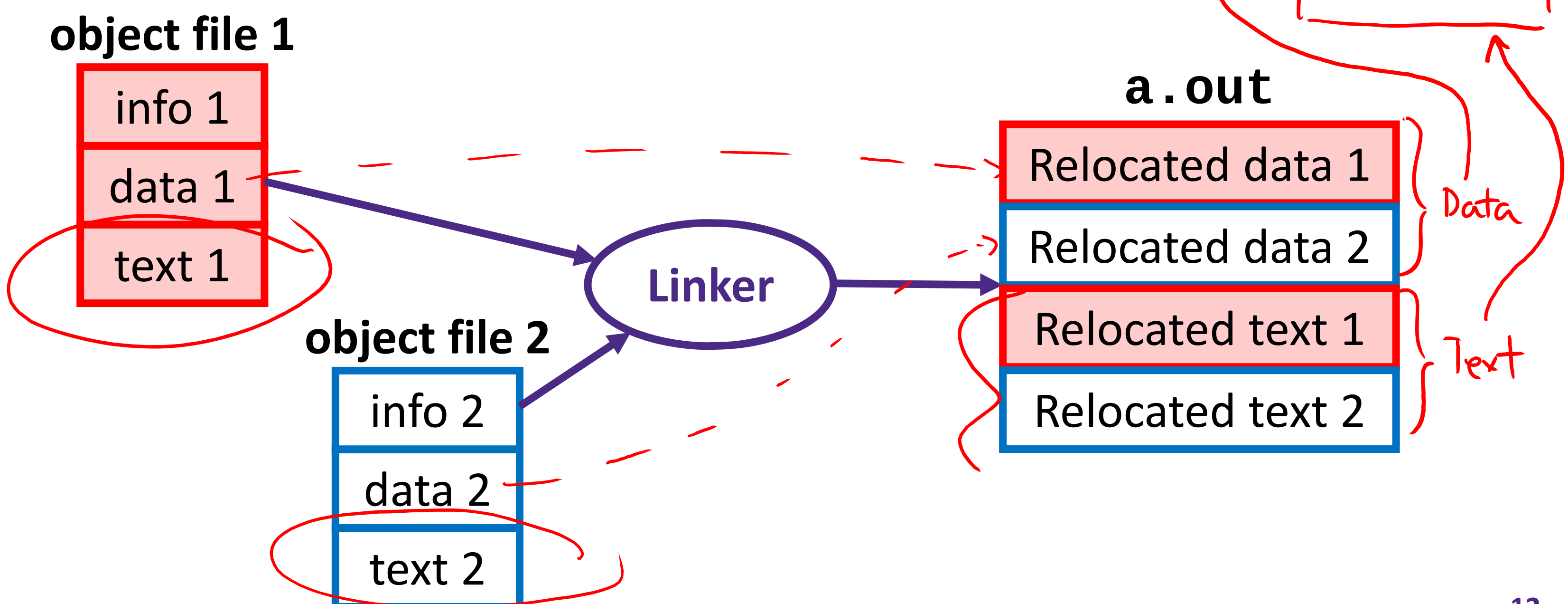
- **Input:** Object files (e.g. ELF, COFF)
  - `foo.o`
- **Output:** executable binary program
  - `a.out`

- 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

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

- Disassembled:

```
0000000000400536 <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.out` (complete executable) or `.o` 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

- **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

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:

Windows 10 OS X Yosemite

Computer system:

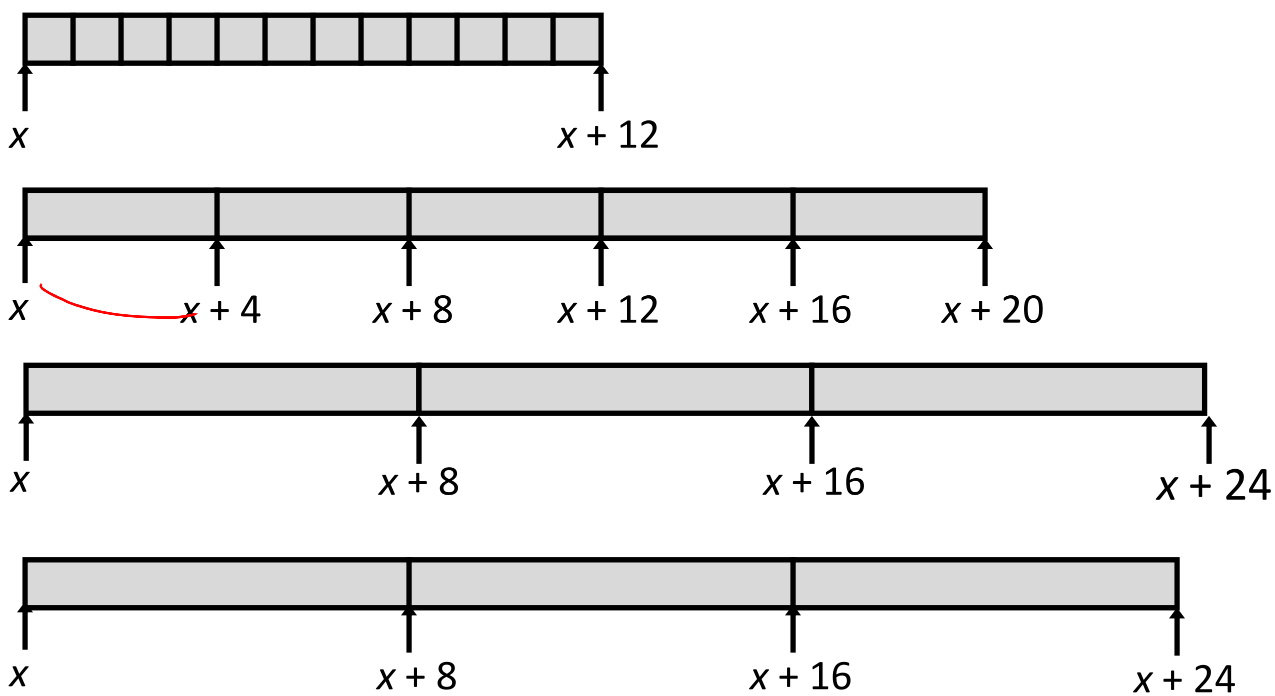

Data Structures in Assembly

- **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***)

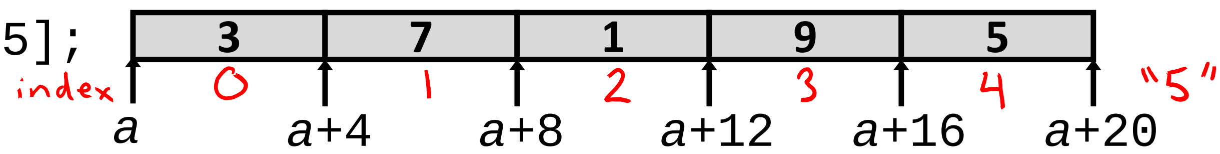
```
char msg[12];
int val[5];
double a[3];
char* p[3];
(or char *p[3];)
```



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
`x[4]`	**int**	5
`x`	**int***	a
`x+1` ← ptr arithmetic	**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 };
```

array of size 5 ints

typedef unsigned long int uli

old data type

new, equivalent data type

initialization

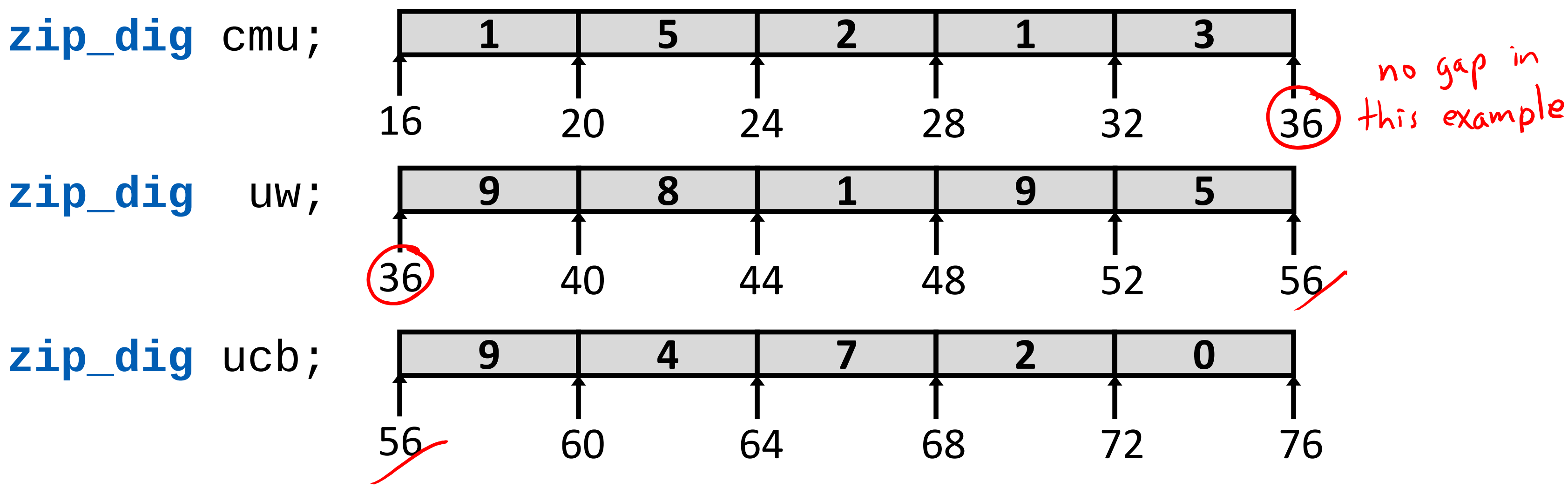
- `typedef`: Declaration "`zip_dig uw`" equivalent to "`int uw[5]`"

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 };
```

20 B each

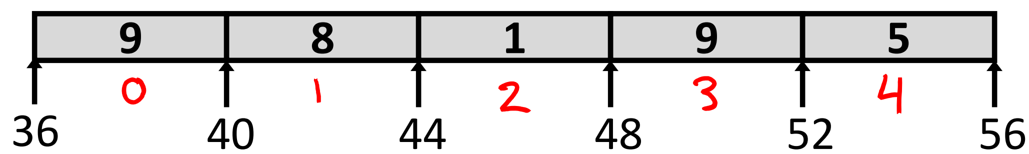


- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general (could have allocated variables in-between)

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

Array Accessing Example

```
zip_dig uw;
```




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

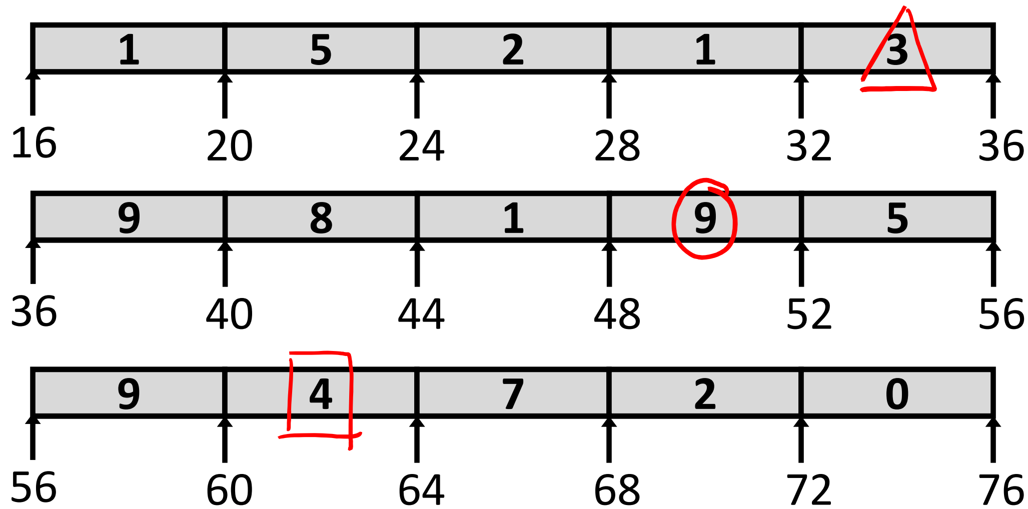
```
get_digit:
  movl (%rdi,%rsi,4), %eax  # z[digit]
```

- 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)`

Referencing Examples

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

Rb Ri S
uw 3 4



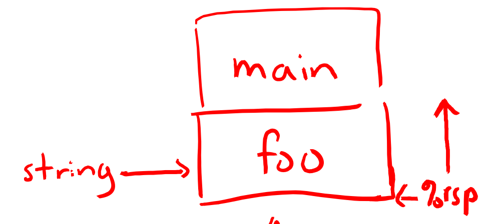
Reference	Address	Value	Guaranteed?
uw[3]	36+3*4=48	9	Yes
uw[6]	36+6*4=60	4	No
uw[-1]	36+(-1)*4=32	3	No
cmu[15]	16+15*4=76	?	No

- 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 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;
}
```

array is allocated on stack

returns stack addr that is < %rsp

data will get overwritten by future stack frames

BAD!

- 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
  - **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 }};
```

2D array

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

same as:

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

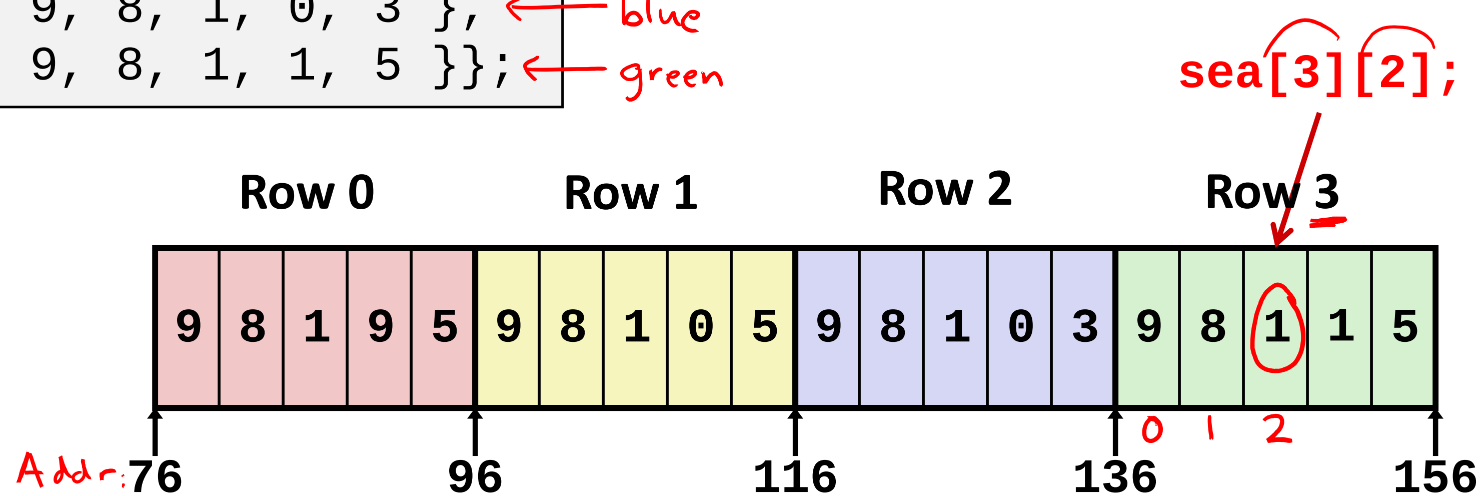
What is the layout in memory?

```
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)

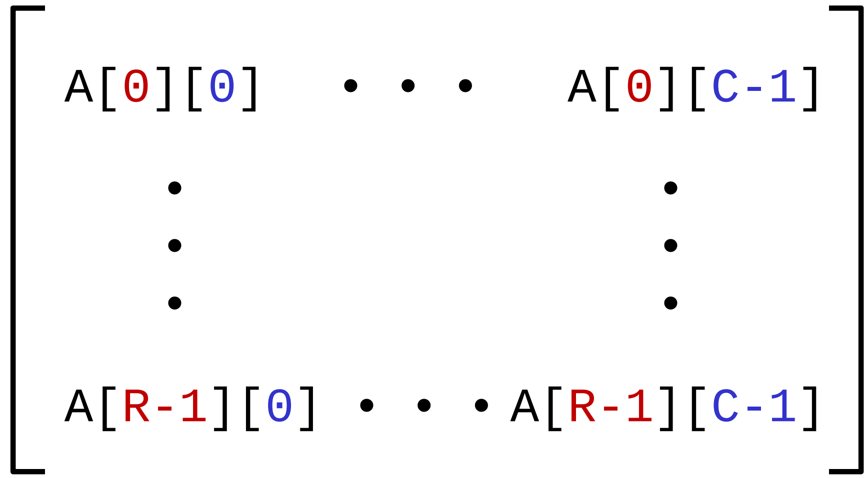
Two-Dimensional (Nested) Arrays

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

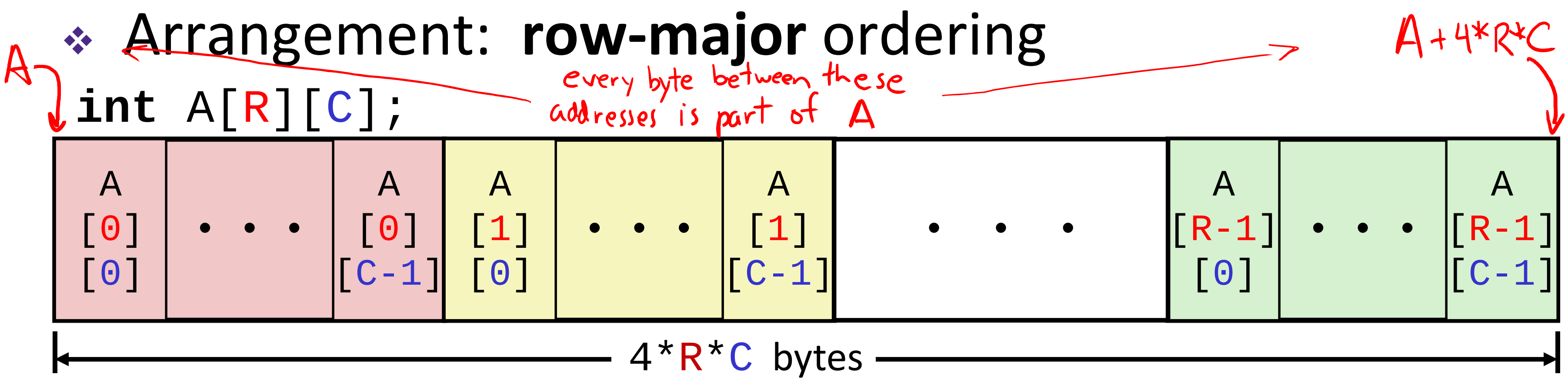
```
A[0][0]    • • •    A[0][C-1]
   •                    •
   •                    •
   •                    •
A[R-1][0]  • • • A[R-1][C-1]
```

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



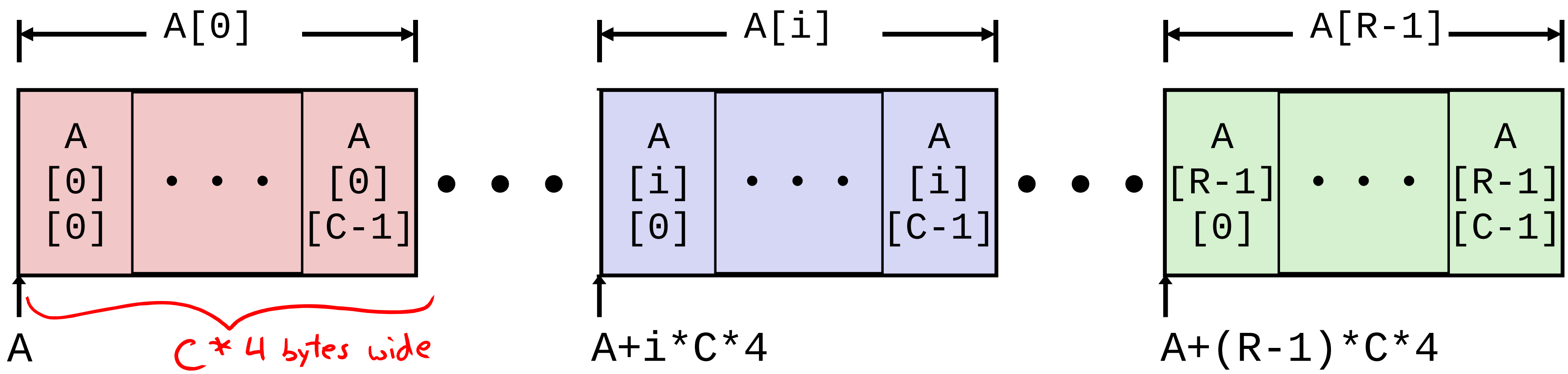
- Array size:
  - `R*C*`**`sizeof(T)`** bytes
- Arrangement: **row-major** ordering



Nested Array Row Access

- Row vectors
  - Given **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 * 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
...
```

address of array →

ends up in memory!

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 }};
```

R C

- What data type is `sea[index]`? address
- What is its value? A+ C*sizeof(T) * i → sea + 5 * 4 * index

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

using a label as D

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)
```

just calculating an address, so no memory access

- 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`

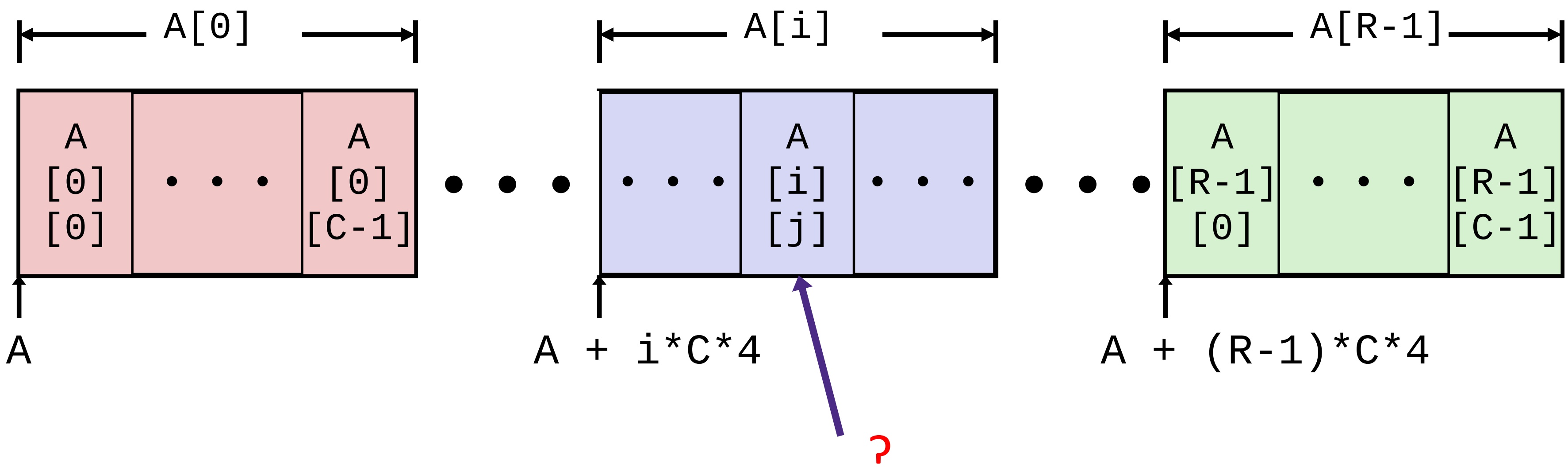
Nested Array Element Access

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

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

  address

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

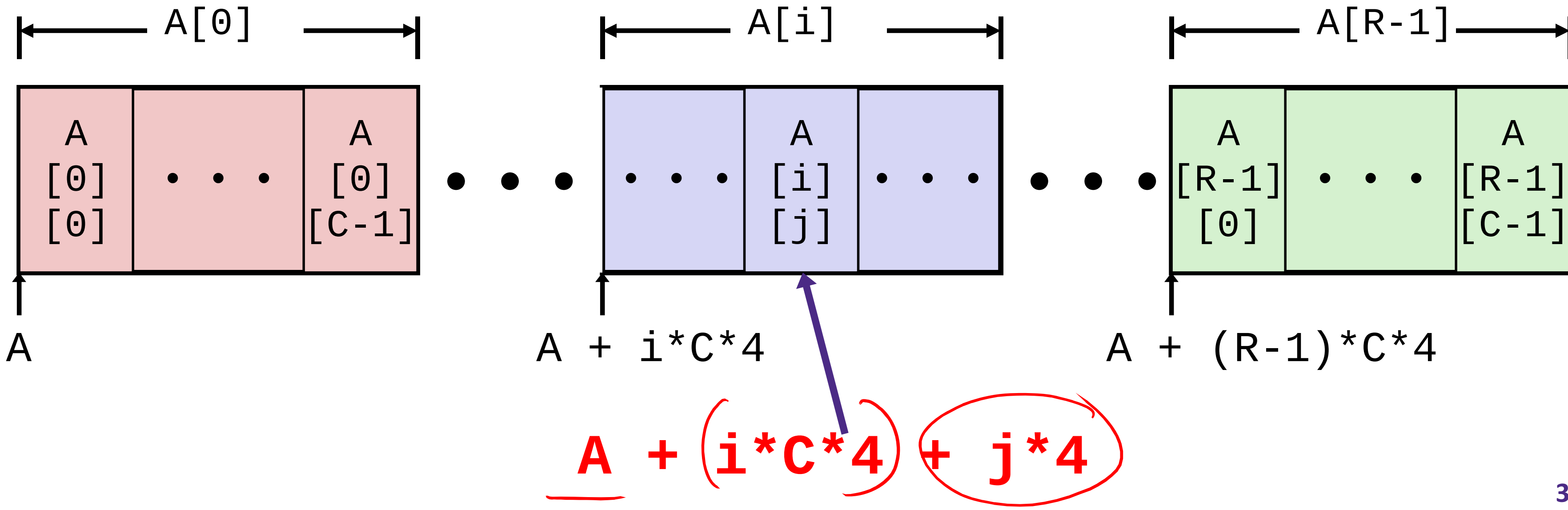


Nested Array Element Access

- 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))
```

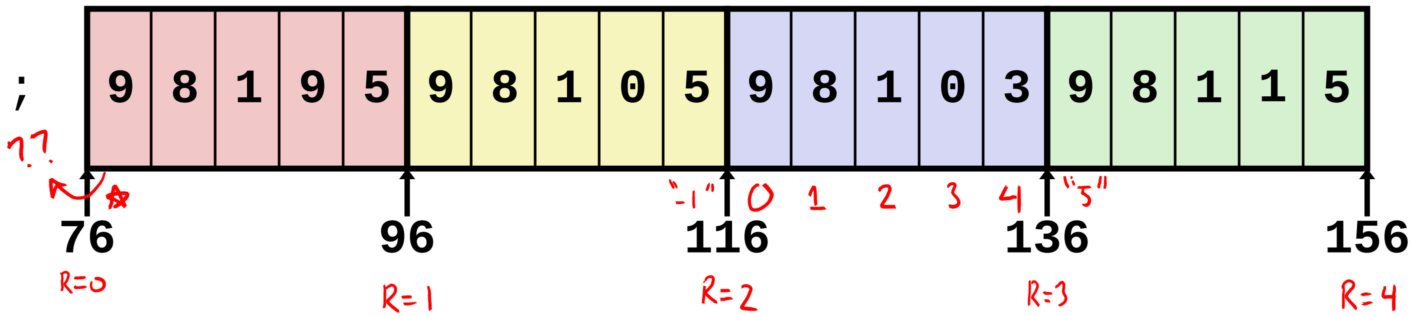
mov gets data

- 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

Multi-Dimensional Referencing Examples

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

sea + 20*R + 4*C



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 };
```

60B — could be apart — 4 arrays

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

24B

univ[2][2] == 7

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 }
};
```

60B — guaranteed contiguous ← 1 array

univ2D[2][2] == 7

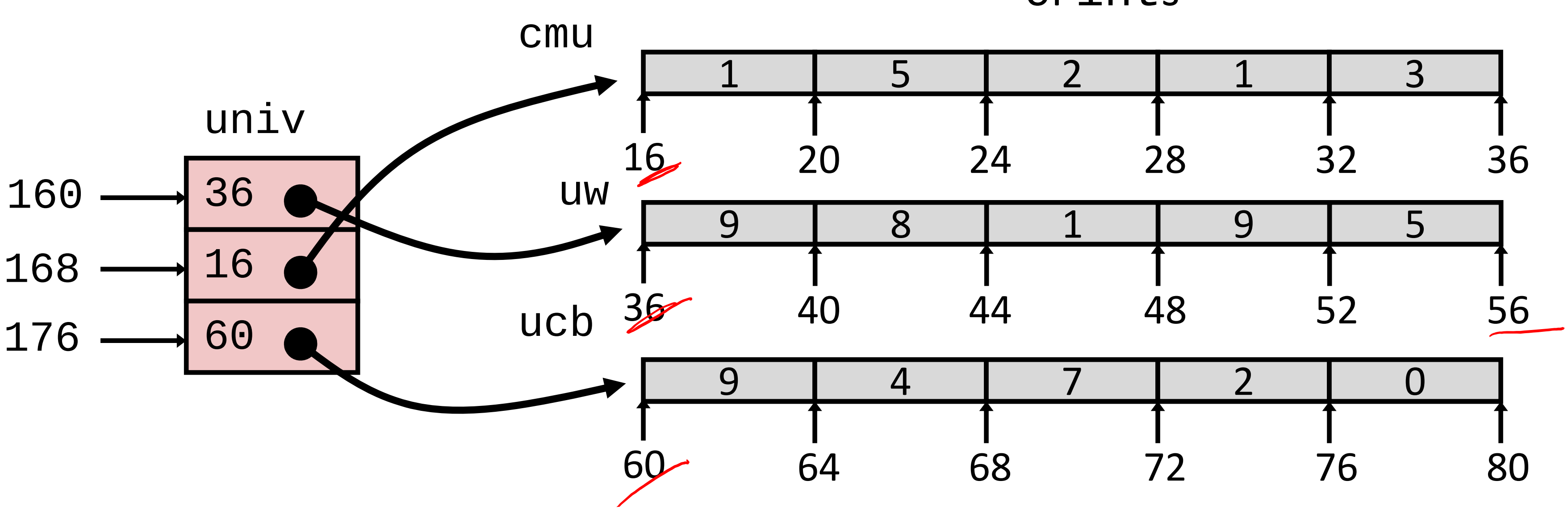
One array declaration = one contiguous block of memory

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};
```

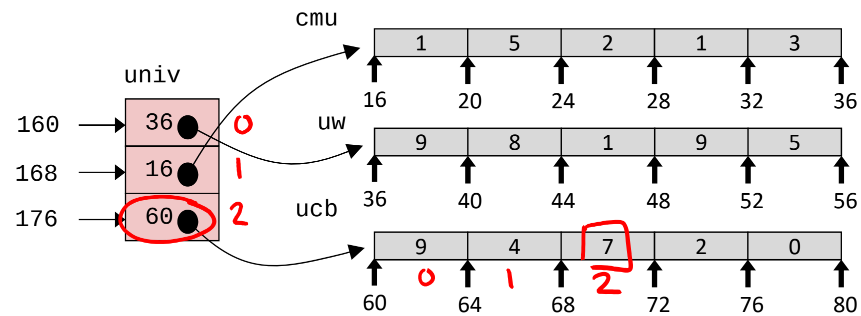
- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 8 bytes each
- Each pointer points to array of `int`s



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
```

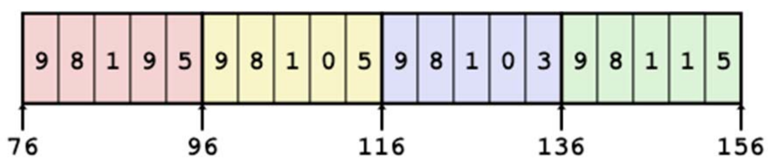
- Computation
  - Element access Mem[Mem[univ+8*index]+4*digit]
  - Must do **two memory reads**
    - First get pointer to row array
    - Then access element within array
  - But allows inner arrays to be different lengths (not in this example)

• also easier to "fit" smaller arrays in memory
• also can "swap out" rows in multi-level

Array Element Accesses

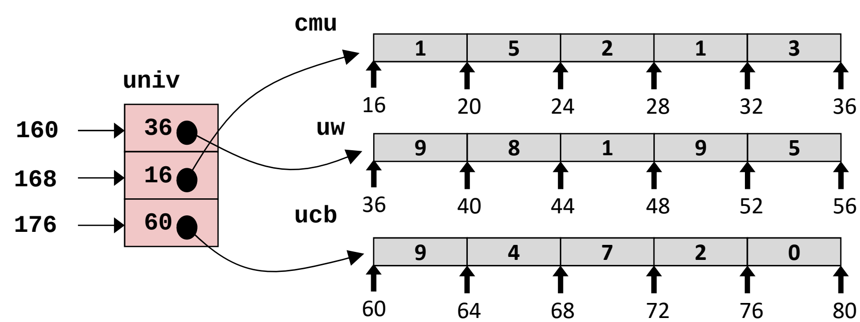
Nested array

```
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];
}
```

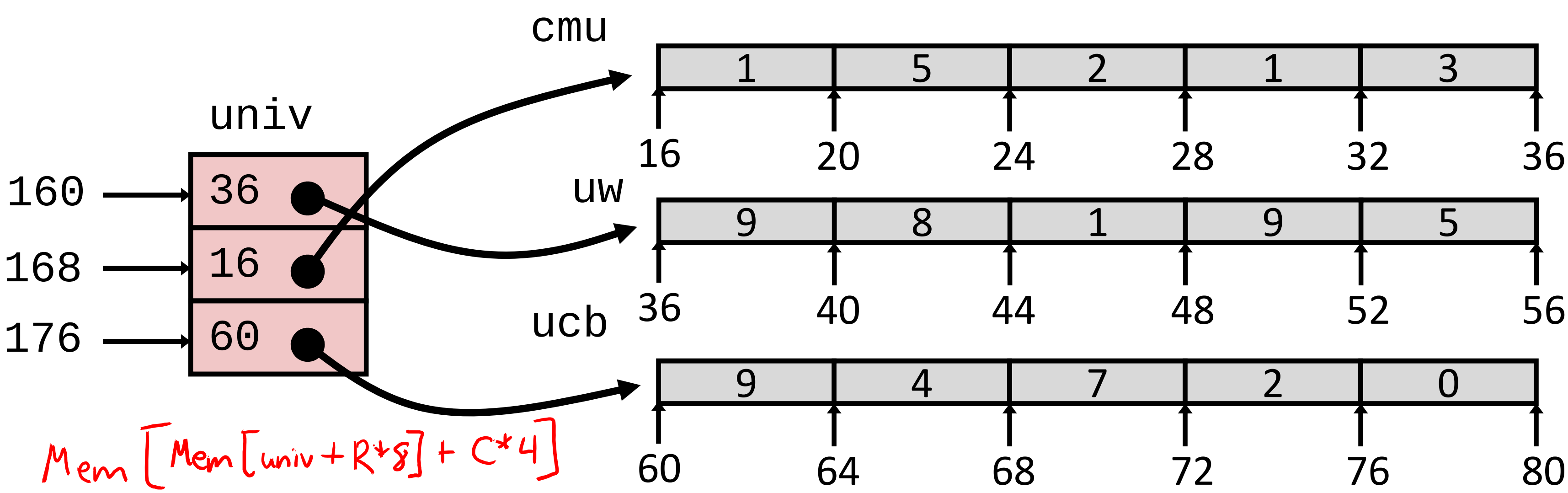


Access *looks* the same, but it isn't:

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

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

Multi-Level Referencing Examples



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

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